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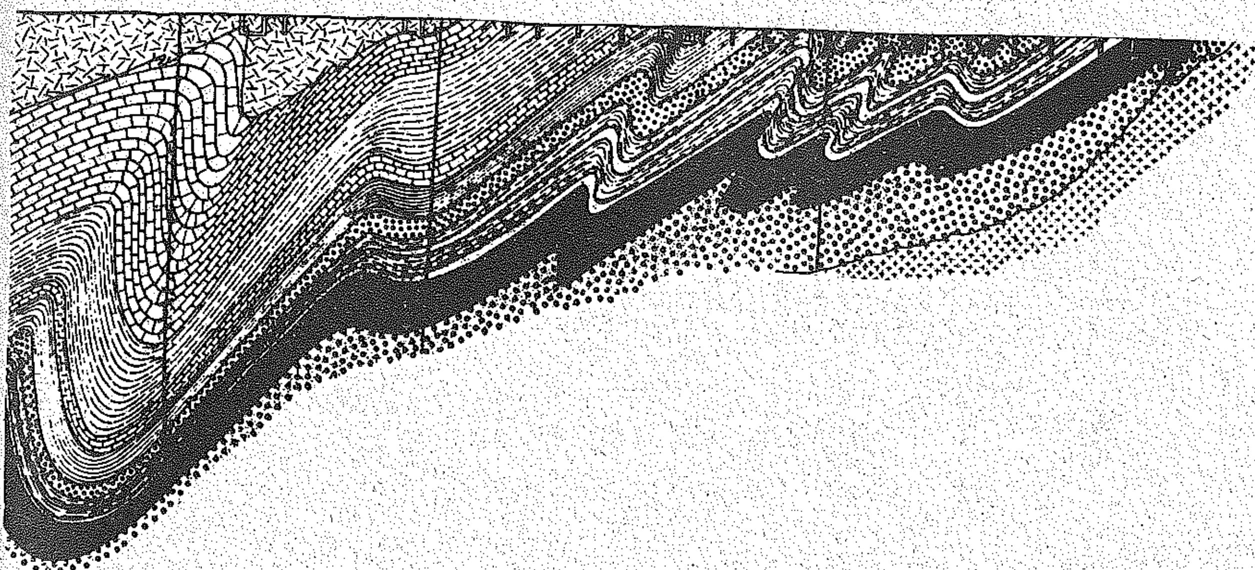

ECONOMIC GEOLOGY

RESEARCH UNIT

INFORMATION CIRCULAR #6

UNIVERSITY OF THE WITWATERSRAND

JOHANNESBURG

THE GEOMETRY OF CONJUGATE FOLD SYSTEMS

by

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FORWORD

During the period May-September, 1961, Dr. John G. Ramsay, of the Imperial College of Science and Technology, London, was actively associated with the Economic Geology Research Unit in the capacity of a visiting specialist in structural geology. He participated in the three research projects then in progress - specialized studies of the Damara System in South West Africa, the Witwatersrand System in the Transvaal and Orange Free State, the Basement Complex in the Barberton Mountain Land, Eastern Transvaal.

The investigation of the tectonic style present in the two last-named groups indicated that deformation had taken place, in part, while the rocks were in a brittle condition and that conjugate folds, an indicator of such conditions, were by no means uncommon. Excellent examples of such folds were seen along the Barberton-Havelock road and in the Zwartkop outlier of Witwatersrand rocks north of Krugersdorp. Using some of these examples as illustrations it was decided to compile a paper on the geometry of conjugate folding and this Information Circular is an adaptation of that paper.

Although the contents are of a general nature, the principles involved have specific application to the methods of deciphering the fold mechanisms which have played an important role in the development of the present distribution patterns of rocks of the Basement Complex and Witwatersrand System. The overall objective of the Economic Geology Research Unit is the delineation of the distribution patterns of the rock groups themselves and of the distribution patterns of economic mineralization within these two groups of rocks.

D.A. Pretorius
Senior Research Fellow

THE GEOMETRY OF CONJUGATE FOLD SYSTEMS

ABSTRACT

Conjugate shear fold systems are often developed when brittle laminated rocks are subjected to stress. These structures may have an orthorhombic, monoclinic or triclinic symmetry depending upon the relationship of the principal axes of stress to the surface being folded. Within first-order shear zones, conjugate second-order shear folds may be developed as a result of reorientation of the stress axes in these zones.

The axes of both first- and second-order conjugate shear folds may form at any angle to the principal stress axes and to the direction of movement within the shear zones. The principal axes of stress are most reliably determined from the orientation of the axial planes of the first-order conjugate folds.

THE GEOMETRY OF CONJUGATE FOLD SYSTEMS

CONTENTS

Enclosed: three diagrams plus explanations of text figures

THE GEOMETRY OF CONJUGATE FOLD SYSTEMS

INTRODUCTION

Conjugate folds may be defined as sets of paired, reversed folds whose axial planes are inclined toward one another. Although they had previously been recorded by earlier workers (GREENLY, 1919; DERTON, 1940), JOHNSON (1956) was the first to give a detailed account of their geometry together with an explanation of their mode of formation. He found that these structures were particularly well developed in deformed Torridonian, Lewisian and Moine rocks which lay within the Moine thrust zone of the Northern Highlands of Scotland. The opposing inclination of the paired axial planes indicated that there was no consistent movement of the upper over the lower beds, and he suggested that these fold systems were produced under brittle conditions by the development of a shear couple formed as a result of stress. The symmetry of the structures described by JOHNSON was orthorhombic and the line of intersection of the conjugate shear planes was coincident with the axes of the folds produced by slip in the shear zones.

During structural investigations in several localities in Britain and in other parts of the world, including the Barberton Mountain Land and the Witwatersrand Basin of the Transvaal, it has been found that folds of the type described by Johnson are common in many regions which have undergone tectonic deformation under brittle conditions, and that, although these structures are commonly associated with and localized near fault zones, they are often developed throughout all the rocks in an area that may extend over many square miles. The aim of this Information Circular is to present further geometrical details of these structures and to describe how the principal axes of stress may be determined from measurements made upon them.

THE GEOMETRY OF CONJUGATE FOLD SYSTEMS

The structures consist of paired monoclinal folds whose axial planes are inclined towards one another (fig. 1). The axial planes appear to represent a pair of conjugate shears, and the folds are the result of deformation of the bedding by slip movements upon these planes. Although the fold axial planes appear to represent shear surfaces, the monoclines themselves are probably developed by a mechanism of flexure, and are often of the type described as "concertina" or "zig-zag" folds (DE SITTER, 1956). The thickness of individual folded beds (measured normal to the bedding surfaces)

/...2

retains a fairly constant value, and in many examples of these folds the bedding planes are slickensided.

Conjugate folds are most commonly developed in thin-bedded or closely-laminated rocks, and only rarely are they found in thickly-bedded strata (where the beds exceed 10cm. in thickness). This feature is also in conformity with their development by a mechanism of flexure, for De Sitter (1958) has shown that it is easier to produce concertina-type flexure folds in a thinly-bedded rock sequence than in a thickly-bedded one.

Although in full agreement with Johnson's kinematic interpretation of these structures (JOHNSON, 1956, fig. 2), the author is of the opinion that these structures often exhibit a far greater variety of geometrical form than those illustrated by him. The examples figured by Johnson satisfy rather specialized conditions, not always occurring in nature, where the axis of axial symmetry normal to the undeformed bedding planes coincideswith the minimum stress direction of the deforming forces. The structure produced by deforming an initially horizontal bedding surface by such a stress system is shown in figures 2 and 3. In these figures the stress system has been arranged so that the minimum stress axis $\underline{P\ min}$ is vertical. The maximum stress axis $\underline{P\ max}$ is oriented E-W and horizontal, and the intermediate stress axis $\underline{P\ int}$ is N-S and horizontal. During deformation the rocks will fail on two conjugate shear planes ($\underline{s}^{1A}$ and $\underline{s}^{1B}$), and slip will proceed independently on these two surfaces along directions $\underline{a}^{1A}$ and $\underline{a}^{1B}$ respectively. At right angles to these two slip directions will be positioned the $\underline{b\ axis}$ of the shear movements: this will have the same orientation for both shear planes, and will coincide with the stress axis $\underline{P\ int}$. Slip on the shear planes will develop monoclinal folds on the bedding planes, and these will have axes $\underline{f}^{1A}$ and $\underline{f}^{1B}$ controlled by the intersection of the shear surfaces $\underline{s}^{1A}$ and $\underline{s}^{1B}$ with the bedding planes. With the relationship between the axes of stress and the bedding planes as shown in fig.2, the fold axes will always be parallel, and will coincide with $\underline{P\ int}$ and the $\underline{b}$ direction on the shear planes. The deforming stress has orthorhombic symmetry: three axes of two-fold symmetry (the principal stress axes), and three planes of symmetry (each containing two of the principal stress axes). The bedding planes before deformation have one axis of axial symmetry, and an infinite number of planes of symmetry containing this axis. Because the axis of axial symmetry of the bedding planes coincides with one of the axes of symmetry of the stress system ($\underline{P\ min}$), the symmetry of the resulting structure will be that of the lowest symmetry combination of these, i.e. orthorhombic (see WEISS, 1955, WEISS and PATERSON, 1961).

The example described above is obviously a special and particular one which has resulted from a specific arrangement of the deforming stresses to the bedding planes, and many, in fact most, conjugate folds have a geometry like that shown in figures 4 and 5. The most striking feature of this structure is the complexity of the appearance of the folds resulting from the crossing of the sets of fold axes related to the two sets of shear planes. Cross-sections of structures like this look similar to those illustrated in figure 2, but because the intersection of the two shear planes $\underline{s}^{1A}$ and $\underline{s}^{1B}$ ($\underline{P\ int}$) does not lie on the bedding surface ($\underline{Pmin}$ not perpendicular to the bedding planes) the shear surfaces develop independently oriented fold axes $\underline{f}^{1A}$ and $\underline{f}^{1B}$ where they intersect the bedding. Although the orientation of the slip planes $\underline{s}^{1A}$ and $\underline{s}^{1B}$, the directions of slip in them ($\underline{a}^{1A}$ and $\underline{a}^{1B}$), and their intersection ($\underline{b}$, at right angles to $\underline{a}^{1A}$ and to $\underline{a}^{1B}$) are controlled by the orientation of the principal stress axes, the location of the fold axes on the shear planes is not dependent upon these stress axes. The fold axes give no indication of either the rock movements or the stress conditions which produced them.

To determine the stress axes of the forces which produced structures like those in figure 4, it is necessary to measure the orientation of the two sets of fold axial planes and to plot them graphically on a stereogram. The intersection of the two shear surfaces will give $\underline{P\ int}$, and the bisectors of the two surfaces will give $\underline{P\ max}$ and $\underline{P\ min}$. It must be emphasised here that, in practice, it may be found that $\underline{P\ max}$ does not always consistently bisect the acute angle between the shears, but that from the shape of the conjugate fold it is always possible to determine which is the correct bisector giving $\underline{P\ max}$. It is not possible to locate the stress axes if only one set of shear structures is developed, nor is it possible to determine the movements on the shear surface from the orientation of the fold axes adjacent to the shear. The often quoted method of determining the movement on a fault plane by discovering the line at right angles to the axes of drag folds produced by movements on the fault (NEVIN, 1936; HILLS, 1940; BILLINGS, 1942) is therefore invalid.

The symmetry of structures of this type is no longer orthorhombic. If the axis of axial symmetry of the bedding planes lies on one of the symmetry planes of the deforming stress system, the resulting structure can only possess one symmetry plane, and, therefore, have a monoclinic symmetry. Even this arrangement is a fortuitous one, however, and, in general, there need be no coincidence between the two groups of symmetry elements. The structure which is produced will then have a triclinic symmetry. Investigations of these structures seems to indicate that, although triclinic forms do occur frequently, monoclinic and orthorhombic forms are more abundant than would be developed

/...4

by chance alone. It would appear that the bedding planes frequently contain P max (as shown in figures 4 and 5), and that the beds act as the transmitting agent for this stress.

An actual example of a conjugate fold of this type will now be described to illustrate the methods whereby the stress axes may be calculated. The exposure of conjugate folds is a particularly fine one, situated 1½ miles ENE of Barberton, Eastern Transvaal. The rocks are shales of the Moodies Formation which has suffered several periods of folding, the last of which produced conjugate shear folds over an area of at least 10 square miles. To obtain a complete geometrical picture of the structure illustrated in figure 6 the following data were obtained:-

Regional orientation of the bedding planes, strike 10° dip 74° WNW.

Axial plane (s^{1A}) of conjugate fold, strike 10° dip 27° WNW.

Axial plane (s^{1B}) of conjugate fold, strike 84° dip 67° S.

Fold axis (f^{1A}), horizontal, trend 10°.

Fold axis (f^{1B}), plunge 55° towards 218°.

Plotting the two axial planes (figure 7), their intersection gives P int (25° towards 253°). Noting the shape of the structure and consequently bisecting the obtuse angle between the planes, P max is obtained (55° towards 27°), and bisecting the acute angle between the shears, P min is found (23° towards 151°). The axes of folding (f^{1A} and f^{1B}) are situated where the shear planes cross the bedding planes, and by themselves give no information about the movements. The symmetry of the structure is triclinic.

If the maximum and minimum stress directions are oriented at about 45° to the bedding planes, then, of the two shears that develop, one will cut the bedding planes at a high angle, and the other may lie so close to the bedding that the shear movements dissipate themselves entirely by slip on the bedding surfaces. This arrangement of stresses, therefore, producesonly one set of monoclinal step-like folds similar to those known as kink-bands, or joint drags.

/...5

SECOND-ORDER CONJUGATE FOLDS

ANDERSON (1951), McKINSTRY (1953), and MOODY and HILL (1956) have examined secondary shear features associated with faults and have developed the theory that movements within a main shear zone may rearrange the stresses in the immediate vicinity of the shear in such a way as to cause failure of the rock on a new set of complimentary fractures known as second-order shears. Second-order structures of this type are occasionally developed within the first-order shear zones of conjugate folds. An example of this is shown in figure 8, taken from the same locality as that of figure 6. The laminated shales are crossed by a first-order shear zone oriented in almost the same way as the shear zone $\underline{s}^{1B}$ of figure 6. Within this zone, however, there are a series of en-echelon second-order shear folds which appear to have been developed as a result of rearrangement of the principal stress directions within the main shear zone.

The axes of these second-order shear folds will only be parallel to those of the first-order if the axis $\underline{P\ int}$ lies within the planes being folded. An example, which illustrates the relationship between the orientation of the fold axes to the stresses producing the shears and which is of more general application, is illustrated in figures 9 and 10. The originally horizontal bedding planes have been subjected to stresses with the axes $\underline{P\ max}^1$, $\underline{P\ int}^1$, and $\underline{P\ min}^1$ as shown. Two parallel first-order shear zones ($\underline{s}^1$) which could develop as a result of this deformation cut the bedding surfaces, and any shear movements on these surfaces in the direction $\underline{a}^1$ would produce folds with axes $\underline{f}^1$, as described previously. The movements within these shear planes could, however, rearrange the stress axes to positions $\underline{P\ max}^2$ and $\underline{P\ min}^2$, so that the angle between $\underline{P\ max}^2$ and s^1 is 75^0 (MOODY and HILL, 1956, p.1211-4). $\underline{P\ int}^2$ will coincide with $P\ int^1$. This reorientation of the axes of stress could lead to failure of the rocks by shear on one or both of two second-order shear planes, $\underline{s}^{2A}$ and $\underline{s}^{2B}$. Slip movements within these surfaces in directions $\underline{a}^{2A}$ and $\underline{a}^{2B}$ respectively will produce zones of en-echelon folds with axes $\underline{f}^{2A}$ and $\underline{f}^{2B}$, respectively governed by the intersections of the bedding planes and the second-order shear planes.

In dealing with structures of this type the orientations of the fold axes again give no indication of the movements which produced the folds, but, if both second-order shear planes can be measured, it is possible to calculate $\underline{P\ int}^2$ (intersection of $\underline{s}^{2A}$ and s^{2B}), $\underline{P\ max}^2$ and $\underline{P\ min}^2$ (acute and obtuse bisectors of $\underline{s}^{2A}$ and $\underline{s}^{2B}$). $\underline{P\ int}^1$ is coaxial with $\underline{P\ int}^2$, but $\underline{P\ max}^1$ and $\underline{P\ min}^1$ are difficult

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to calculate. If the second-order stresses are positioned according to the theories of MOODY and HILL (where $\underline{P\ max}^1 \angle P\ max^2\ 75^\circ$), then it should be possible to calculate the positions of the primary stress axes; but wherever practicable, a more reliable estimate should be made from measurements of paired first-order shears.

CONCLUSIONS

Conjugate folds and related structures (kink bands, knick bands, joint drags) are characteristic of rock deformation under brittle conditions, and appear to be produced by movements on one or more shear surfaces which usually (but not invariably) make an angle of less than 45° to the principal stress axis. They are frequently found in rocks deformed during the later phases of orogenic deformation, and are often related both in space and in time with the development of faults, thrusts and joints.

Under certain conditions the geometry of the structures may show the orthorhombic symmetry of the deformin movements, but generally these structures possess a much lower symmetry, and are either monoclinic or triclinic. Conjugate folds with this low symmetry have a highly complex appearance as a result of the development of crossing fold axes. Measurements of the axial planes of these folds can be employed to deduce the stress axes of the forces which produced the structure. The axes of conjugate folds cannot be used to determine the principal axes of stress.

Complex en-echelon second-order shear folds may be developed within the primary conjugate shear zones. These structures cannot be used to determine all the primary stress axes without employing some theoretical assumptions as to the angular relations between the first- and second-order shear zones.

If, during regional structural studies, the principal stress axes for individual conjugate fold sets are calculated, it is generally found that, although there may be some local variation in the position of these axes, there is some systematic regional orientation. There may be a consistently oriented maximum stress direction, or only the minimum stress axis may show any constancy, a feature which suggests that conjugate folds may, in some instances, develop under conditions of regional tension.

/...7

ACKNOWLEDGEMENTS

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LIST OF REFERENCES

ANDERSON, E.M.	1951	The dynamics of faulting. 2nd Edn. Oliver & Boyd, Edinburgh.
BILLINGS, M.P.	1942	Structural geology. Prentice Hall, New York.
DARTON, N.H.	1940	Some structural features of the Northern Coal Basin, Pennsylvania. U.S. Geol. Survey, Prof. Paper 193.
GREENLY, E.	1919	The Geology of Anglesey. Mem. Geol. Surv. Gt. Britain.
HILLS, E.S.	1940	Outlines of structural geology. Methuen, London.
JOHNSON, M.R.W.	1956	Conjugate fold systems in the Moine thrust zone in the Lochcarron and Coulin Forest areas of Western Ross. Geol. Mag. xciii, p.345-350.
McKINSTRY, H.E.	1953	Shears of the sedcond-order. Amer. Jour. Sci. v.251, pp.401-414.
MOODY, J.D. & HILL, M.J.	1956	Wrench fault tectonics. Bull. Geol. Soc. Amer. v.67, pp.1207-1246.
NEVIN, C.M.	1936	Principles of structural geology. Wiley, New York.

SITTER, L.U. de, 1956 Structural geology. McGraw Hill. London.

SITTER, L.U. de, 1958 Boudins and parasitic folds in relation to cleavage and folding. Geol. en Mijn. v.20, pp.277-286.

WEISS, L.E. 1955 Fabric analysis of a triclinic tectonite and its bearing upon the theory of flow in rocks. Amer. Jour. Sci. v.253, pp.225-236.

WEISS, L.E. & PATERSON, M.S. 1961 Symmetry concepts in the structural analysis of deformed rocks. Bull. Geol. Soc. Amer. v.72, pp.841-882.

EXPLANATIONS TO TEXT-FIGURES

FIG. 1 Cross-section of conjugate folds in mylonized quartzo-felspathic Lewisian gneiss from the base of the Tarskavaig nappe, Sleat, Isle of Skye, Northern Highlands of Scotland.

FIG. 2 Geometry of conjugate folds with orthorhombic symmetry. For a structure of this symmetry to develop, P min must be positioned normal to the surface being folded. The rocks fail on two shear surfaces s^{1A} and s^{1B} and develop parallel fold axes f^{1A} and f^{1B}.

FIG. 3 Stereographic plot of the geometrical features illustrated in Fig. 2. The folded surface was initially horizontal.

FIG. 4 Geometry of conjugate folds with monoclinic symmetry. Structures with monoclinic symmetry develop where P max is contained in the surface being folded, but P min is not normal to this surface; structures with a lower symmetry (triclinic) will form when P max is not contained in the surface. The rocks fail on two shear surfaces s^{1A} and s^{1B} and develop folds f^{1A} and f^{1B} respectively.

FIG. 5 Stereographic projection of the elements of a conjugate fold system with monoclinic symmetry developed on an initially horizontal surface as shown in Fig. 4.

FIG. 6 Cross section of a conjugate fold system with triclinic symmetry from near Barberton, Eastern Transvaal.

FIG. 7 Stereographic plot of the triclinic conjugate fold structures shown in Fig. 6, illustrating the method of constructing the principal axes of stress.

FIG. 8 A zone of en-echelon second-order shear folds from the Barberton area, Eastern Transvaal.

FIG. 9 Geometry of second order conjugate shear folds. The stresses $P\ max^1$, $P\ int^1$ and $P\ min^1$ lead to the development of two conjugate shear zones (only one of which is represented in this diagram, s^1). Within the shear zone s^1 new principal stresses may be set up ($P\ max^2$, $P\ int^2$ and $P\ min^2$), and these could lead to the failure of the rocks on two second-order shear surfaces s^{2A} and s^{2B} and the production of second order folds f^{2A} and f^{2B}. The structure has a triclinic symmetry.

FIG. 10 Stereographic plot of the geometrical features of Fig. 9.

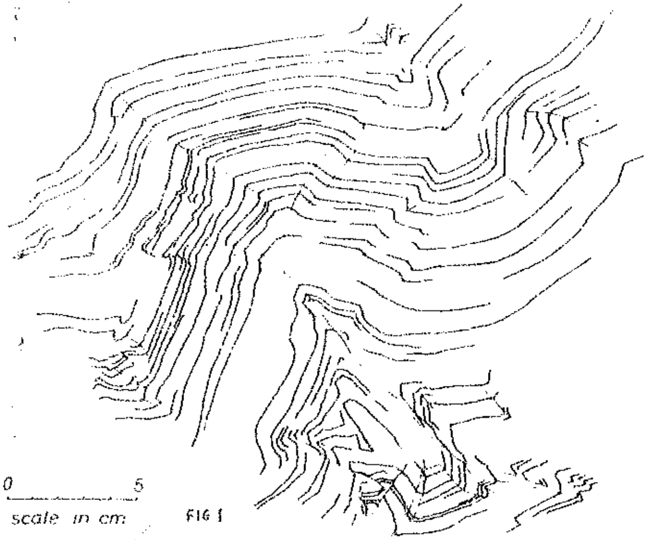

FIG 1

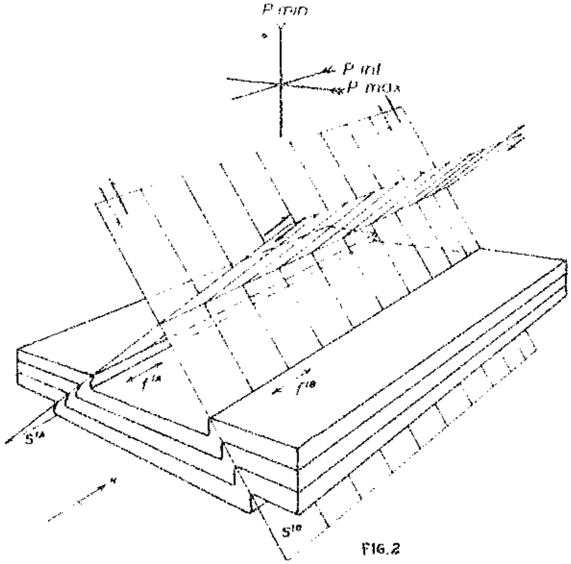

FIG. 2

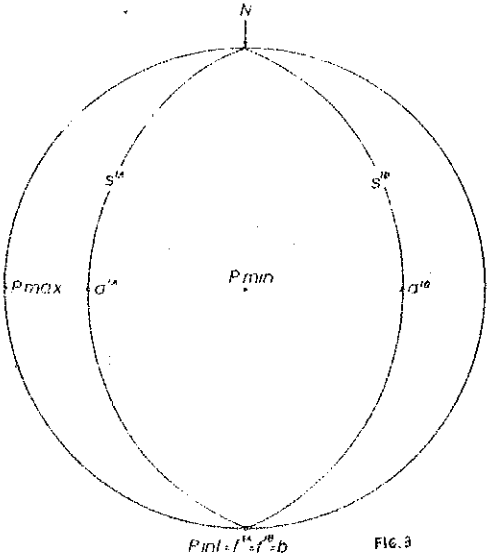

FIG. 3

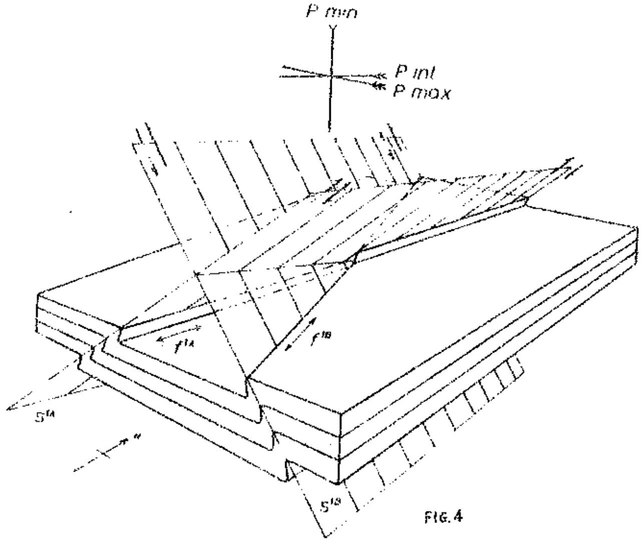

FIG. 4

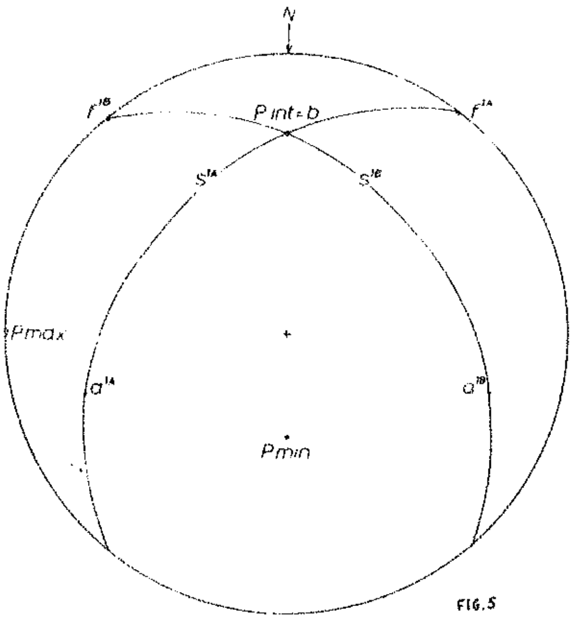

FIG. 5

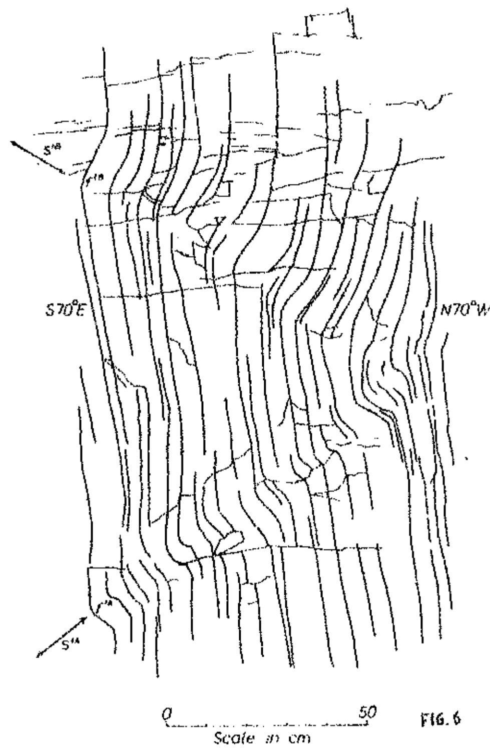

FIG. 6

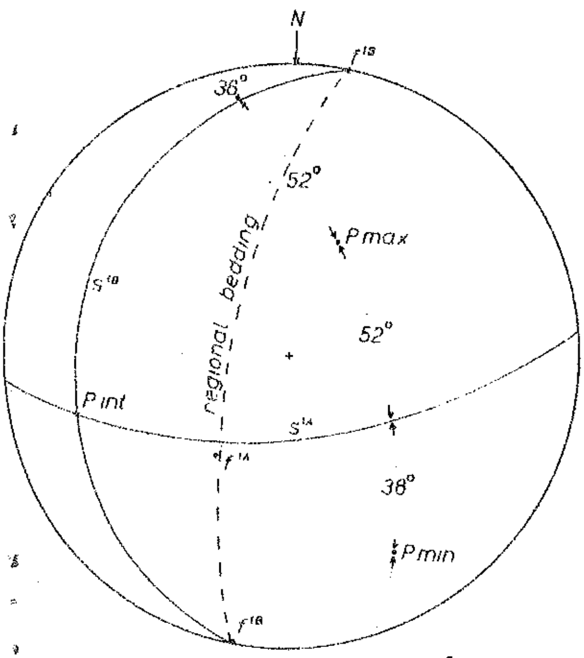

FIG. 7

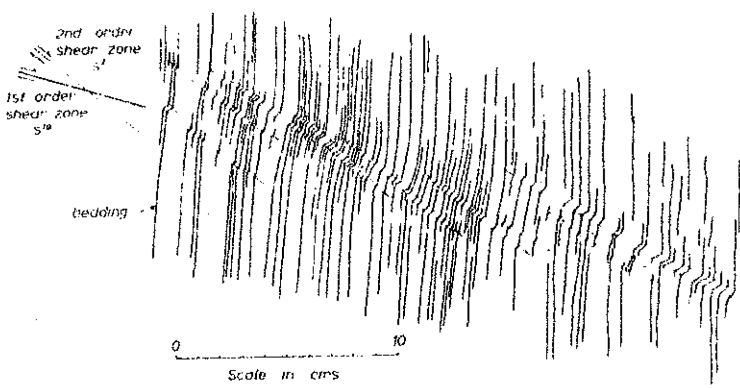

FIG. 8

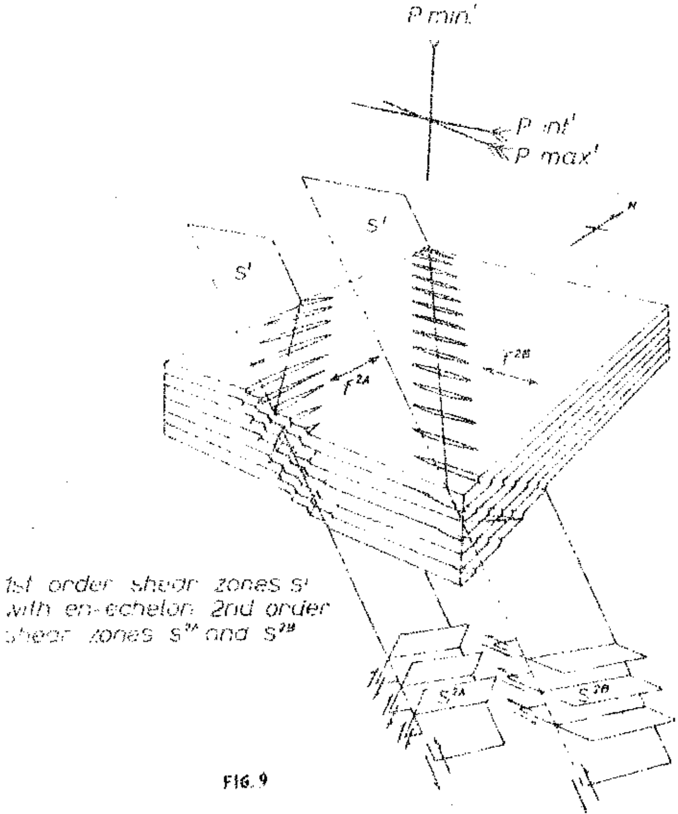
P min'
P int'
P max'
N
S'
S'
f2B
f2A
1st order shear zones S' with en-echelon 2nd order shear zones S2A and S2B
S2A
S2B

FIG. 9

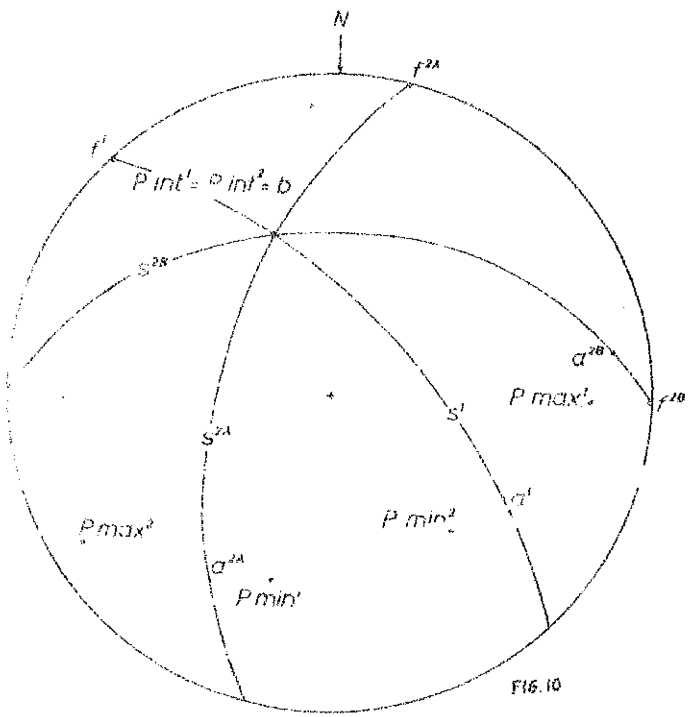
N
f2A
f'
P int' = P int2 = b
S2B
a2B
P max'
f2B
S'
S2A
a'
P min2
P max2
a2A
P min'

FIG. 10