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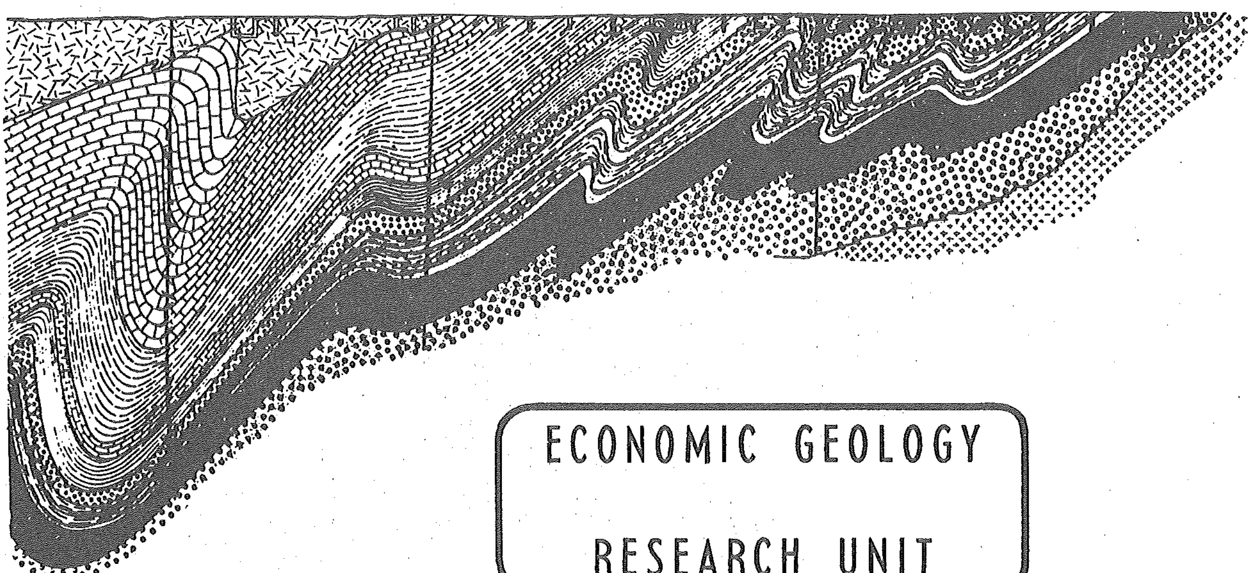

ECONOMIC GEOLOGY RESEARCH UNIT

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THE GEOMETRICAL SIGNIFICANCE OF NATURAL EN-ECHELON CRACK-ARRAYS

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THE GEOMETRICAL SIGNIFICANCE OF NATURAL EN-ECHELON CRACK-ARRAYS

ABSTRACT

Various types of en-echelon crack-arrays and feather fractures have been observed in Hospital Hill quartzites of the Lower Division of the Witwatersrand System in the Florida Hills, west of Johannesburg. Several different geometrical arrangements have been related to the principal stress axes. It has been established that the formation of these fractures is a first-order phenomenon. This means that they do not develop from re-adjusted stresses in shear zones where a couple is the dominant force, contrary to conventional interpretations.

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THE GEOMETRICAL SIGNIFICANCE OF NATURAL EN-ECHELON CRACK-ARRAYS

CONTENTS

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THE GEOMETRICAL SIGNIFICANCE OF NATURAL EN-ECHELON CRACK-ARRAYS

INTRODUCTION

A. LOCATION OF STRUCTURES

Recent work on the tectonics of the Witwatersrand Basin has shown that a study of quartz veining may be useful in the solution of structural problems. Foliations and lineations, which are normally used in structural analysis, are not developed to the extent of being penetrative, but quartz veins are ubiquitous in virtually all the quartzite members of the Witwatersrand System. The main object of this paper is to draw attention to the geometrical arrangement of these quartz-filled fracture systems, particularly en-echelon and feather fractures, and to show how these structures are related to particular stresses. In recent years, investigators of rock mechanics have emphasized the importance of en-echelon arrays. It has been suggested, from experimental work, that macroscopic shear fractures, or faults, develop from en-echelon crack-arrays which are present before the fault forms (Brace and Bombolakis, 1963). Naturally occurring arrays can possibly substantiate this postulate.

The area selected for a detailed study of quartz-filled fractures is located approximately 9 miles west-northwest of Johannesburg Station, and has passing through it the main road from Johannesburg to Krugersdorp (Ontdekkersweg) and the road from Roodepoort to Pretoria, which crosses the Florida Hills at Allen's Pass. The rocks are southwesterly-dipping quartzites, shales, and slates of the Hospital Hill Series at the base of the Witwatersrand System. This group is underlain by basement schists and granites (Mellor, 1917). The latter, intrusive into the schists, have an age of 3000 million years (Allsopp, 1961). In places, the sediments show distinct, but gentle, folding. Highly complex faulting is the most common structural feature of the area. The area forms the eastern portion of the refolded West Rand Syncline (Brock and Pretorius, 1964).

B. THE NATURE OF EN-ECHELON FRACTURES

En-echelon veinlets have been described by Sherril (1929), Riedel (1929), Shainin (1950), Wilson (1950, 1952), and Cloos (1955). Such structures have also been referred to as en-echelon gash veins and en-echelon tension fractures. Feather fractures are related phenomena.

From experiments with clay and from natural phenomena, Cloos (1932) concluded that feather fractures (joints), emanating from a major fault at an angle of approximately 30°, represent "local tension joints produced by the rotational impulse in the vicinity of a zone of differential movement". The usual diagrammatic representation of en-echelon veinlets (Figure 1) shows a couple acting parallel, and marginal, to the zone containing the fractures, with a compressive stress parallel to the long axis of the individual gashes or veinlets and a state of tension at right-angles to the veinlets (Engels, 1959; Wilson, 1950, 1952; Goguel, 1962; Muller, 1963). The implication is that the compressive and tensional stresses are directly derived from the couple, and must, therefore, be caused by some re-arrangement of the major stress field which produces the couple or shear zone. However, in many instances, there is no evidence of a shear zone, apart from the overall geometrical arrangement of the gashes, and these fractures would thus appear to develop in a potential shear zone before any visible shear strain can be identified. Wilson (1952) states, of an en-echelon zone in the Moine Series, "theoretically they should be accompanied by complementary shear planes, but the latter have not developed".

Conjugate en-echelon veinlets have been described by Shainin (1950) in the Athens limestone of Virginia. The conjugate sets intersect at an angle of 40°, and the individual gashes within a zone are essentially parallel to the complementary conjugate shear zone. Similar features were experimentally created in clay by Cloos (1955), where one part of a clay cake was moved over the other portion along a straight line. A zone on, and bordering this line, contained tension gashes, but the areas above and below the zone were unaffected. The cake on either side of the 'shear zone' was unstrained, and, apart from being bodily transported, remained static. These conditions cannot be compared with those in a confined rock, where applied stresses affect the entire system, and not a narrow zone only. The experiment is valid only for a deformed zone, where a rotational movement gives rise to tension gashes oriented at 45° to the 'shear'. This shear couple can be resolved into a major compressive force, oriented at about 45° to the shear, so that tension gashes appear in the direction of the major compressive force. The en-echelon fractures can develop only in the strained zone near the shear.

The work of Anderson (1964) and Dewey (1965) shows the confinement of en-echelon veinlets to kink-bands where this type of deformation is present. The quartz-filled veinlets are believed to be parallel to the rotated foliation in the kink-band, because of the necessity for extending the rock in the kink-band under certain conditions (Figure 2). It was suggested that an analogous mechanism may operate in more massive rocks with a weaker foliation.

C. ACKNOWLEDGEMENTS

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OBSERVATIONS AND INTERPRETATIONS

A. ORIENTATIONS OF EN-ECHELON CRACK-ARRAYS

The en-echelon veinlets found within the area are $3\frac{1}{2}$ - $4\frac{1}{2}$ inches in length, and vary in width from a hair-line to 1 inch. Two elements were measured in the field, viz. the average orientation of the long axes of the individual veinlets, and the orientation of the zone containing the veinlets. These structures were only observed in quartzites, and, because of the massive nature of such rocks, outcrops tended to be flat and without relief, so that three-dimensional orientations could not be obtained. However, at a few localities it was observed that the quartz-filled fractures are essentially vertical.

Data from the area are presented in Table I. Six observations were made of the right-lateral group of veinlets, and 13 of the left-lateral group. It appears that only two geometric elements are contained in Table I, considering both veins and zones, indicating that, for either en-echelon arrangement, a zone consists of veinlets oriented parallel to the complementary zone. The two zones intersect at an angle of about 40°, so that the angular difference between a particular zone and its associated veinlets is also about

40^o. The σ_1 orientations, calculated by bisecting the angle between the orientation of the zone and the orientation of the veinlets, show a higher degree of consistency. The angles between the shears and the σ_1 directions may vary with differences in phyllo-sillicate content of the quartzites. The σ_1 orientations are, therefore, more reliable and consistent than vein or zone orientations.

LEFT–LATERAL ARRAYS				RIGHT–LATERAL ARRAYS			
Veins	Zones	Angular Difference	Deduced σ_1	Veins	Zones	Angular Difference	Deduced σ_1
165^o	193^o	28^o	179^o	199^o	161^o	38^o	180^o
158^o	200^o	42^o	179^o	202^o	160^o	42^o	181^o
152^o	192^o	40^o	172^o	210^o	172^o	38^o	191^o
166^o	202^o	36^o	184^o	208^o	162^o	46^o	185^o
165^o	202^o	37^o	183^o	193^o	158^o	35^o	175^o
158^o	193^o	35^o	176^o	201^o	165^o	39^o	184^o
162^o	205^o	43^o	183^o				
163^o	215^o	52^o	189^o				
163^o	208^o	45^o	185^o				
167^o	195^o	28^o	181^o				
173^o	222^o	49^o	197^o				
166^o	205^o	39^o	186^o				
165^o	197^o	32^o	181^o				
Mean 163^o	202^o	39^o	183^o	Mean 202^o	163^o	39^o	183^o
Std.Dev. 5^o	9^o	-	6^o	Std.Dev. 6^o	5^o	-	5^o

Table I : Orientations of quartz veins and zones in en-echelon crack-arrays, as observed on outcrop in Hospital Hill quartzites in the Florida Hills, west of Johannesburg. (bearings clockwise from north at $360^o/0^o$).

The zones in the Athens limestone (Shainin, 1950) also intersect at 40^o, and the veinlets are oriented parallel to the complementary shear direction.

In the area of the present study, the conjugate sets of en-echelon veinlets shown in Figure 3 are related to a vertical major compressive stress, as distinct from the horizontal, major compressive stress which produced the fractures listed in Table I. For the right-lateral arrays, it was established that the mean vein orientation (88 measurements) differed by 5^o from the zone orientations (6 measurements). For the left-lateral arrays, the mean vein orientation (42 measurements) differed by 3^o from the zone orientations (5 measurements). The major factor contributing to this divergence is the fact that the quartz veins have been rotated within their respective zones. The bedding-planes show rotation in a zone containing en-echelon veinlets. Figure 3 also shows the presence of certain arrays containing veinlets oriented in the σ_1 direction. Similarly oriented veinlets occur where the conjugate sets intersect each other.

B. ZONES OF EN-ECHELON VEINLETS RELATED TO KNOWN SHEAR ZONES

In one particular case, it can be observed that the en-echelon veinlets are parallel to a zone of shearing. Marker horizons in the quartzites show clear signs of deformation and differential movement (Figure 4). Two complementary shear zones can be established in the outcrop, and en-echelon veinlets have their zones oriented parallel to these. The veinlets within the zones are essentially parallel to the observed complementary shears. Some veinlets, however, lie close to the σ_1 direction. Within this single outcrop, there exists confirmation of the deductions made from the collective data. Another important fact emerges from the right-lateral shear of Figure 4. Grit particles within the grit band are flattened in the shear zone, the orientation of the flattened particles being 135°. Any tensional phenomena related to readjusted stresses, and thus associated with the compression in this shear zone, should occur at right angles to this trend, viz. at 225°. The mean orientation of all veinlets having a similar orientation on this outcrop is 194°. It follows, therefore, that the en-echelon veinlets are not related to readjusted stresses on the shear zone, as has been accepted in the past. The quartz-filled fractures are parallel to first-order shear directions.

Figure 5 shows quartz veins emanating from larger quartz-filled fractures. The former have a trend of 270°, which is parallel to a series of right-lateral wrench faults occurring within the area. The fractures and en-echelon zones which are at an angle of 74° to the major fracture give way locally to en-echelon fractures oriented in two distinct directions. The conventional explanation of this phenomenon would be that the two zones, with associated veinlets, are shear fractures, and that the en-echelon veinlets are formed by tension related to the couple. However, this would give rise to en-echelon veinlets of one orientation only, and not two, because the movement on the zones would have to be the same. A more acceptable explanation would be that the zones are tensional, possibly of second-order origin on the east-west-trending larger veinlets. The en-echelon veinlets within these zones would then be oriented parallel to two second-order shear directions.

Similar features can be observed in Figure 6. A large quartz vein, some 10 feet in length, ends on an obliquely-trending veinlet (Figure 6a). Slightly offset from this larger vein, but parallel to it, is a zone of en-echelon fractures with complex shapes. On the continuation of this zone, the en-echelon array gives way to a quartz veinlet with feather fractures oriented in the same direction as the individual en-echelon veinlets. Thirty feet away from this, parallel fractures are found. Several feather fractures on the larger fractures show a differing orientation to the en-echelon group (Figure 6b). The data from this locality suggest the same phenomenon as described above, viz. larger tension fractures giving way to en-echelon fractures on strike, or having emanating feather fractures parallel to one or the other of the principal shear directions.

These examples show the incorrectness of the conventional conclusion that the major fracture (or spine of feather fractures) is a shear fracture, and that the associated en-echelon veinlets (or spines) are tension fractures. The opposite is the case.

C. FEATHER FRACTURES

Several localities contain feather fractures which give way to en-echelon fractures along strike, indicating that one unifying mechanism must have been responsible for the formation of both phenomena (Figure 7). In some of the feather fractures, which have a mean orientation of 207°, there is a decided tendency for their tips to swing parallel to the major vein direction. The spine of the feathers is oriented at 175°, as compared to the 163° orientation of the conjugate en-echelon veinlets. This is an example of larger, more persistent, tension cracks (lying parallel to the $\sigma_1 - \sigma_2$ plane), with associated shear fractures in the 207° direction forming the feathers.

The $\sigma_1 - \sigma_2$ plane has an orientation of 175° in this locality, which differs from the 183° direction deduced from the data in Table I. The angular difference between σ_1 and the shear plane is approximately 30°, whereas, from the regional en-echelon arrangements, an angle of 20° was indicated. The variation of this angle may bear some relationship to the energy requirements which affect the geometry of the various arrays. Another influencing factor may be the variable strength characteristics of the rocks. The 30° angle was observed in a very pure quartzite, almost devoid of phyllosilicates.

Figure 8 is a larger scale representation of feather fractures. Here, the major shear, gives way to en-echelon veinlets, and is then developed again. The spine is oriented at 160°, while the feathers have an orientation of about 195°. Shear displacements on the spine of the feather fracture can be determined from the relative positions of marker horizons. The manner in which this shear displacement distributes itself where the fracture itself ends can be partly seen in the larger quartz vein emanating from close to the tip of the major fracture. This vein shows displacements which tend to place the bedding-planes in their original position, outside of the disturbed zone. Some of the other feather fractures also show displacements offseting the overall displacement of the major shear. It would appear from this outcrop that two systems of shear fractures are present. An adjacent outcrop contains feather fractures with the spine oriented at 220°, and the feathers at 160°. These data suggest that both outcrops belong to the same system of fracturing, and that three elements are present, viz. two shear fractures (the spines) oriented at 160° and 220°, and tensional fractures (195°), or complementary shears, at about 160° (the feathers).

D. THE IDEAL ARRAY

Figure 9 depicts an outcrop where there is a series of larger veinlets, oriented at 205° - 210°, pervading the whole exposure. Several different en-echelon arrays are present, one of which contains veinlets arranged to form a zone oriented at 165°. The individual veinlets have a complex form, but are, in general, oriented parallel to the major vein trend at 205° - 210°. Closer examination of these veinlets shows that they may consist of a shear component and a tensional component. The former may contribute to the offseting kinks observed in the larger veinlets.

Figure 10, representing a different section of the same outcrop, shows two distinctly different en-echelon arrays. The first is similar to that already described, but the second is parallel to the major vein direction (205° - 210°), and is made up of veinlets oriented parallel to the zone below it.

Yet another array is found in this outcrop. This consists of veinlets in the 165°-trend, but oriented in zones oriented at about 240°. They are thus shears arranged in the complementary shear zone positions to those described above (Figure 11).

Figure 12 is an idealized diagram, showing the various types of arrays found within the area investigated. It reveals that fracture formation is far more complex than has been previously assumed, and that, in each and every case, the fractures are related to the primary stress field. The fractures are not formed as the result of local readjustments of this major stress system close to a couple, which has previously been considered to be the dominant force in operation.

E. COMPARISON WITH EN-ECHELON KINK-BANDS

In a recent paper by Dewey (1965), a spectacular array of en-echelon kink-bands shows each band as a shear displacement, parallel to a major zone (Figure 13). The interpretation presented classifies the individual kink-bands as second-order Riedel shears, despite the fact that no first-order strain is visible. However, true second-order shears (second-order kink-bands) have been produced in the laboratory by Patterson and Weiss (1966), with first-order strain being visible. Dewey (1965) also suggested that σ_1 would act in the north-south direction on the diagram (Figure 13), and pointed out that σ_1 need not intersect the acute angle of conjugate folds (see also Patterson and Weiss, 1966). An interpretation, based on the results of the present investigation, favours σ_1 as lying in, or close to, the foliation, and the shears as being first-order shears arranged in an en-echelon fashion in the complementary shear direction. The shortening necessitated by the crumpled foliation would support this contention, i.e. the foliation would be shortened in σ_1.

The array is an example of those found, during the present study, in brittle material, where fracture results. Dewey's (1965) example is of the geometrical arrangement in more ductile material.

CONCLUSIONS

It is concluded that numerous en-echelon crack-arrays exist in nature. In the area investigated, it has been possible to relate these to a primary stress field, and to demonstrate that en-echelon fractures are first-order phenomena, and not the result of a readjusted stress (second-order phenomenon) acting in a shear zone. The main argument in favour of this is that first-order strains do not, in general, accompany these structures. Commonly they occur in zones of potential shear, preceding this shear. Where second-order strains are associated with such shears, the geometry of associated en-echelon veins is unrelated to these strains, and the fractures themselves are related to first-order shears.

The possible geometrical arrays within Lower Witwatersrand rocks in the area investigated are shown in Figure 12. Commonly, the quartz filling these fractures shows a columnar fabric oriented at right-angles to the fracture walls. It is suggested that one, or more, of the following features may be responsible for the widening of the fractures:

(i) the force of crystallization of the quartz-filling,

(ii) the action of the associated shear couple on a particular zone of en-echelon fractures (Figure 1), and

(iii) the deformation of the fracture by shear in a more ductile environment.

A problem that arises from the arrays investigated concerns the method of determining the orientation of the stress axes from the orientations of a particular array. Since several arrays can be formed from a particular stress field, the problem is not directly open to solution. Several observations have to be made in an area to determine the degree of consistency of the arrays, and other diagnostic data have to be recorded, such as the angular relations of zones to fractures. Because macroscopic shear fractures occur at angles close to 30° from the maximum principal stress and because conjugate en-echelon zones intersect at angles of approximately 40°, whether in Witwatersrand quartzites or in the Athens limestone of Virginia, certain generalizations can be made. Those en-echelon arrays made up of shear fractures occurring in a complementary shear zone should give an angular difference between the two elements of 40° - 60°. Where the angular difference between veinlets and the associated zone is of the order 20° - 30°, no positive conclusions can be drawn, since such a relationship indicates either a shear zone with gashes oriented in the σ_1 direction, or a tensional zone, parallel to σ_1 and made up of individual veinlets parallel to the one or other principal shear direction. The same conclusions apply to feather fractures. Where three-dimensional data are available, the stresses can be determined by means of a stereo-net, in the same way as with conjugate folds (see Ramsay, 1962).

The arrays and geometrical combinations shown in this paper do not cover the entire spectrum of arrangements. For example, feather fractures may be second-order, with the spine representing a first-order shear fracture along which there has been displacement. Adjusted stresses adjacent to this fracture may result in second-order fractures of various types (Figure 5). In this example, the east-west-trending larger fracture (parallel to known wrench faults) has emanating from it fractures making an angle of 74° with the primary shear. This is in the direction of the second-order major compressive stress. Shear fractures may develop as a direct result of this stress. However, fractures formed under these conditions can be distinguished from others described in this paper by establishing the presence of a first-order shear strain which has given rise to readjustments of the primary stress field. Shear faulting, with displacements, would appear to be the most diagnostic characteristic for distinguishing the two modes of formation.

Present-day knowledge, based on experimental evidence, is such that no clear understanding exists as to how a shear fracture, or fault, grows (Brace, 1964). It has been suggested that the Griffith theory and the modified Griffith theory of McClintock and Walsh (see Jaeger, 1956; Hoek and Bieniawski, 1965 and 1966) do not adequately explain the direction and rate of fracture propagation under compression, and that they are limited to predicting conditions of fracture initiation (Hoek and Bieniawski, 1965). Experimental evidence shows that "critical Griffith cracks", made in glass, for example, and inclined at approximately 30° to σ_1, tend to propagate along a curved path which ultimately becomes parallel to the direction of principal compression. When the crack parallels the direction of compression, crack growth stops (Brace and Bombolakis, 1963; Bombolakis, 1964; Hoek and Bieniawski, 1965). For this reason, it is assumed that shear fracture is brought about by the presence of pre-existing en-echelon crack-arrays which link up to give faults. The arrays observed in the Witwatersrand rocks, particularly those parallel to the principal shear directions, may represent potential fault zones. In some of the examples given (Figure 4), shear strain is evident. Had the stresses been sufficiently strong, in particular the shearing stresses acting parallel to these zones, faulting may have followed. Such faulting would presumably have taken advantage of zones that had already been segmented, and thus weakened, by the en-echelon arrays. The area examined, therefore, probably provides excellent examples of embryonic faulting.

Shainin (1950) referred to the 'anomalous' shape of en-echelon gashes (Figure 14e). Had any form of shear deformed pre-existing veinlets, configurations such as those in Figure 14b, c, and d would possibly have resulted. However, it would appear that the veinlets kink in a direction opposite to that which would form by shear (Figure 14e). Moreover, no evidence of the deformation of the veinlets has been found. The 'anomalous' shapes of these veinlets could be due to fracture propagation from Griffith cracks, in the manner described above, and which has been observed in experiments (Hoek and Bieniawski, 1965). This process is diagrammatically illustrated in Figure 14f. Figure 9 may represent veinlets formed in this manner, where the en-echelon array is parallel to a shear direction and the individual veinlets are parallel to the σ_1 direction. However, as pointed out previously, the latter may comprise two components, one of which is parallel to the complementary shear direction from which fractures grow parallel to the σ_1 direction.

The individual fractures found in various arrays which are parallel to the principal shear directions may represent Griffith-type cracks. No exact limit has been set to the size of a Griffith crack, which may be related to the scale of the experiment. The individual cracks in the arrays may grow to a particular size (several inches in the area examined), and then, for further propagation into the σ_1 direction, require greater stresses. Increased stress would also be required to convert those arrays parallel to the shear directions into shear faults.

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Key to Figures

Figure 1 : The conventional interpretation of en-echelon 'tension' gashes. The cracks are formed in a zone along which a shear couple acts. The shear couple can be resolved into a compressive and tensile component.

Figure 2 : Formation of en-echelon veinlets in kink-bands where the foliation has been systematically rotated in a zone. (after Anderson, 1964).

Figure 3 : En-echelon cracks in quartzite. Individual cracks parallel the complementary shear or σ_1 direction. Deviation from this is caused by rotation within shear zones. Dotted lines indicate bedding. (drawn from a photograph).

Figure 4 : Confinement of en-echelon arrays to zones of definite shear strain. Bedding planes (continuous lines) show rotation within these zones. Gashes parallel complementary shear directions, but have also been rotated by the action of the shear couple. The dotted band is a gritty layer in the quartzites. σ_1 has a bearing of 171° in this locality. (drawn from a photograph).

Figure 5 : Two quartz veins with associated en-echelon crack-arrays, in two distinct directions, emanating from a larger quartz vein. The vein is parallel to known right-lateral wrench faults. The en-echelon arrays are related to a second-order stress system formed adjacent to the major east-west quartz vein. (drawn from a photograph).

Figure 6 : Quartz vein patterns in two outcrops 50 feet apart. The major trends are identical, but the en-echelon fractures and feather fractures have two distinct orientations parallel to the principal shear directions. (drawn from a photograph).

Figure 7 : Association of feather fractures and en-echelon veinlets showing the intimate relationship of the two. Several of the feather fractures swing parallel to the major quartz vein trend.

Figure 8 : Large-scale feather fractures and the interpretation of their development. Dotted lines represent bedding planes. (sketched on outcrop).

Figure 9 : En-echelon array with cracks oriented parallel to σ_1, but lying in one of the principal shear directions. Some of the cracks may represent two components - a complementary shear direction and the σ_1 direction, parallel to which the fractures grow from the shear.

Figure 10 : Two distinct types of en-echelon array, one in which the fractures are parallel to the principal shear direction and the zone oriented in σ_1, the other in which the zone is parallel to the principal shear direction, but the fractures are parallel to σ_1.

Figure 11 : Two further types of crack-arrays, one with fractures parallel to the principal shear direction, and the zone parallel to σ_1, the other with the fractures parallel to a shear direction, and the zone parallel to the complementary shear direction.

Figure 12 : Idealized representation of all en-echelon crack-arrays found in the Hospital Hill quartzites of the Lower Division of the Witwatersrand System in the Florida Hills.

Figure 13 : En-echelon kink-bands in phyllite, with σ_1 oriented north-south, according to Dewey (1965). The interpretation, based on the results of the present investigations would place σ_1 in an east-west direction. The individual kink-bands parallel the complementary shear direction. There is a lack of first-order strain on the individual zones.

Figure 14 : En-echelon veinlets (a) before shear deformation, and (b), (c), (d) deformed by various shear strains. The actual, observed shape of en-echelon veinlets (e) contrasts with (b), (c), and (d). In the formation of 'anomalous' shapes (f), fractures grow from the shear cracks, and are parallel to σ_1. (see Brace and Bombolakis, 1963; and Hoek and Bieniawski, 1965).

* *

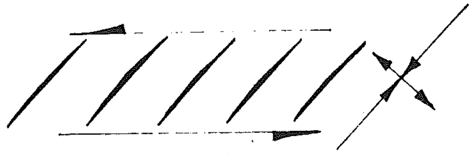


FIG 1

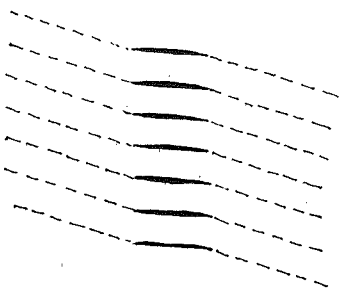


FIG 2

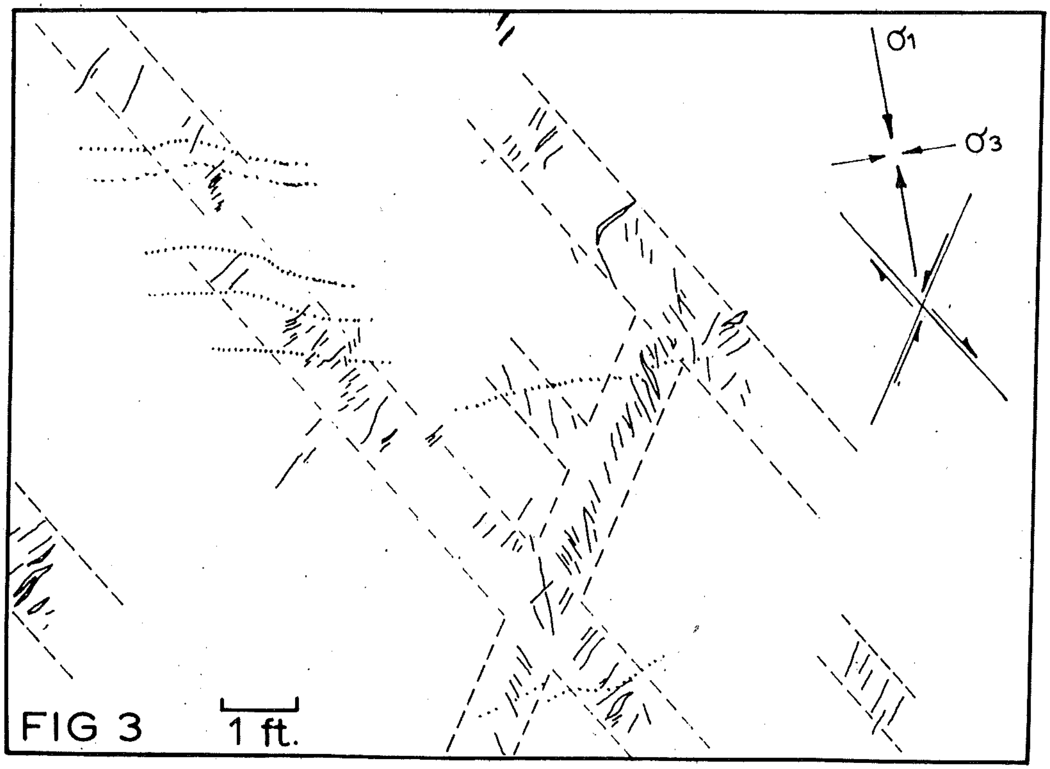


FIG 3

FIG 4

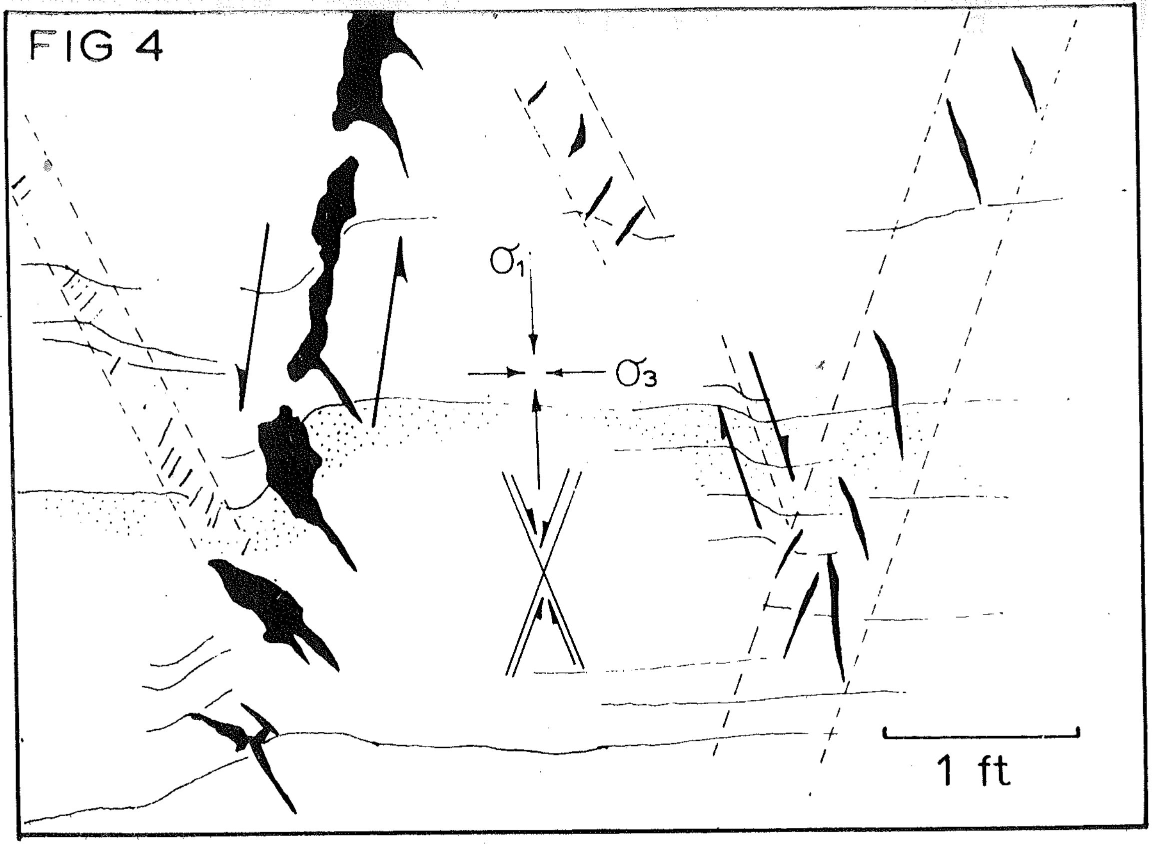


FIG 5

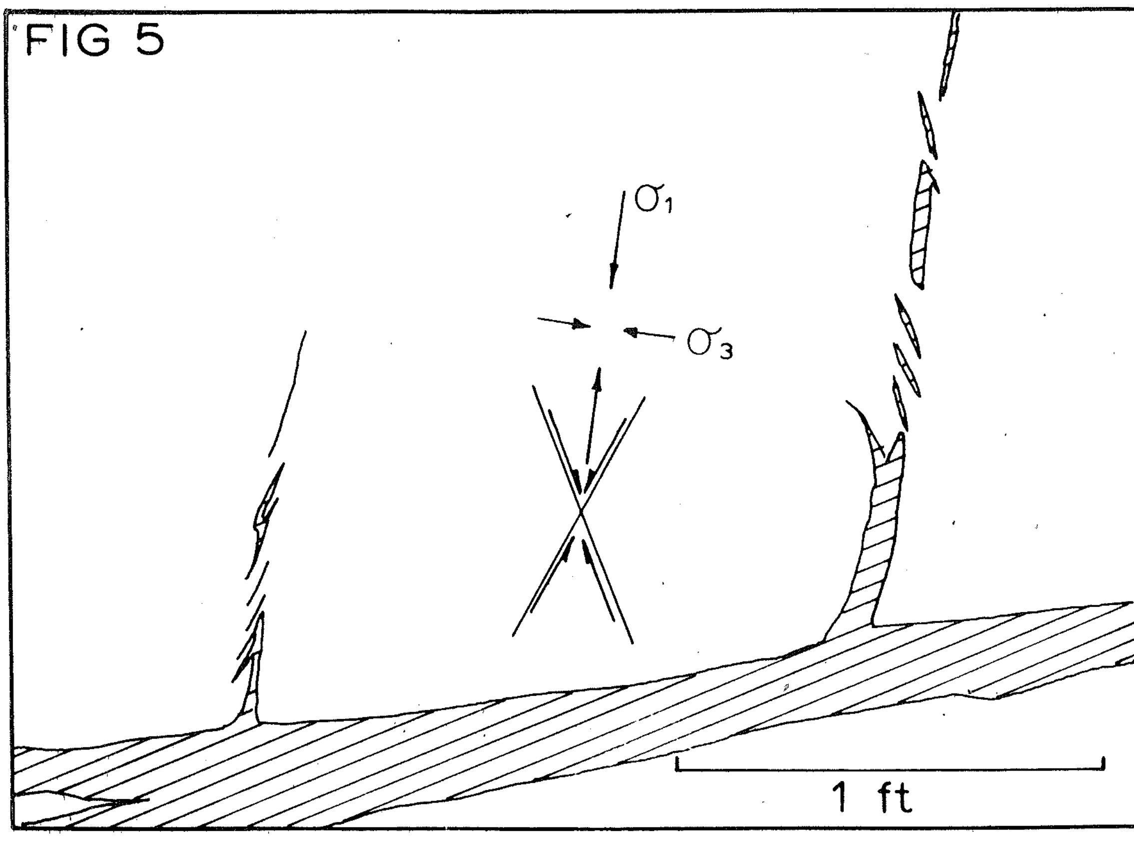


FIG 6a
FIG 6b

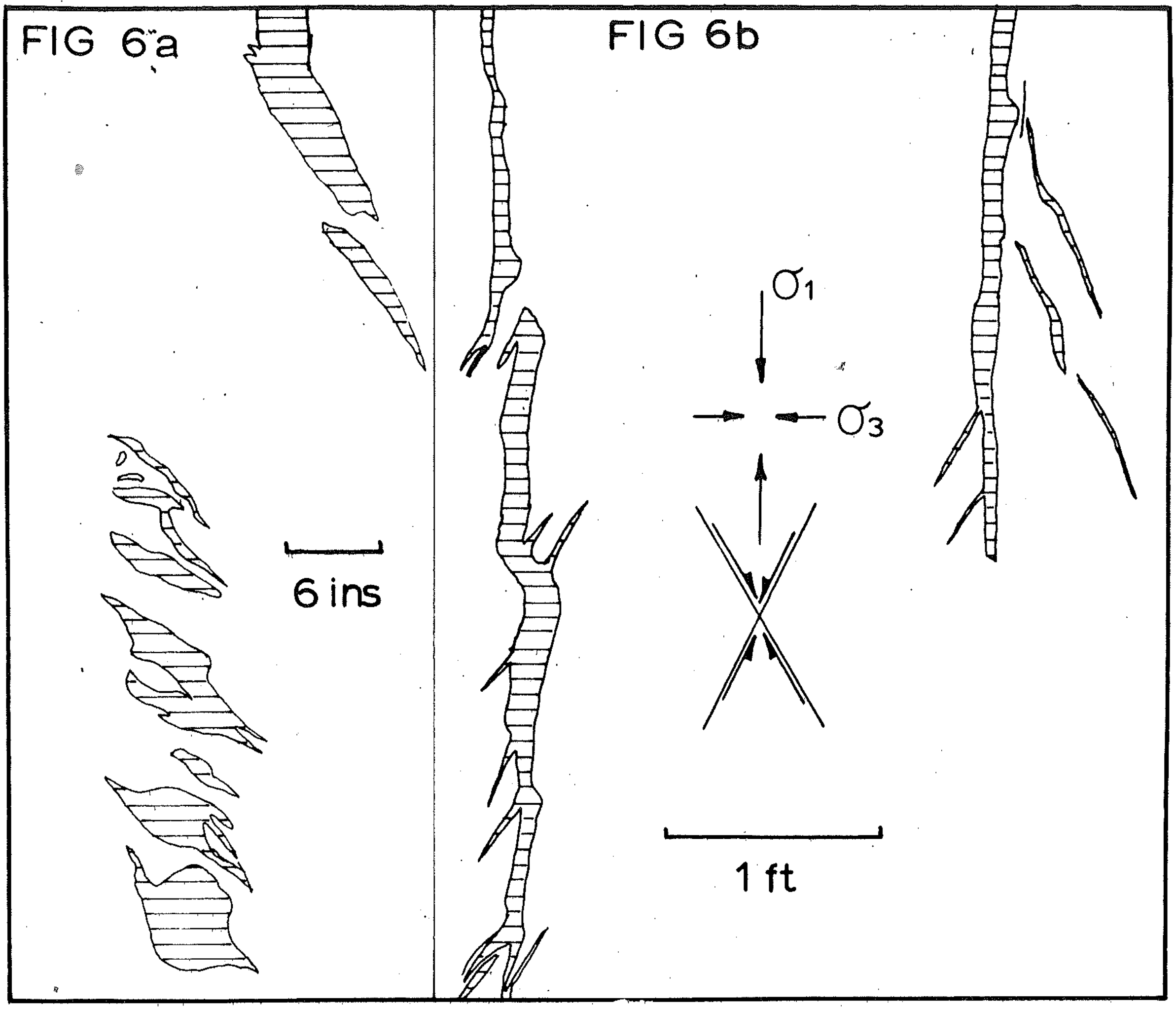
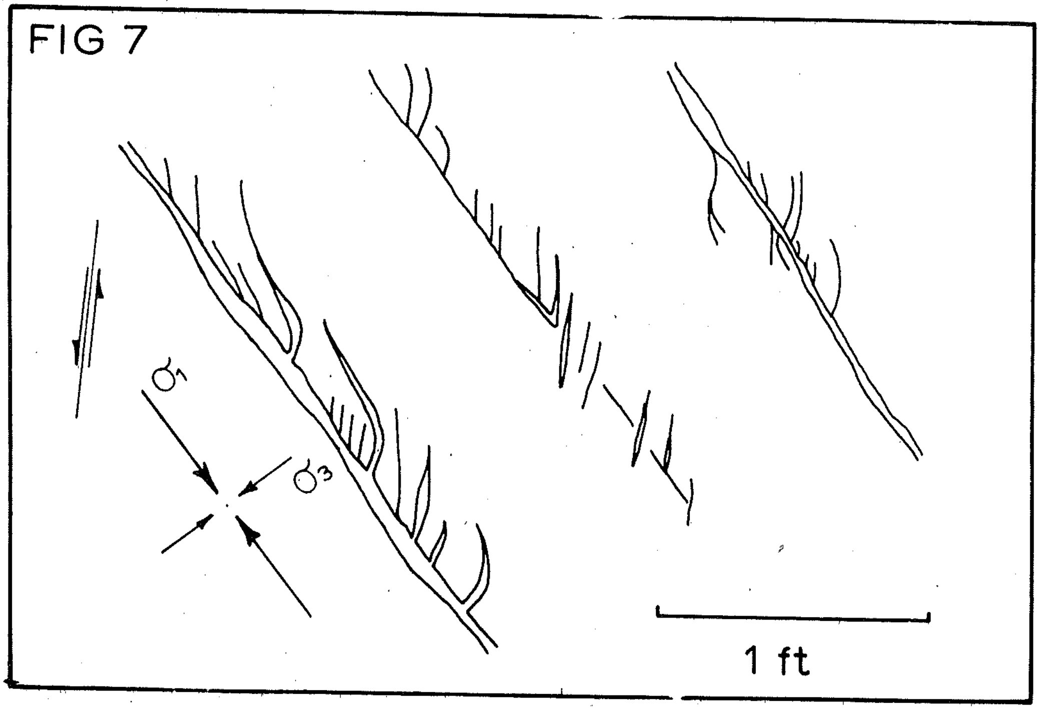


FIG 7



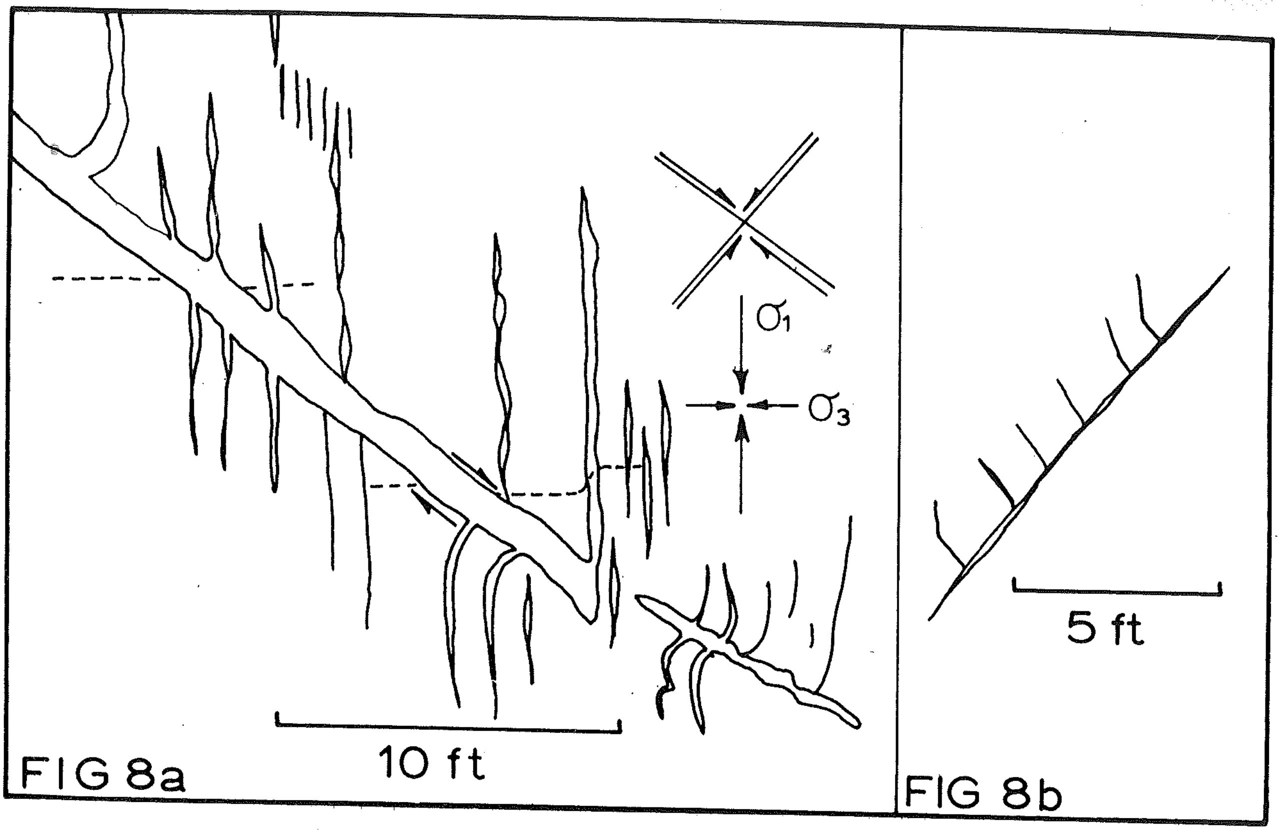


FIG 8a

FIG 8b

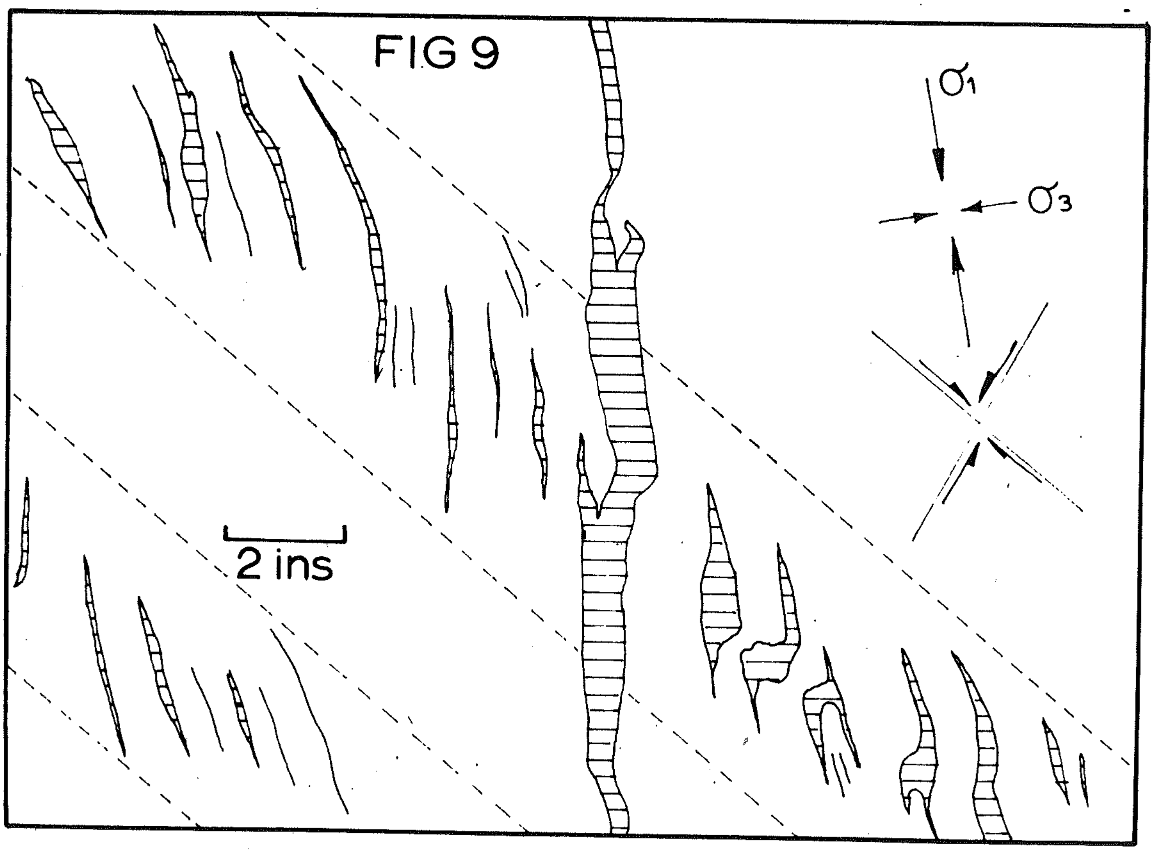


FIG 9

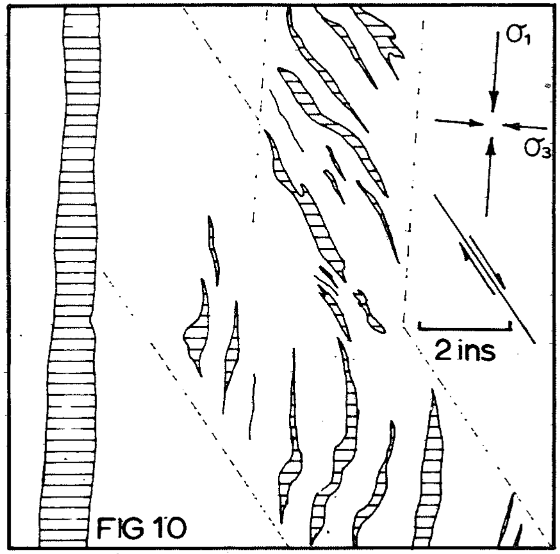


FIG 10

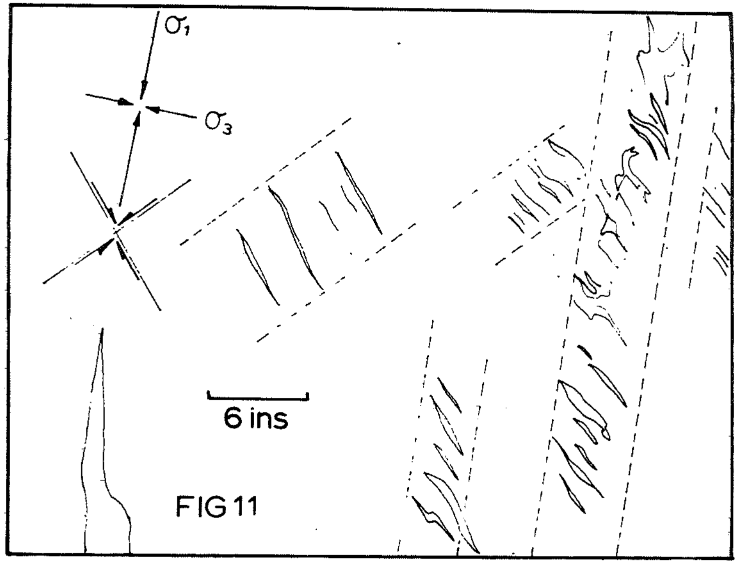
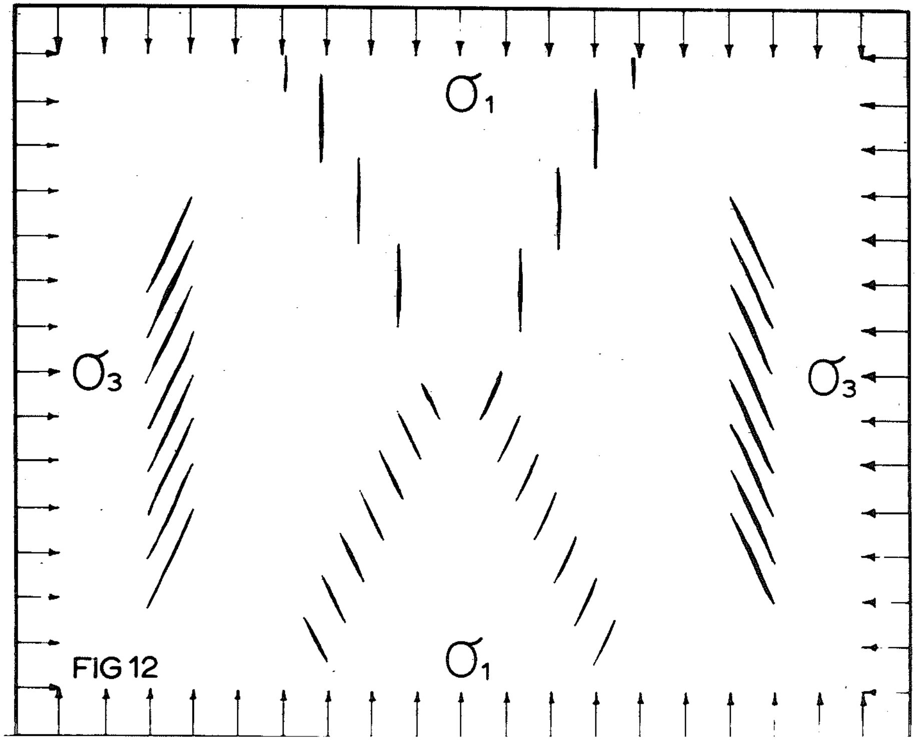


FIG 11



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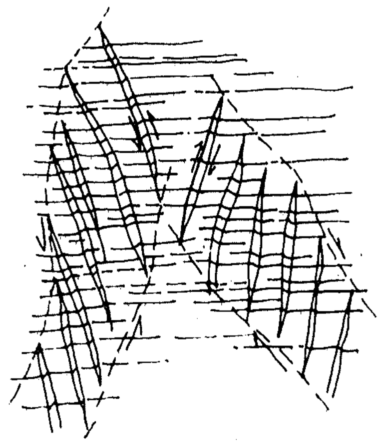

FIG 13

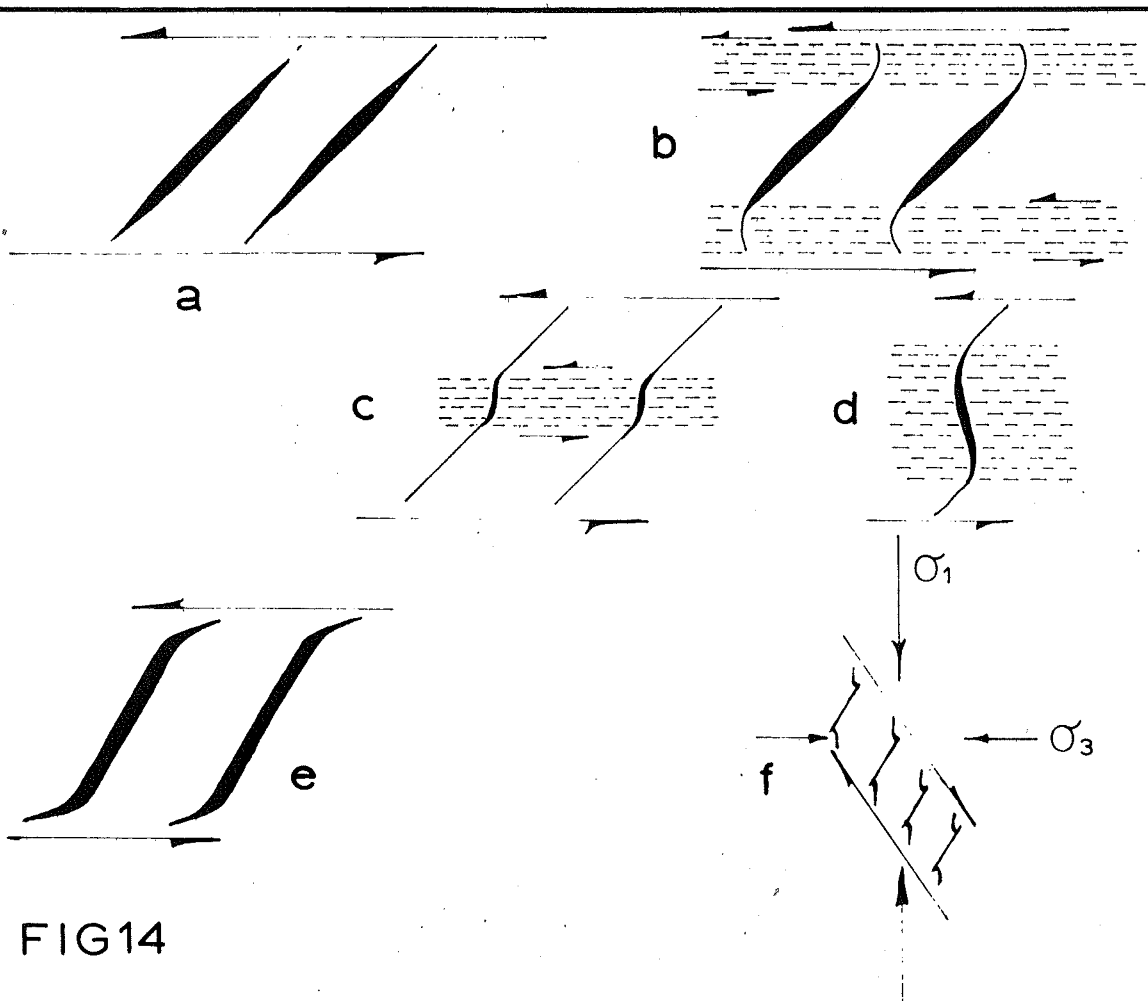

FIG 14