A STUDY OF FRACTURES IN THE MID-NORTH OF SOUTH AUSTRALIA

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ABSTRACT

Fracture sets within the mid-north of South Australia are analysed and related to local structures. Most fracture sets can be related to folds and have orientations controlled by bedding anisotropy. Some other sets may be earlier and have orientations dependent on sedimentary transport directions. Very few fractures post-date the folding. The fracture pattern contains no evidence for major faults oblique to fold trends.

The history of fracture development and the growth of syntectonic quartz fibres in fractures is related to stresses induced during folding. Variations in fracture patterns are discussed and found to be due to (1) changes in lithology; (2) changes in fold orientations; (3) the effect of pre-existing fractures, and (4) variations in palaeocurrents.

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INTRODUCTION

In this study natural fractures within a portion of the Adelaide fold belt are described and related to the structure and tectonics of the region. The investigation was undertaken to test the proposition that there might be a relationship between the regional fracture pattern and seismicity within the fold belt. To this end an area of study was selected where the folding was uncomplicated and where the rocks had not suffered greatly from metamorphism. The area of investigation is contained within the Burra (Mirams, 1964) and Orroroo (Binks, 1968) 1:250 000 map sheets published by the S.A. Department of Mines.

The fractures studied are of a scale suitable for in-the-field determination of their orientations. Fractures being defined as discrete breaks in rock which are not parallel to a visible fabric (Bridges, 1977). Since fractures may have different orientations in different lithologies the locations were carefully chosen, so that wherever possible data was collected only from competent rock types such as sandstones and quartzites. These locations, which were mainly quarries are shown in fig. 1. Location 1 was selected to investigate any change in the fracture pattern across a fold and relation of fractures to a fold, while locations 4 - 7 were chosen to determine any variation in fracture patterns along strike within a fold. The other locations were chosen in order to establish a regional interpretation of fracture patterns.

A regional analysis of fractures, has not been attempted in this area before. Fractures have been studied at specific locations to the south by Wilkie (1973) and Bridges (1977). Firman (1974) has made an analysis of lineaments from aerial photographs of this area; these lineaments are thought to represent large scale fractures. The geological history of the area is described in general terms by Parkin (1969), and the style of folding within the area has been investigated by Webb (1962).

Fractures are extremely common geological features and numerous studies have been made to try to determine their nature and origin. Despite these studies the origin of fractures remains problematic. This is largely because fractures may form under a wide range of geological conditions and time relations between fractures are usually difficult to establish.

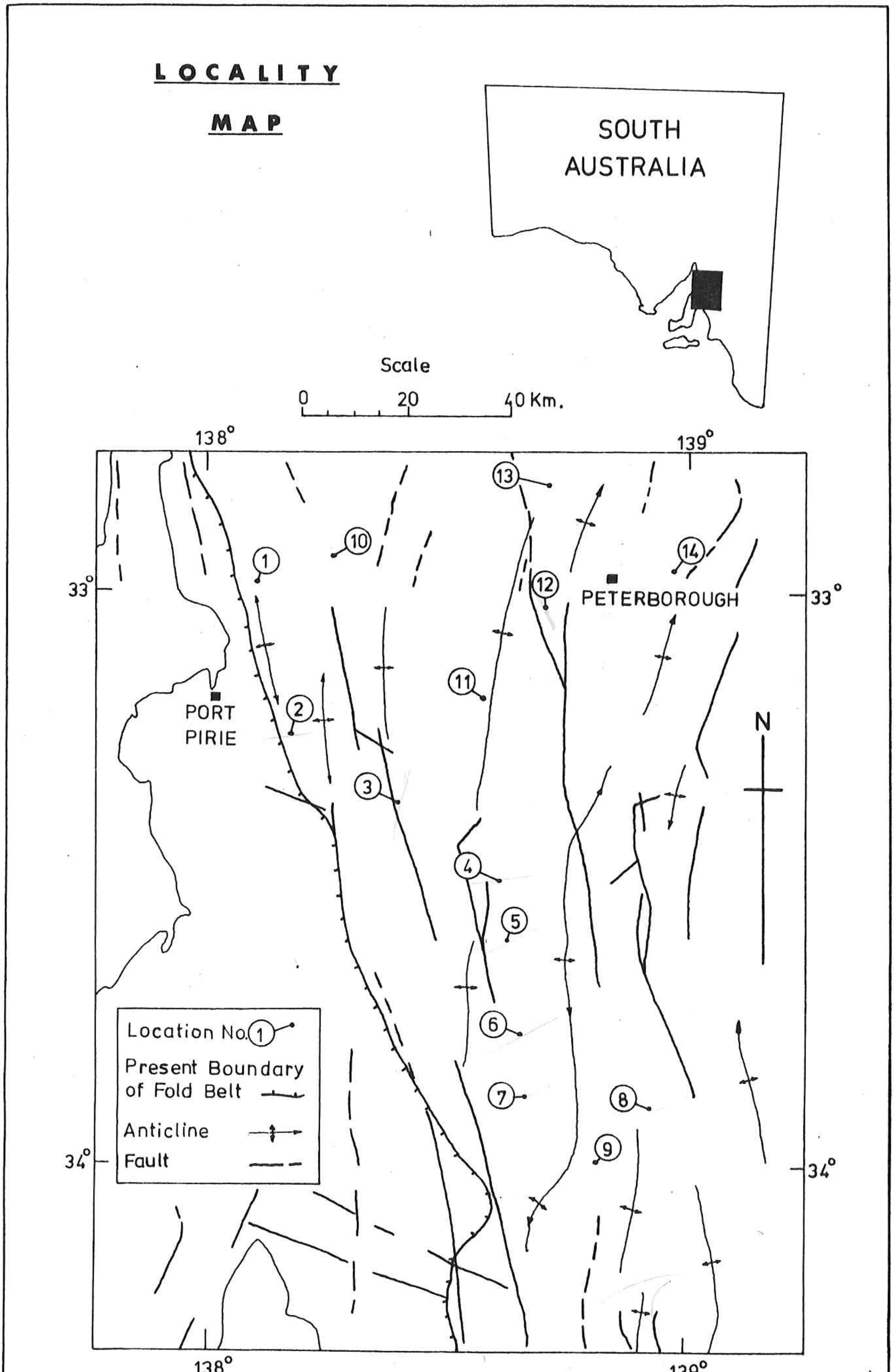

LOCALITY
MAP
SOUTH
AUSTRALIA
Scale
0
20
40 Km.
138°
139°
33°
34°
PORT
PIRIE
PETERBOROUGH
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Location No. 1
Present Boundary of Fold Belt
Anticline
Fault
CNW/77

FIGURE 1

METHOD OF STUDY

At each location observation of the rock faces revealed the major fracture sets. By walking along the rock face, measurements were made of the dip and strike of fracture planes. Fracture sets were distinguished in the field using criteria such as orientation and morphology (eg. whether the fractures were filled with quartz). Notes were made of any displacements or offsets between fractures and on the relative frequency and continuity of sets. The occurrences of surface features such as plumes was also noted. Where a number of lithological units were present at any one location, measurements were made of the orientation of fractures within each unit. When at a single location bedding changed its dip and/or strike to a significant degree fracture orientations were determined along rock faces with different bedding orientation.

The method of study was not as rigorous as those used by Wilkie (1973) and Bridges (1977), where measurements were made of the orientation of each fracture that intersected a stretched out tape. Such a method would have been extremely time-consuming and not practical. For the purpose of the present study the three dimensional orientation of fractures and their notable characteristics was all that was required. Errors in measuring fracture planes are considered to be $\pm 5^{\circ}$ in dip and $\pm 10^{\circ}$ in strike (Piteau, 1973).

Initially, each fracture plane was plotted as a pole on an equal area stereonet, with different fracture sets as recognised in the field plotted with different colours. Later the poles to fractures were contoured with the aid of the computer program ORIENT (Bridges, 1977). The modal orientations of different sets could then be determined. Each contour connects points with the same percentage of readings within a selected counting area. The contour intervals correspond to 2, 4, 8 & 16%. In most cases the counting area was chosen as 2% of the total area.

Thin sections were made so that the influence of rock fabrics, either sedimentary or tectonic on fractures could be established. Analysis was also made of pressure solution activity and quartz overgrowths. Where quartz was found filling fractures thin sections were made across fractures to determine the nature of this quartz filling and its relationship to fractures.

FRACTURES RELATED TO A FOLD

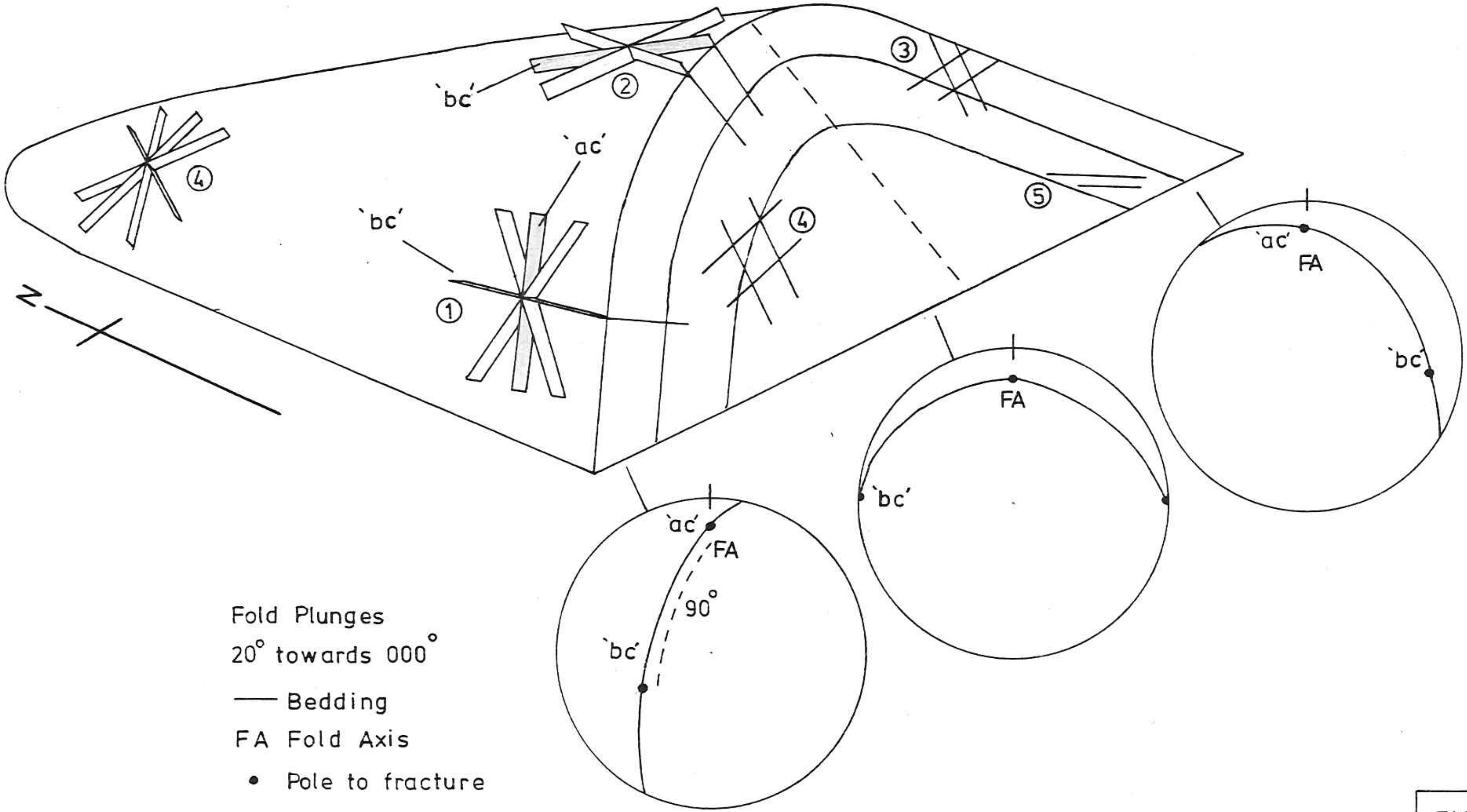
Across any fold a number of fracture sets may be found that have a consistent orientation relative to the fold. Stearns (1964, 1968) has found five different assemblages developed on a natural fold. These assemblages are shown in fig. 2 on an asymmetrical, plunging anticline. The assemblages comprise extension and conjugate shear fractures that can be related to the orientation of the principal stress axes at the time of fracturing. It is often difficult to relate fracture sets to stress axes as usually not all the members of an assemblage are developed. Under isotropic conditions extension fractures are expected to form normal to one of the principal directions of stress, from experimental tests (Griggs & Handin, 1960) this is expected to be the minimum principal stress (σ_3). Shear fractures form at any angle to the principal stresses other than 90°. Handin et al (1972) have found elements of three of the natural assemblages in experimentally produced folds. The origin of assemblage 1 is uncertain as it has not been produced experimentally, it is related to a σ_1 axis normal to the fold axis and σ_2 normal to bedding. Assemblage 2 can be related to extension normal to the fold axis where σ_1 is parallel to the axis and σ_2 normal to bedding. Assemblages 3 and 5 comprise conjugate shear fractures, assemblage 3 contains shear fractures related to thrust faulting in the inflection region, while assemblage 5 contains shear fractures conjugate to shearing along bedding planes. Assemblage 4 is indicative of localized bending.

The main extension fractures related to folds are contained within assemblages 1 & 2. Fractures developed normal to the fold axis on the limbs of folds have been historically called 'ac joints'; while fractures developed parallel to the fold axis in the extended portion of folds have been called 'bc or longitudinal joints'. Both 'ac & bc joints' form perpendicular to bedding, so that poles to 'ac joints' plot on a stereonet with the fold axis, while poles to 'bc joints' plot 90° away from the fold axis as measured along the bedding great circle. The strike of 'bc joints' will thus vary across the fold if it is plunging (see fig. 2).

Fractures of assemblages 2, 3 & 4 have been produced experimentally so that it is likely that they could form as a result of brittle failure during folding. Assemblage 1 fractures may form during or

FRACTURES ON AN ASYMMETRICAL PLUNGING ANTICLINE

After Stearns, 1968, fig.10.



Fold Plunges
20° towards 000°
—— Bedding
FA Fold Axis
• Pole to fracture

CNW '77

FIGURE 2

after folding. They may result from a slight elongation of rocks parallel to the fold axis during folding (Hobbs et al, 1976). Price (1959, 1966) on the other hand considers that these fractures formed as a result of uplift after folding. A theory has been proposed by Price, whereby residual strains build up in the rock during folding and give rise to fractures when later uplift occurs. As shown by Friedman & Logan (1970) residual elastic strain can control later fracture orientations.

FRACTURE PATTERNS ACROSS A FOLD - THE NALSHABY ANTICLINE

General Geology

The Nelshaby anticline is located on the present west boundary of the fold belt near Port Pirie; locations 1 & 2 are contained within this structure. Location 1 comprises the Port Germein gorge area, where it was possible to determine fracture orientations across the fold within one stratigraphic unit. This section will be concerned with the fracture patterns at location 1.

The most recent geological study of the Port Germein gorge area was undertaken by McCarthy (1974) who adequately described the geology and history of geological investigation of the area. The structure consists of a broad asymmetrical, plunging anticline. Contoured poles to bedding across the fold in fig. 3a show that the fold plunges 20^{o} due north. The west limb is considerably steeper than the east and the axial plane is orientated 165/55E. The axial plane has been determined as the great circle passing through the fold axis and the trough between poles to bedding on each limb. An axial plane cleavage is well developed in incompetent lithologies.

The rocks comprise shallow water sediments of the Burra Group which are unconformably overlain by glaciogene sediments of the Yudnamutana subgroup. The Stratigraphic nomenclature used is similar to that adopted by McCarthy. The oldest formation in the area has been called the Emeroo Quartzite as defined by Mawson (1947) instead of the 'Rhynie Sandstone' as used by McCarthy (1974) and Binks (1971). Detailed mapping by Forbes (1976) established that in some areas rocks had been incorrectly mapped as 'Rhynie Sandstone'. Forbes (pers. comm.) suggests that it would be more appropriate to use the term Emeroo Quartzite than Rhynie Sandstone for this group of rocks in the Port Germein gorge area.

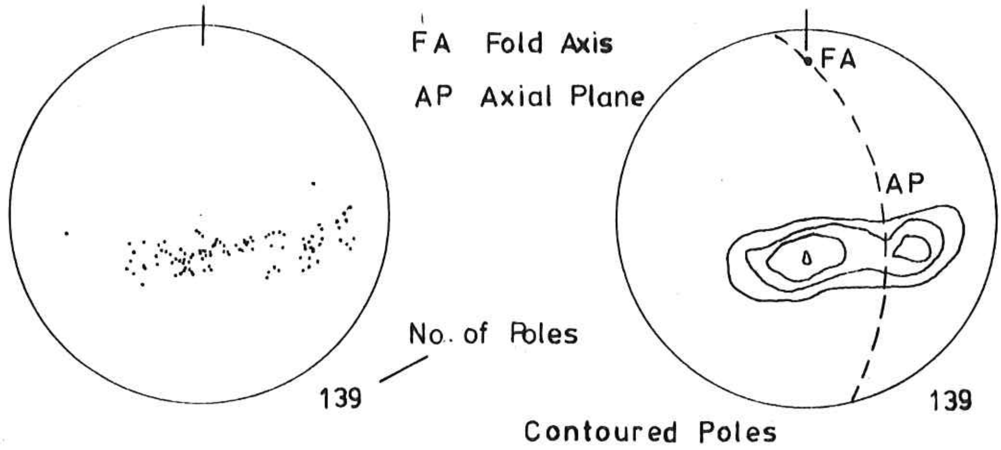
Four lithological units have been recognised within the Emeroo Quartzite. Fracture orientations were taken almost exclusively within unit 3. This unit consists of a fine to coarse grained, well sorted, flat bedded feldspathic sandstone. Sedimentary structures include abundant ripple marks, mudcracks and occasionally large cross beds.

As ripple marks show variable orientations McCarthy suggests that they formed in a shallow water beach or tidal flat environment, where current and tidal directions were changeable. Sediment influx is considered to be from the west or north west.

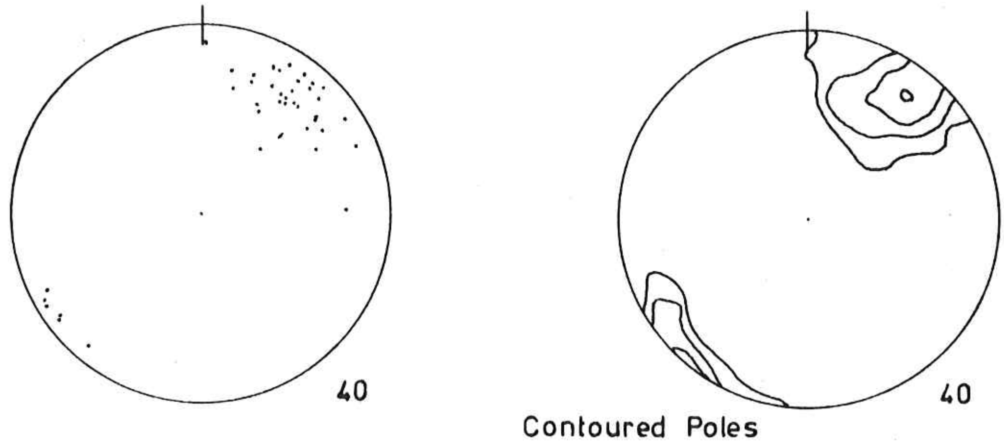
EQUAL AREA PROJECTIONS OF STRUCTURAL DATA

PORT GERMEIN GORGE AREA

(a) Poles to Bedding



(b) Poles to Faults



(c) Quartz fibre Orientations

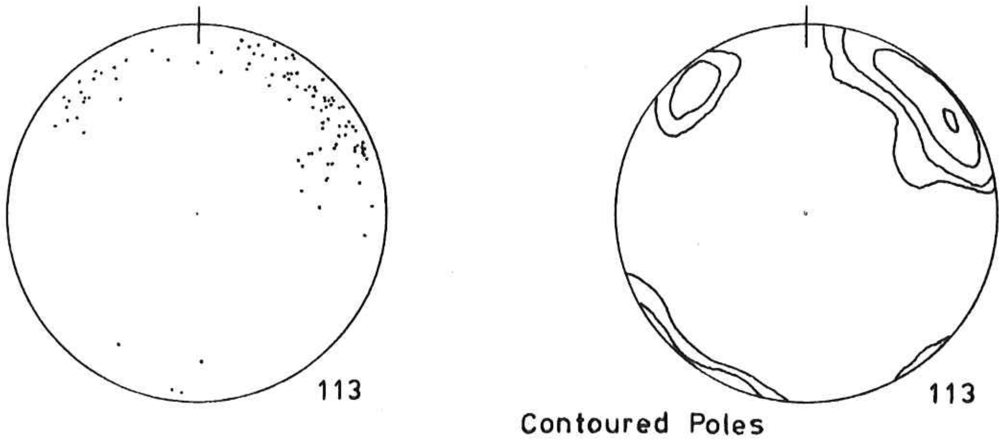


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FIGURE 3

Description of Fractures & Fracture Sets

A detailed investigation of the fracture sets across the anticline has been made from twenty one locations, nineteen of which are in the same stratigraphic unit. This reveals that four major sets persist across the structure. The gorge provides almost complete exposure on the west limb and hinge of the fold, fractures being very well developed. All the main sets are approximately normal to bedding ($\pm$ 20^{o}). The fracture sets are described in order of frequency as sets T_1 - T_4. The fracture patterns at Port Germein gorge are shown in fig. 4.

Set T_1

This is the major fracture set at the gorge. It occurs at all locations. The surfaces of these fractures are smooth and planar. A large proportion of the fractures have been filled with quartz, and sometimes hematite. The Quartz appears mostly as small clear crystals growing out from either side of the fracture. In other cases extensional quartz fibres are present, normally orientated normal to the fracture surface. The quartz veins range in width between 0.1 & 1.5 cm. Fracture surfaces with mineral lineations or striations were sometimes observed.

Set T_2

The surfaces of these fractures are smooth and planar. Quartz is often found filling fractures of this set. The width of the set T_2 veins (0.1 - 0.5 cm) is generally less than that of set T_1 veins. Most of the quartz in set T_1 veins is in the form of extensional quartz fibres developed normal to fracture surfaces.

The angle when measured along the bedding plane great circle between poles to set T_1 & T_2 fractures is approximately 90^{o}. The quartz veins of set T_1 commonly offset the veins of set T_2 (see plate 1a).

Set T_3

This set appears at most locations although it is generally absent on the limbs of the fold. The surfaces of these fractures are irregular and continuity is not as good as set T_1 & T_2. No quartz was found filling these fractures.

Set T_4

Fractures of this set are best developed in the limbs of the anticline, and generally absent in the hinge. The surfaces of these fractures are irregular and continuity is inferior to Set T_1 & T_2; quartz in the form of extensional fibres was found normal to the fractures. This quartz was introduced subsequent to the introduction of quartz in set T_2, but before growth into set T_1. The veins of set T_4 are much thinner than the veins of set T_1 or T_2.

Surface markings as described by Hodgson (1961) and Syme Gash (1972) are generally absent from all the major sets, they were only rarely observed and then only on fractures of local importance.

Geometrical Relationship Between Fracture Sets and the Fold

Sets T_1 & T_2

These fracture sets are orientated approximately normal to bedding and normal to each other, they thus appear to be genetically related. In the hinge of the fold, poles to both sets plot approximately 45^{o} away from the fold axis as measured along the bedding plane. This relationship is not maintained in the limbs of the fold, in particular locations 18 - 21, and not maintained within different stratigraphic units (ie. locations 1, 4 & 13). The quartz fibres in these fractures indicates that they are extension fractures. But the fractures do not have orientations expected for extension fractures related to a fold (i.e 'ac & bc'). In order to investigate the relationship between these fractures and the fold the sedimentary layering was rotated to horizontal. The method used is that described by Ramsay (1961) in which the modal pole of each fracture set at each location was rotated so that the fold axis and bedding were restored to the horizontal. Another method of rotation involves first rotation of the axial plane to vertical and then fold axis and bedding to horizontal. This method involves the same rotation stages as those used by Ramsay (1961), but in a different order. The result is not the same, the difference in fracture orientations between the methods being about 10^{o}. Which method is most appropriate to use depends on how the fold was developed, a factor almost impossible to determine. If the asymmetry of the fold was established before the plunge, the method proposed by Ramsay (1961) should be used. If, however, a plunging symmetrical fold is later made asymmetrical, then the other method is more appropriate. For the purpose of the present study the method used by Ramsay (1961) will be employed, although the other method seems equally plausible.

In fig. 5a the strike orientations of the fractures from both sets before and after rotation are compared, while in fig. 5b the poles to fractures before and after rotation are shown. Also shown in fig. 5b are mean poles to both sets before and after rotation from each limb of the fold. These diagrams show that after rotation the orientation of these fractures are slightly more consistent across the fold, but that there is still a significant variation, which is most pronounced in different stratigraphic units. Within unit 3 of the Emeroo Quartzite the fracture sets are nearly constant in orientation on the west limb and in the hinge of the fold, but diverge significantly on the east limb. The observation that the fractures are more consistent in orientation after rotation suggests that they probably did not form after folding.

It should be noted that fractures, whether they formed before or during the folding would be expected to rotate to a constant orientation. That is, if prefold fractures were consistent in orientation or if the direction of the principal stresses did not vary across the fold during folding. The divergence in fracture orientations suggests either one of these possibilities. The fact that poles to fracture sets are orientated 45^{o} away from the fold axis in the hinge supports the idea that the fractures formed during the folding. However, as the fracture sets are at right angles and not related to the fold in orientations expected for extension fractures it appears equally likely that they formed before the folding.

Sets T_3 & T_4

Fracture sets T_3 & T_4 appear to be spatially related to the fold, set T_4 mainly occurring on the limbs of the fold, while set T_3 predominantly occurs in the hinge. Poles to set T_4 plot close to the orientation of the fold axis and are regarded as 'ac joints'. Poles to set T_3 plot in positions expected for 'bc joints'. Sets T_3 & T_4 are thus related in orientation to the fold as expected for extension fractures of assemblages 1 & 2 in fig. 2.

Faulting & En - Echelon Arrays

Faulting

Apart from the major fault on the west side of the map area which does not appear to have affected fracture orientations, the most significant faults appear to be closely related to set T_1 fractures.

STRIKE ORIENTATION OF FRACTURES ACROSS THE FOLD BEFORE AND AFTER ROTATION

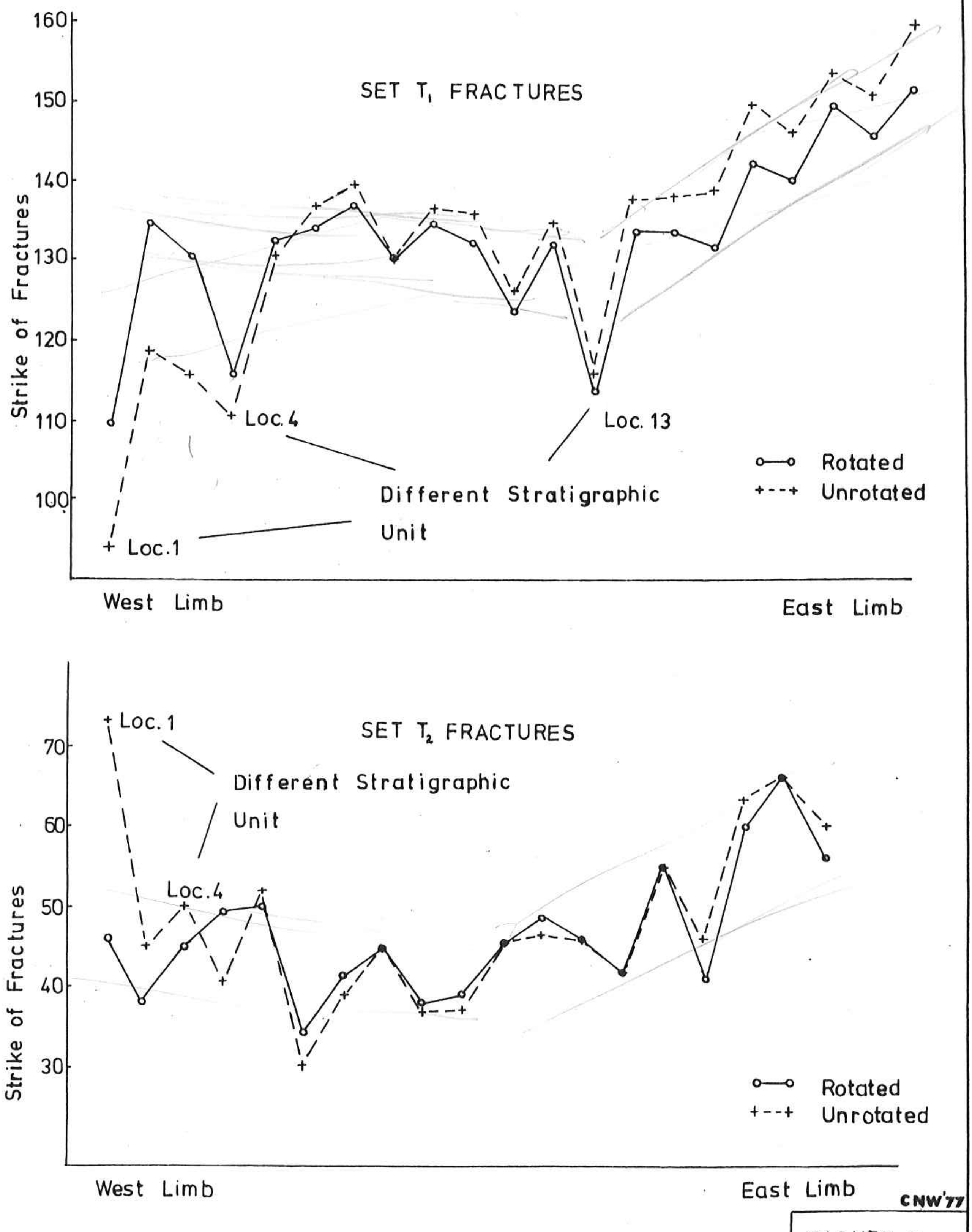

FIGURE 5a

EQUAL AREA PROJECTIONS, POLES TO FRACTURES IN ROTATED AND UNROTATED STATES

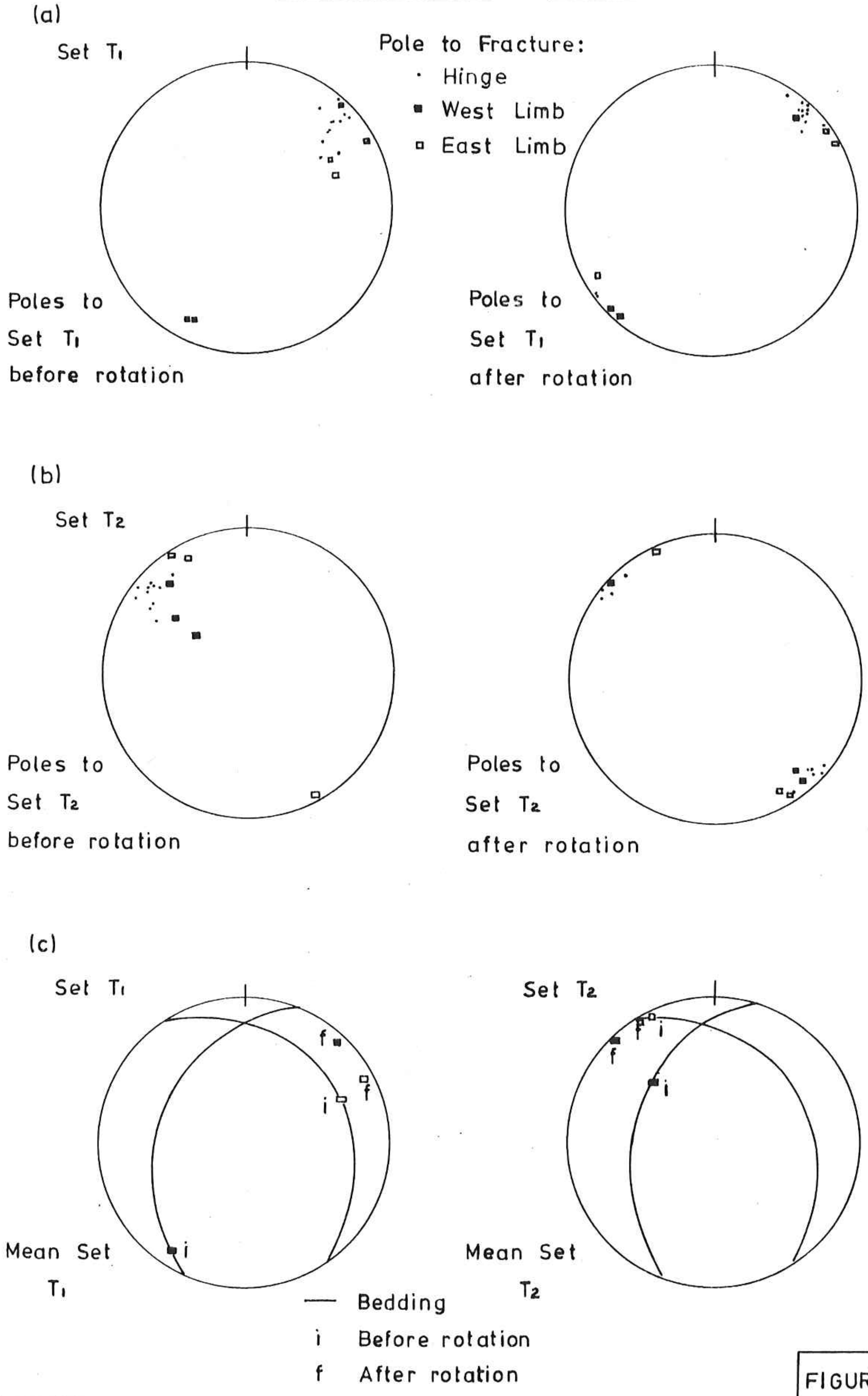

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FIGURE 5b

When poles to 40 observed faults are plotted and contoured on a stereonet (fig. 3b) it is revealed that the modal orientation of the faults (130/75W) is very close to the average orientation of set T_1 fractures (139/80W). Since set T_1 fractures are thought to originate as extension fractures, faulting must have occurred subsequent to their formation. The faults are in general small scale normal or strike - slip type with displacements vertically of between 0 & 2 metres (see plate 1b). Brecciated zones as wide as 2 metres were associated with some faults.

Where the sense of movement could be determined on strike-slip faults it was found to be in general dextral. Difficulty was experienced in distinguishing between faulting along set T_1 fractures and faulting in en-echelon arrays, as discussed below. Striations were commonly found on fracture surfaces; they were generally orientated at low angle to the north west. A thin film of quartz was found on striated surfaces suggesting that the striations are quartz fibres growing in the direction of movement of the fault; a similar situation has been found by Durney & Ramsay (1972).

Faults were observed on the west limb and hinge of the fold, but were absent on the east limb. This may in part be related to poorer rock exposure on the east limb or it may be related to the asymmetry of the fold.

En-Echelon Arrays

Conjugate shear zones containing en-echelon sigmoidal and non sigmoidal quartz veins appear on the west limb and hinge of the fold (see plate 1c). Both sinistral and dextral arrays have been observed, although they rarely occur together. Sinistral arrays appear predominantly on the west limb, while dextral arrays are more common in the hinge. The strike orientations of the arrays and veins contained within them are shown in table 1, from which it can be seen that the veins in one shear zone are almost parallel to the complementary zone. The angle between the two arrays is 37° while the angle between arrays and veins is 31°. Beach (1975) suggests that in these situations the fractures in the arrays originate as shear fractures; the arrays forming as a result of progressive deformation within established shear zones. There is some confusion in the literature as to whether veins that form at between 20 & 40° to an array originate as extension or shear fractures. Extension fractures are generally expected (Ramsay

TABLE 1

STRIKE ORIENTATION OF EN-ECHELON ARRAYS AND VEINS

SINISTRAL ARRAYS

Location No.	Array	Vein	Difference
4	160	120	40
	150	105	45
7	144	110	34
	145	115	30
	140	115	25
	143	124	19
	146	119	27
14	155	118	37
	146	112	34
Mean	148	115	32
s.t.	±6	±5	

DEXTRAL ARRAYS

Location No.	Array	Vein	Difference
4	105	155	50
	102	132	30
	110	140	30
7	115	150	35
12	105	135	30
	110	140	30
	110	150	40
	110	140	30
14	116	135	19
	115	140	25
	118	137	19
	117	135	18
Mean	111	141	30
s.t.	±5	±7	

& Graham, 1970) to form at 45° to the shear zone. This angle may, however, vary if there were pre-existing fractures (Ramsay, 1967). Extension fractures, if they developed at the same time in conjugate shear zones, are expected to have the same orientation, but with a different sense. Conjugate shear fractures generally have a dihedral angle of about 60°, so that, in these cases, the angle between veins and arrays should also be 60°. This angle may also vary as shown by Muehlberger (1961), Parker (1942) and Donarth (1961), being as low as 15° in the case of Riedel shears (Hancock, 1972). In this study the fractures in the shear zones are considered to be shear fractures, since veins in the arrays are parallel to the complementary zone and set T_1 extension fractures (strike 139°) approximately bisect the two shear zones. For the fractures to form as extension fractures it is necessary for them to form at different times; this appears unlikely for they display a conjugate relationship. The quartz in veins in the shear zones is in the form of extension fibres normal to the fractures. The later history of these shear fractures has thus involved extension and dilation. This should not be confused with their initial formation.

The veins within the arrays are orientated approximately normal to bedding so that the angle between arrays is about 40°. Total shear in the most sigmoidal veins is between 0.4 and 1.8γ and shear displacements vary between 9 and 23 cm. This shear involves the rotation of the portion of the vein central to the shear zone after the introduction of quartz. In most arrays the veins were essentially non-sigmoidal and had not undergone large dilation. Offsets between the quartz occurring in set T_1 fractures shows that quartz was introduced into these fractures after the fractures in the sinistral arrays. A number of the shear zones have developed into small strike-slip faults with displacements commonly of the order of several centimetres.

Relationship Between Fractures, Palaeocurrents & Rock Fabrics

Diessel et al (1967), Cook & Johnson (1970) and Moelle (in press) have established a direct relationship between diagenetically formed fractures and transport directions within a fluvial sequence of the Sydney basin. One fracture set is observed to be parallel to the sedimentary transport direction with a complementary set normal to it. It is suggested that these fracture sets formed during the final stages of diagenesis with orientations controlled by the anisotropy established when the sediments were deposited. The fractures are thought to develop by brittle failure while under compactional load in an extensional stress regime (Moelle, in press).

The idea that fracture orientations may be influenced by a primary depositional fabric has not been investigated to any great extent. Certainly preferred grain orientations are established within certain types of environments as shown by Reineck & Singh (1975). The study by Lafeler & Willoughby (1971) showed that within two soils the most important anisotropy was parallel to the transport direction and that failure is most likely to occur along that direction. Friedman and Logan (1970) showed that grain fabric anisotropy influenced the orientations of fractures in three quartzose sandstones.

Within deformed rocks only a few studies have been made relating primary rock fabrics to fractures. The main reason for this is the belief that any fracture formed soon after deposition would be destroyed by compaction and consolidation during deep burial and later folding (Price, 1966). However, Parker (1942), Hodgson (1961) and Wise (1964) have all come to the conclusion that fractures formed before or at the initial phases of folding could survive the deformation. Secor (1965, p. 635) also supports this view with the comment, "There is a growing realization that the fundamental fracture pattern of a rock mass is established early in its history". Bonham (1957) studied petrofrabics and fractures across an anticline but could not find any relationship between micro and mega structures. Reik & Currie (1974) in a study of the relationship between rock fabrics and fractures in sandstone came to the conclusion that sediment diagenesis and initial tectonic loading influenced the orientation of later formed fractures.

McCarthy (1974) in a preliminary study of palaeocurrent directions from asymmetrical ripples and cross beds in the Port Germein gorge area suggested that the main current flowed from the west or north west. Since fracture sets T_1 and T_2 form an orthogonal pair which may have formed before folding, with set T_1 orientated approximately after rotation northwest - southeast, it was possible a more detailed investigation of palaeocurrent directions might indicate a relationship between them and fracture sets T_1 and T_2.

As cross bedding is relatively poorly developed in unit 3 of the Emeroo Quartzite it was necessary to rely on the more abundant ripple marks to determine current directions. For the purpose of this study current ripple marks were classified as either symmetrical or asymmetrical. Within unit 3 the orientation of 164 ripple marks were determined and rotated so that the fold axis and bedding were horizontal (Ramsay, 1961). The results are shown in fig. 6, along with the orientations of set T_1 & T_2 fractures after rotation. Note that only the modal orientations of the fractures are shown for each location. The palaeocurrent data indicates a unimodal current direction of 130-140 azimuth. From fig. 6 it can be seen that there is a strong relationship between the palaeocurrent direction and fracture sets T_1 & T_2. Fractures of set T_1 are parallel to the palaeocurrent direction while fractures of set T_2 are normal to it. The change in the fracture orientations on the east limb is also reflected in the palaeocurrent data, The palaeocurrent direction changing from 130-140^o to 140-150^o azimuth. Changes in fracture orientations in different stratigraphic units noted earlier, are thought to be a result of a slight change in the palaeocurrent direction with time.

In order to obtain evidence for a relationship between set T_1 & T_2 fractures and primary anisotropy on a micro scale three thin sections were made parallel to bedding from rock specimens collected at locations 3, 11 & 17. The strike of the long axis of clasts within these thin sections was determined relative to an azimuth after bedding had been rotated to horizontal. The preferred orientation of 968 clasts of sizes between 0.2 mm and 3.0 mm have been determined by magnification of thin sections. The results are shown in fig. 7, also shown is the strike of set T_1 & T_2 fractures from each location after rotation and the combined palaeocurrent data. From fig. 7 it can be seen that there is a definite preferred grain orientation parallel to set T_1 and T_2 fractures. The orientation of clasts normal to the palaeocurrent is thought to be the result of the rolling of clasts in the direction of the current. The asymmetry in the preferred orientation about 135^o may be a result of rotation of clasts towards the fold axis or asymmetry in the palaeocurrent direction.

The main controls on the degree of preferred orientation are expected to be current strength and gravity. Other factors may be the nature of clasts, cement and compactional loading (Moelle, in press). As noted by McCarthy (1974) the sediments are texturally mature and under the depositional conditions the current strength is not considered

PALAEOCURRENT DATA AND RELATED FRACTURE SETS

PORT GERMEIN GORGE AREA

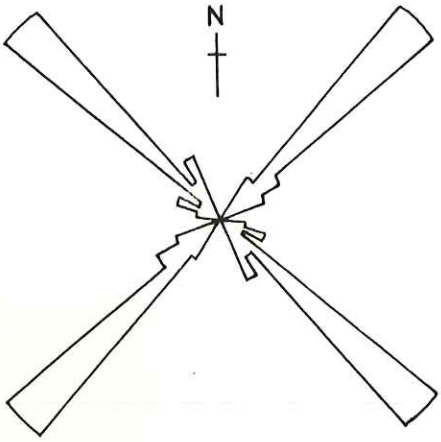
SOUTH AUSTRALIA

FIGURE 6

FRACTURES AND EVIDENCE FOR SEDIMENT ANISOTROPY

Mean strike of set T_1 & T_2 fractures, from 21 locations after rotation.

10° Class Intervals



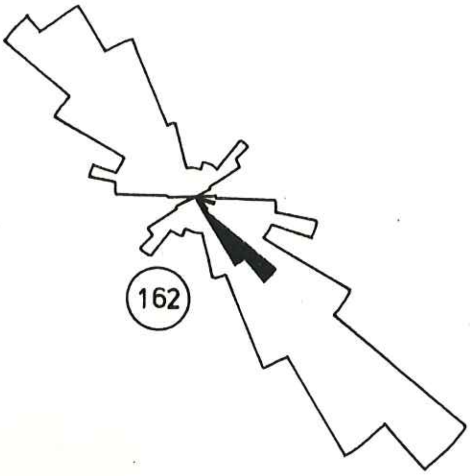
Palaeocurrent Data

Ripple marks

△ Symmetrical ripples

▲ Asymmetrical ripples

10° Class Intervals



Apparent elongation of clasts in thin sections parallel to bedding.

10° Class Intervals

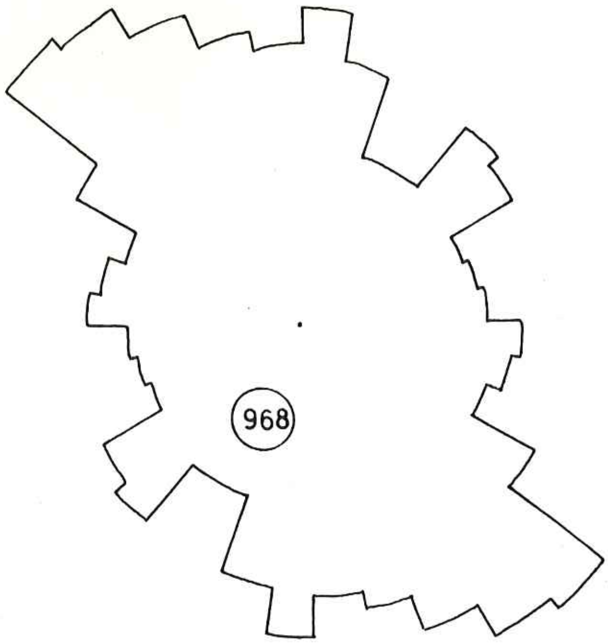


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FIGURE 7

to be exceedingly strong. Thus only a weak preferred orientation is to be expected.

The orientations of set T_1 & T_2 are explained as directions of primary anisotropy established when the sediment was deposited. Although this relationship supports the idea that the fractures formed before the folding, other independent evidence is required before a firm conclusion can be made. The orientation of poles to set T_1 & T_2 fractures 45^o away from the fold axis is now seen to be a coincidence.

Orientation and Nature of Quartz Fibres

In order to determine the relationship between set T_1 & T_2 fractures and the quartz fibres within them the orientation of the fibres has been determined. Such crystal fibres have been termed syntectonic by Durney & Ramsay (1973). Most measurements were made in the field with the direction and plunge determined. In a few cases samples were taken and fibre orientations determined using the method outlined by Phillips (1971, p. 20). Syntectonic crystal fibres have been previously studied by Durney & Ramsay (1973), Phillips (1974) and Wickham (1973, 1977). Such studies have been very useful in establishing incremental strain variations. Durney & Ramsay (1973) regard fibres of this type as forming due to pressure solution in the surrounding rock, with the direction of growth occurring parallel to the maximum strain axis (X).

Across the anticline quartz fibres are generally orientated normal to the fracture surfaces. This observation suggests that the fracture formed as the quartz was introduced and dilation of the fracture normal to its surfaces accompanied the growth of the quartz. As noted before, in a number of set T_1 fractures, small crystals have grown from either side of the fracture leaving a cavity in the centre, indicating that in at least some cases a fracture was present before the quartz was introduced.

In a number of fractures fibres were observed to have curved forms. In these cases an initial and final fibre orientation was determined. For set T_1 fractures four examples of curved fibres were found; in each case the crystal growth is syntaxial (Durney & Ramsay, 1973), as would be expected for quartz fibres in a feldspathic sandstone. The rotation is dextral away from the normal position. A typical example is shown in fig. 8a. In a few cases two closely orientated veins of set T_1

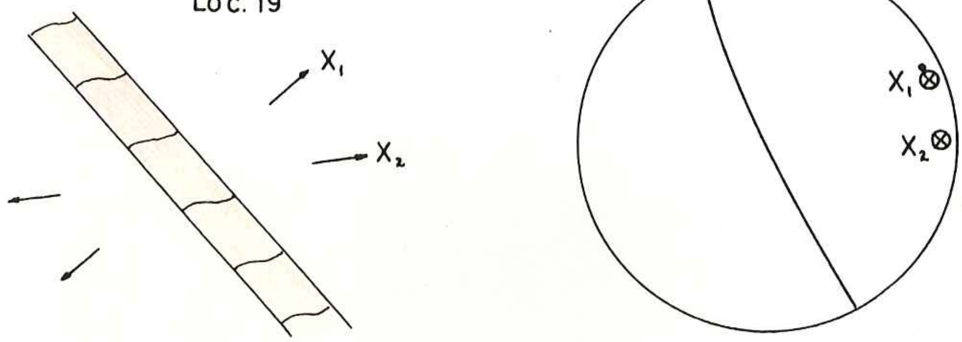
fractures display cross-cutting relations. For example, a vein with dip and strike 120/75W was observed to be offset by a later vein 152/62W. Fibres were orientated normal to each fracture so that the rotation in the orientation of fibres is in the same sense as that determined for curved fibres in individual veins. This example is illustrated in fig. 8b. In set T_2 veins one case was found of fibres curved in a dextral sense; this example is illustrated in fig. 8c.

The fibres filling set T_1 & T_2 fractures are generally coarser than the surrounding material and consist of single crystals extending across the fracture, see plates 2a and 2b. Optical continuity is not always maintained across the fractures; the fibres often have sutured crystal faces and appear to have undergone recrystallization. In some cases recrystallization has been so severe that the original preferred shape orientation is almost completely destroyed. Fibres do not show the characteristics of a median line and absence of cavities usually associated with syntectonic fibres. As seen in plates 2a & 2b the fracture surfaces are irregular on a microscale. Micro fractures were sometimes observed in individual clasts, as in plate 2c, quartz is again found filling these fractures. These fractures appear limited in extent to individual clasts.

There is abundant evidence within thin sections for pressure solution activity. Quartz grains commonly have welded and sutured contacts. The original curved clast shape is often truncated, with mutual - impringement grain boundaries. The fabric in sandstones consists of a closed framework of welded quartz clasts, feldspar and minor rock fragments. Indentations are often observed between quartz grains, as shown in plate 2d. Quartz overgrowths are also common; they are clear and can be distinguished from the original clasts by the presence of hematite rims. The overgrowths which may also be developed on feldspar grains occur on clasts of all sizes; they have been described in more detail by McCarthy (1974). Pressure solution and cementation are generally related to lithification during diagenesis rather than metamorphism (Spry, 1977). The process of lithification involves pressure solution at points of high pressure and precipitation at points of low pressure. Pressure solution provides the necessary silica solution for the formation of quartz fibres. It is postulated that the fibres grew either during diagenesis or early folding. The recrystallization of some quartz fibres also suggests that they formed early in the tectonic history.

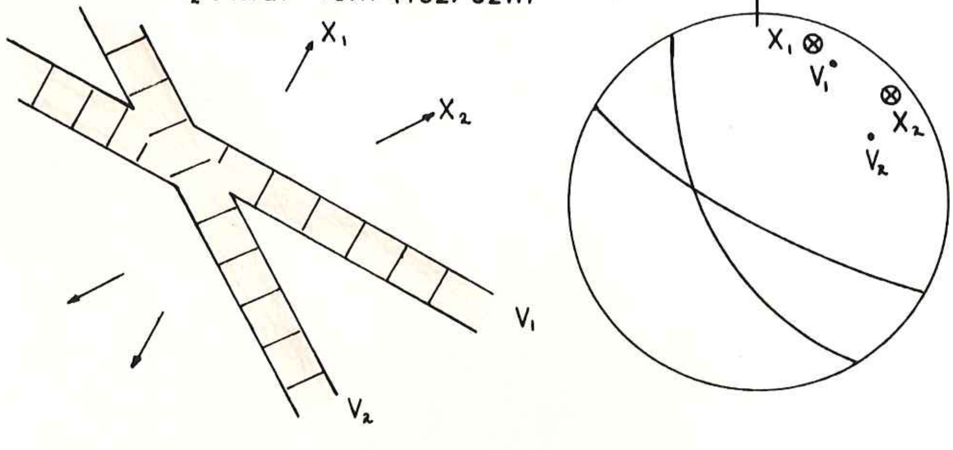
CHANGE IN FIBRE ORIENTATION IN FRACTURES

(a) SET T_1 FRACTURE (155/85W)
Loc. 19

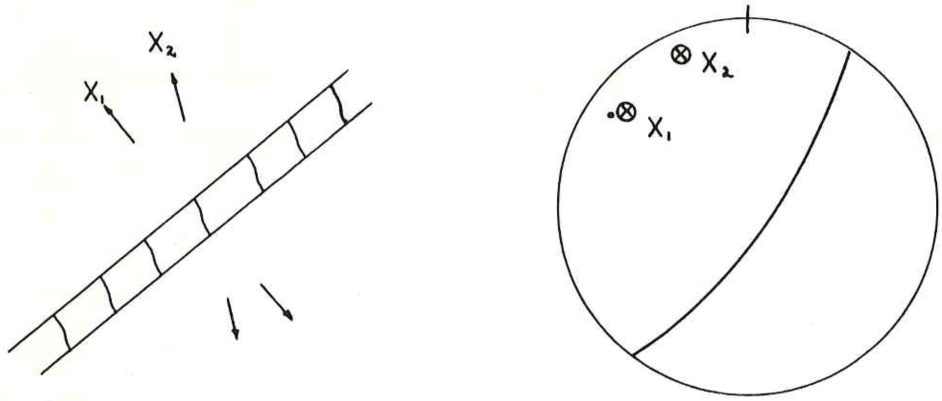


(b) SET T_1 FRACTURE Loc. 17

V_1 Initial Vein (120/75W)
V_2 Final Vein (152/62W)



(c) SET T_2 FRACTURE (35/80S)
Loc. 11



— Fracture • Pole to Fracture

⊗ Fibre Orientation X_1 Initial X_2 Final

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FIGURE 8

Interpretation & History of Fracturing

From the analysis of fracture patterns in the Port Germein gorge area the following conclusions can be drawn:

(1) All fractures (T_1 - T_4) initially formed as extension fractures, the order of fracture formation is first T_2,T_4 'ac', T_1 and finally T_3 'bc. Set T_3 is thought to have formed last since quartz does not fill these fractures.

(2) The fractures in the en-echelon arrays are considered to have formed initially as shear fractures, with later development as extension fractures. They formed before set T_1 but after set T_4 (see plate 3a).

(3) As syntectonic quartz fibres are orientated normal to set T_1 & T_2 fractures, it is very likely that these fractures formed when the quartz was introduced, either during diagenesis or early folding. The dextral curvature of these fibres suggests that they formed during folding. The curvature of fibres in set T_2 veins is seen as change in the direction of extension away from fracture normality to be parallel to the fold axis, after which the 'ac' fractures (set T_4) formed. Curvature of fibres in set T_1 veins is seen as a change in the direction of extension to be normal to the fold axis, after which the 'bc' fractures, set T_3 formed. Fracture sets T_1, T_2 & T_4 are regarded as forming during the process of folding. Although Beach (1977) has suggested that quartz veins may form before folding this is not considered to be the case in the present study, based on the orientation of the quartz fibres. It is not possible to say definitely whether set T_3 ('bc') formed during folding or during later uplift as proposed by Price (1966). Some set T_1 fractures were probably present before quartz was introduced into these fractures; it is likely that they formed during the late stages of diagenesis. The relative low angle between shear zones is thought to be a result of the early formation of some T_1 fractures.

(4) Strike-slip and normal faulting occurred along set T_1 fractures as a result of changes in the orientation of the principal stresses during folding. As both types of faulting has occurred σ_1 and σ_2 were probably close in magnitude at the time of faulting, either before or during the formation of set T_3.

(5) The occurrence of set T_4('ac') mainly on the limbs of the fold and set T_3 ('bc') mainly in the hinge can be related to expected fracture patterns across a fold, as shown in fig. 2.

In attempting to relate the fracture history to stresses active during folding it is necessary to make a number of assumptions:

(1) That extension fractures unrelated to anisotropy form normal to σ_3.
(2) That during the process of folding σ_3 was initially parallel to the fold axis and finally normal to it, while at the time of the formation of shear zones σ_1 and σ_3 bisected these zones. During the folding σ_2 was normal to bedding.
(3) Quartz fibres develop parallel to the strain axis X.
(4) During diagenesis the stress conditions were such that σ_2 was vertical.

Assumptions 1 - 3 are based on evidence gathered by Stearns (1964, 1968), Handin (1972), Griggs & Handin (1960) and Durney & Ramsay (1973). These observations have been made on isotropic rocks, so that the effect that anisotropy exerts on the orientation of the stress axes is unknown. For this reason at the initial stages of fracturing it is not possible to distinguish between σ_1 and σ_2 . Assumption 4 is based on observation of the rock fabrics in sections normal to bedding, which shows that clasts have been flattered parallel to bedding.

The postulated history of fracturing and relations between principal stress and strain axes are shown in fig. 9 and table 2. The history of fracturing is seen to be a consequence of the orientation of the palaeocurrent, related fractures; and the stresses induced into the rock as a result of folding. The timing of the dilation and growth of quartz in fractures related to palaeocurrents is controlled by the orientation of these fractures relative to the fold. Extension fractures (T_2) first formed normal to the palaeocurrent, their later history involving dilation nearly parallel to the fold axis. Later fractures (T_4 'ac') formed normal to the fold axis. A change in the orientation of the principal stress axis caused the formation of extension fractures (T_1) parallel to the palaeocurrent, with later extension normal to the fold axis. This led to faulting along these fractures and the formation of fractures (T_3'bc') parallel to the fold axis. The strain axis (X) is seen to be constantly changing to be parallel to σ_3.

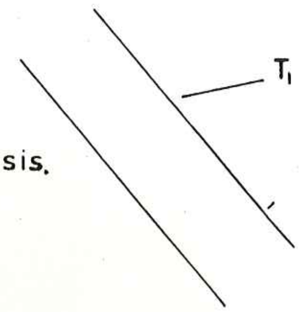
As a consequence of the introduction of quartz into the early formed fractures the strength of the rock was maintained, so that further fractures could form and existing fractures could survive burial and uplift. The degree of deformation was probably a major factor in the

TABLE 2: FRACTURE HISTORY PORT GERMEIN GORGE AREA

Stage	Sedimentation	Fracture formation	Growth of quartz fibres	Faulting	Folding
1	Deposition of sediments in a beach or tidal environment. Primary anisotropy established.				
2	Late diagenesis.	Some set T_1 fractures formed.			
3		Formation of set T_2 fractures.	Growth of quartz fibres into set T_2 fractures.		Early stages of folding?
4		Formation of set T_4 'ac' fractures.	Introduction of quartz into set T_4 with dilation.		Extension parallel to fold axis.
5		Formation of conjugate shear zones and en-echelon shear fractures. Dilation of fractures and rotation of veins.	Introduction of quartz fibres into shear fractures in shear zones.		
6				Shear movement in shear zones.	
7		Formation and dilation of set T_1 fractures.	Introduction of quartz fibres into set T_1.		
8				Faulting along set T_1 fractures.	
9		Formation of set T_3 'bc' fractures.			Final stages of folding? Extension normal to fold axis.

HISTORY OF FRACTURING AND RELATION TO STRESS & STRAIN AXIS, FOR A LOCATION IN THE HINGE OF THE FOLD

(1) Formation of some set T_1 fractures parallel to the palaeocurrent during diagenesis. Under compactional load σ_1 vertical.



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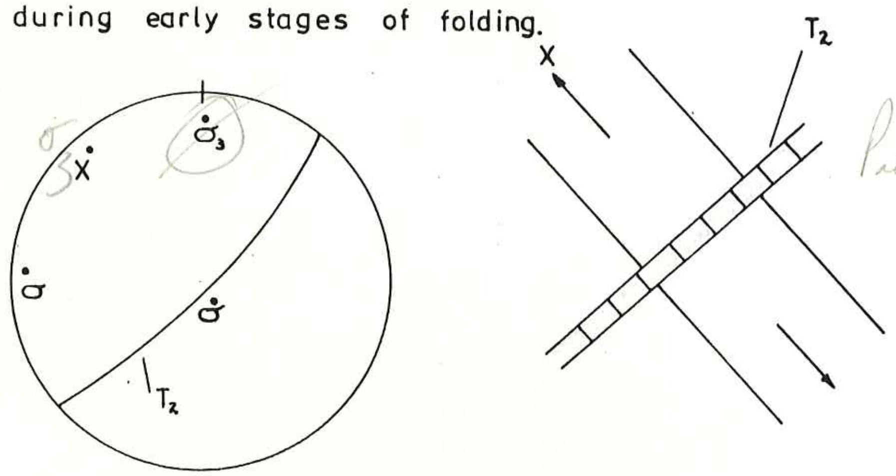
(2) Formation, dilation and growth of quartz into set T_2 fractures during early stages of folding.



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(3) Further dilation of set T_2 fractures.

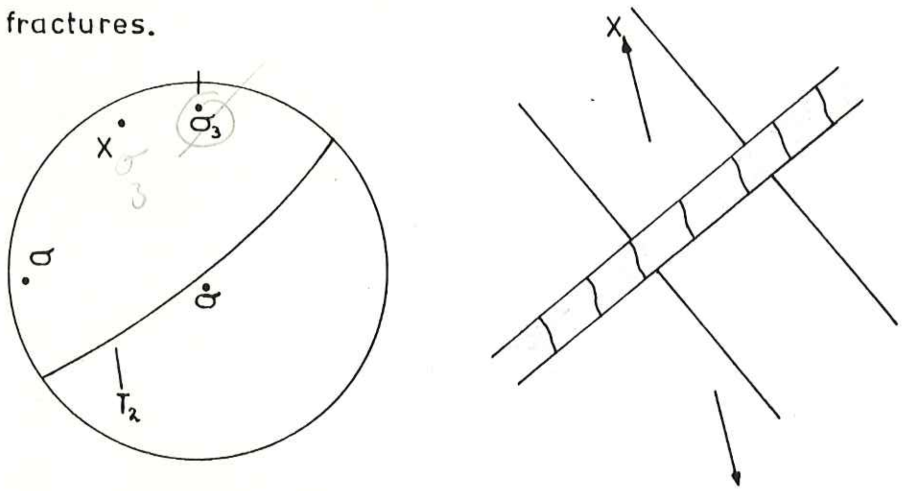

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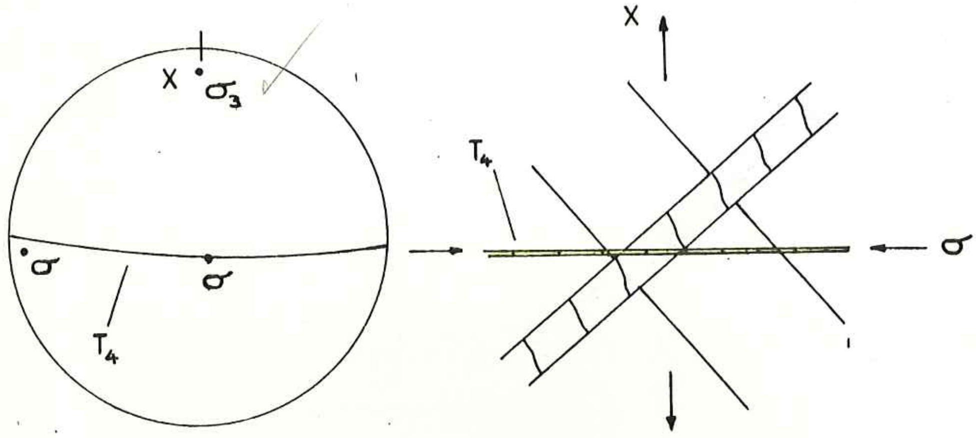
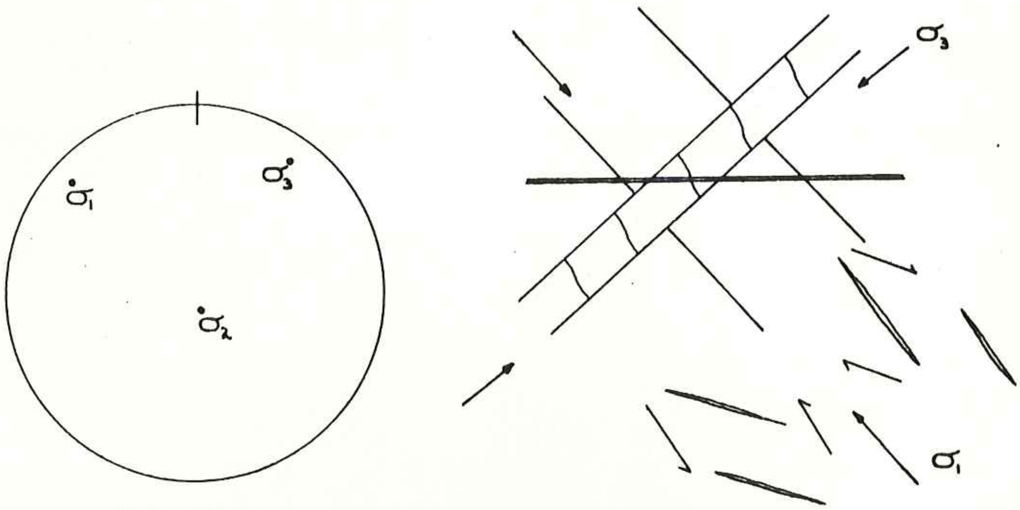
FIGURE 9

(4) Formation of set T_4 fractures by extension parallel to the fold axis, introduction of quartz.



(5) Formation of shear zones & shear fractures within those zones.



(6) Dilation and introduction of quartz into shear fractures.

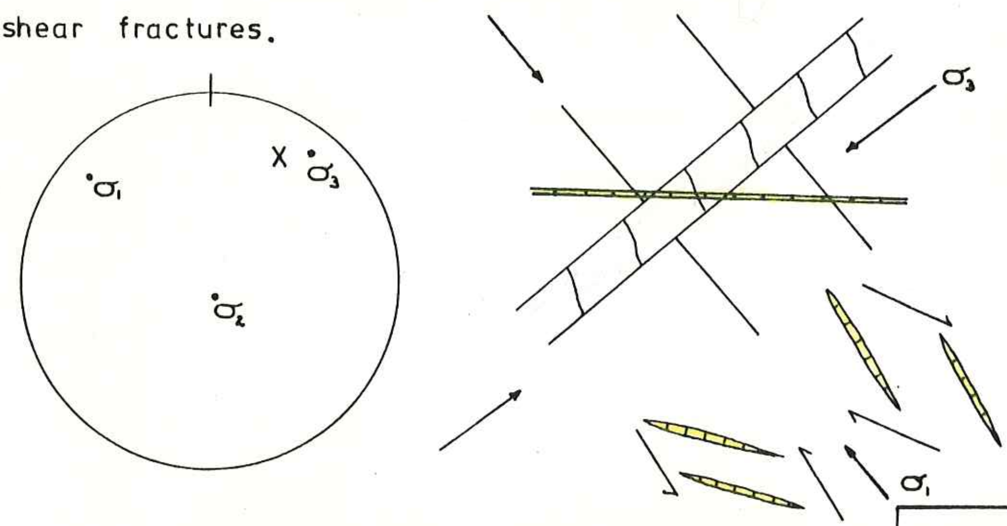


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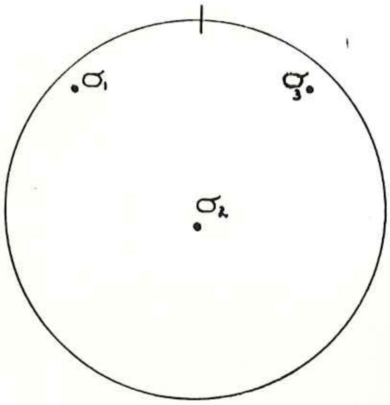
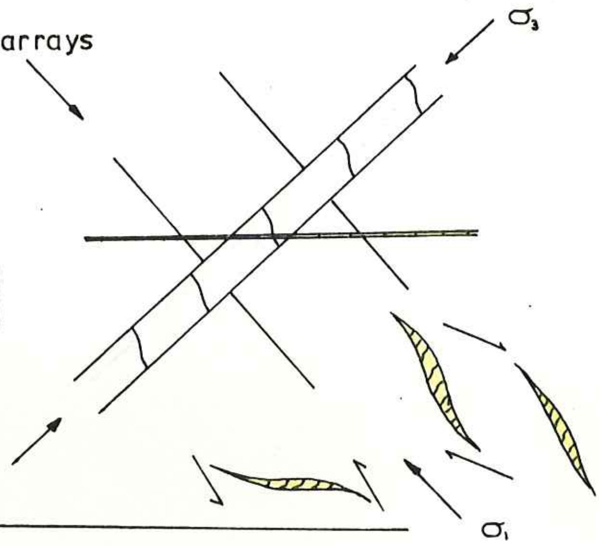
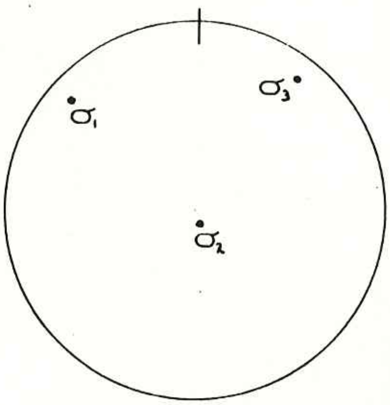
FIGURE 9

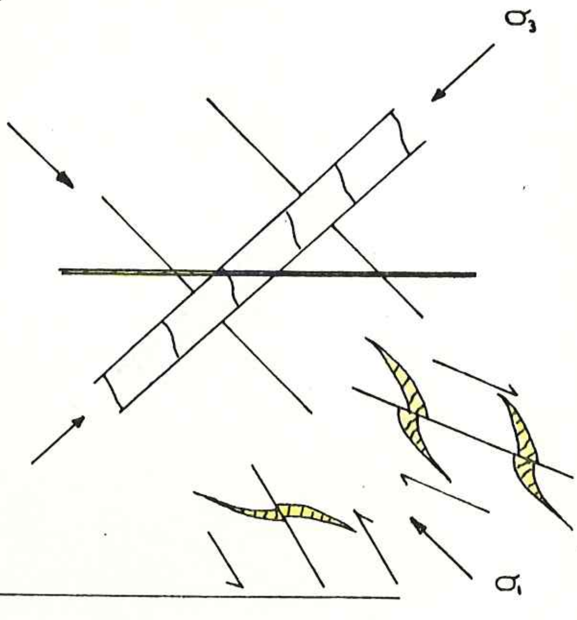
(7) Rotation of the central portion of veins in en-echelon arrays



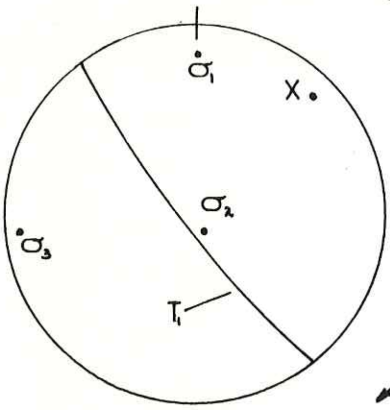


(8) Strike - slip faulting in shear zones.





(9) Dilation and growth of quartz into set T_1 fractures



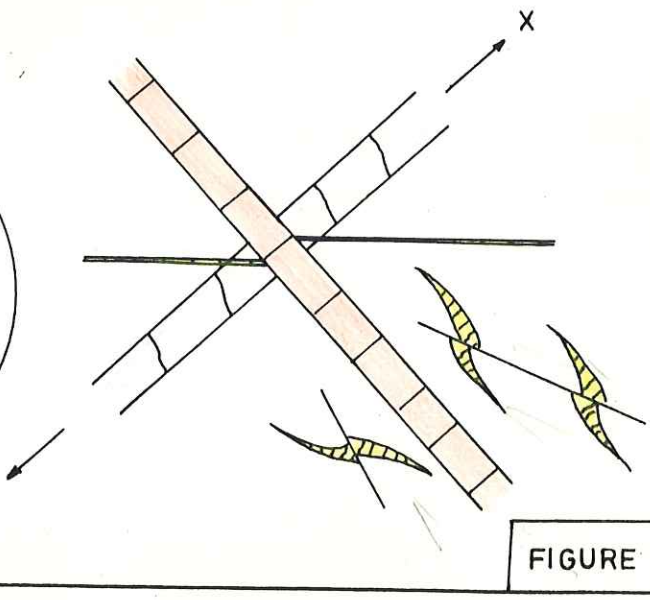


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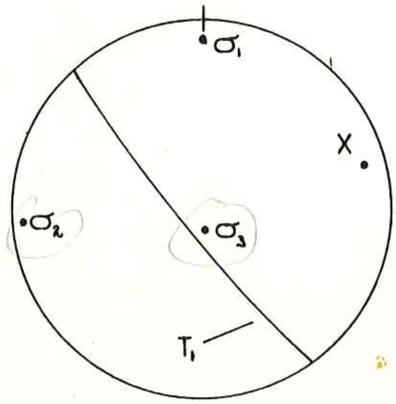
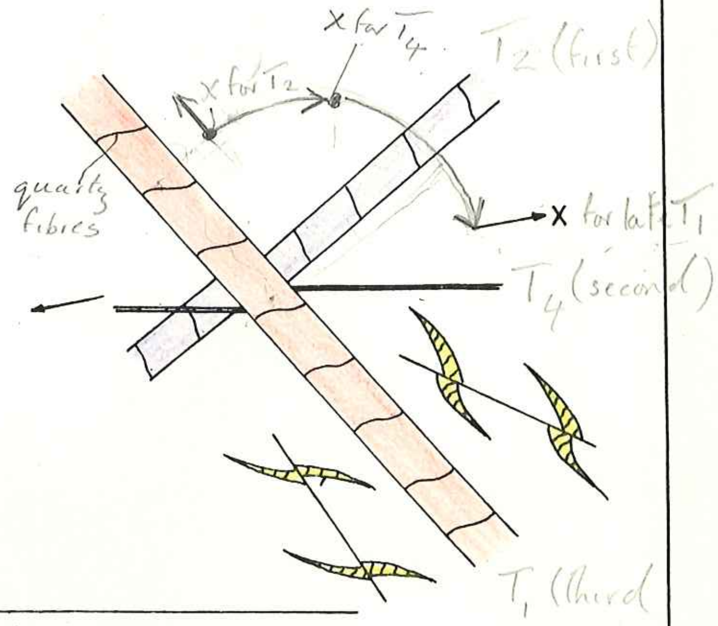
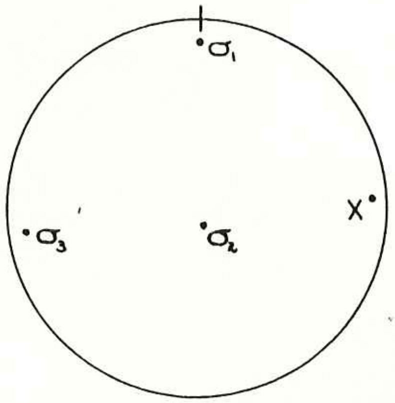
FIGURE 9

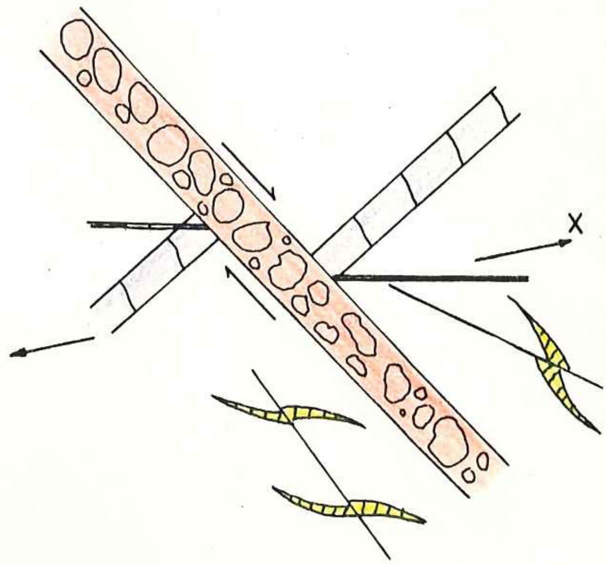
(10) Further dilation of set T_1 fractures.



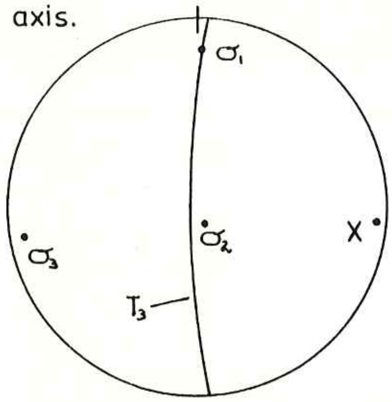


(11) Strike-slip faulting along set T_1 fractures.





(12) Formation of set T_3 fractures, extension normal to the fold axis.



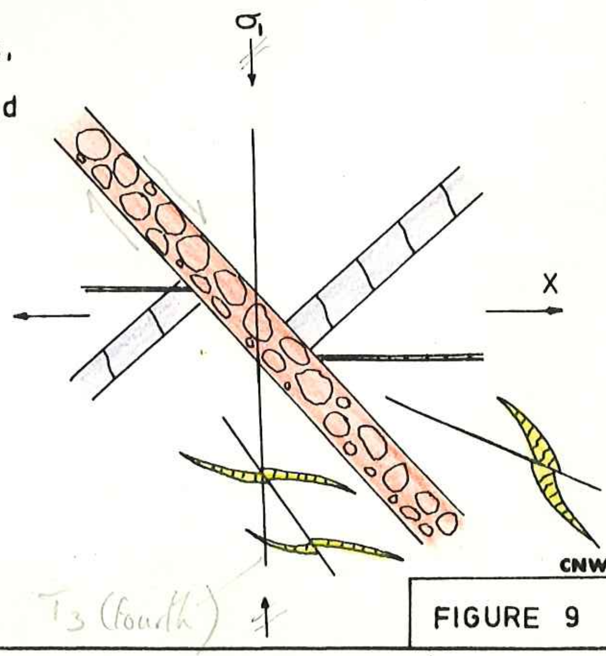


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FIGURE 9

survival of fractures. With tighter folding and a higher grade of metamorphism fracture sets are less likely to survive. Previous attempts to relate stress fields to fractures formed during folding have been made by Norris (1967), Thomas (1970), Reckes (1976) and Burger & Thompson (1970). These studies have little in common with the present analysis as the nature of the fractures varies considerably.

The fracture pattern at location 2 has many features in common with that in the Port Germein gorge area. Two fracture sets are developed normal to each other that have similar orientations to sets T_1 & T_2; they appear unrelated in orientation to the fold. At location 2 it was not possible to determine whether these sets were related to palaeocurrents. Faulting is very common at this location. Where the sense of movement could be determined the faults were observed to be normal. Two sets of faults are developed, one that dips to the west and another that dips to the east. Faults dipping to the east appear to be earlier and represent faults that were parallel to set T_1 fractures at location 1. The other faults are thought to be Tertiary in age. A fracture set developed at location 2, that appears unrelated to the fold, may be related to these west dipping faults.

VARIATIONS IN FRACTURE PATTERNS ALONG STRIKE

General Geology

In order to determine the significance of any changes along a fold it was necessary to take measurements of fracture orientations within the same lithology at locations on the same limb of a fold and as far as possible within the same stratigraphic unit. Four locations were selected having a total separation of about 40 kilometres. At the most northern location (loc. 4, fig. 1) measurements were taken in the Leasingham Quartzite of the Burra Group, while at the other three locations (5 - 7) measurements were taken in the Gilbert Range Quartzite, also of the Burra Group. All locations are on the west limb of a syncline, plunging about 5^o due north at locations 4 & 5 and about 5^o due south at locations 5 & 6. The axial trace is essentially orientated north-south and the axial plane dips to the west. At all locations bedding is overturned and steeply dipping to the west. Cleavage was only observed at location 5 where it was poorly developed but dipping at a lower angle than bedding to the west.

Description of Fracture Sets

A total of five main fracture sets were observed; three sets T_1 - T_3 were observed at all locations, while sets T_4 & T_5 were restricted to locations 4 & 6 respectively. The contoured poles to fractures and a diagrammatic illustration of fracture orientations are shown in fig. 10.

Set T_1 ('ac' extension)

The surfaces of these fractures are generally smooth and planar. A few fractures have been filled with vein quartz. Poles to these fractures plot close to the fold axis on a stereonet and are thus 'ac' fractures. At location 7 some fractures of this set do show evidence of shear movement and displacement of other fractures. This is thought to have occurred after the fracture formed, possibly related to uplift.

Set T_2 (shear)

Fractures of this set are moderately well developed at location 4, 6 & 7. The surfaces of these fractures tend to be irregular and fractures are not filled with quartz. These fractures were observed to have shear movement along their surfaces of up to 5 cm, at locations 4, 6 & 7. Movement on fractures was in all cases in the reverse sense (see plate 3b).

Set T_3 ('bc' extension)

This fracture set is best developed at location 5, where the fractures are smooth and planar. Quartz was observed as filling in some fractures of this set. This quartz offsets that in set T_1 fractures. As poles to these fractures plot 90^o away from the fold axis as measured along the bedding plane they are thought to be 'bc' fractures. At location 5 it was observed that these fractures show their best development close to the present geomorphic surface, possibly due to weathering.

Set T_4 (shear)

The surfaces of these fractures are irregular. Fractures of this set are observed to displace set T_1 and set T_3 fractures. The movement along these fractures was in all cases in the reverse sense. As developed at location 4, set T_2 and T_4 form a conjugate shear set separated by about 60^o. Sets T_2, T_3 and T_4 thus correspond to assemblage 2 in fig. 2. The shear movement along set T_2 and T_4 is in the reverse sense, so that the minimum principal stress (σ_3) was normal to the fold axis when these fractures formed.

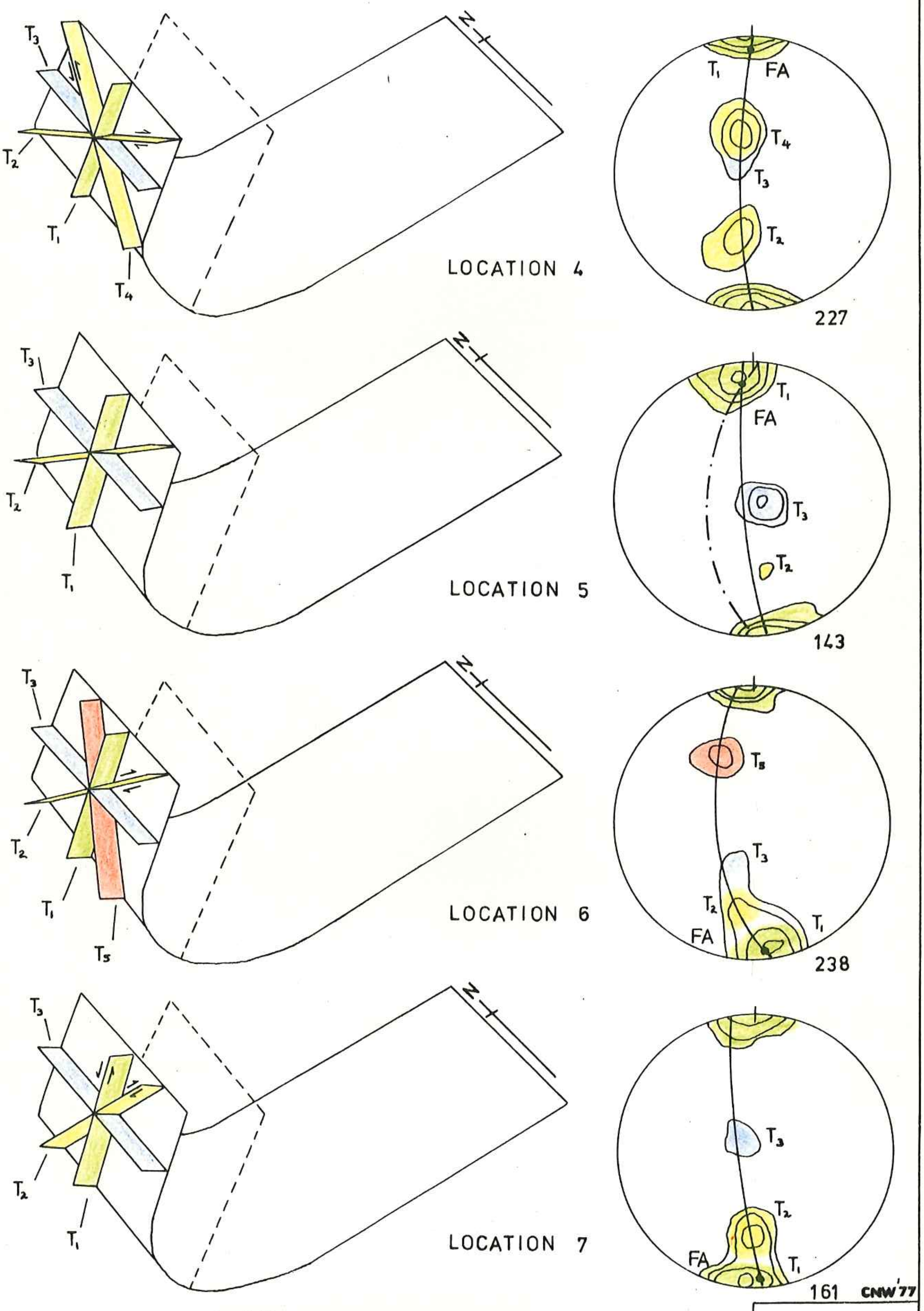
Set T_5

All fracture sets discussed so far appear to be related in orientation to the fold; set T_5 as developed at location 6 does not. Fractures of this set are commonly filled with vein quartz between 0.1 and 2.0 cm wide. Set T_2 fractures are found to displace these veins. Offsets between the quartz in these veins and that in set T_1('ac') and set T_2 ('bc') veins indicates that quartz was introduced into these fractures after set T_5 (see plate 3b). This suggests that set T_5 fractures formed before those that are related in orientation to the fold (i.e. set T_1 - T_4).

Variations Along Strike

The most obvious variation in the fracture pattern along strike is the occurrence of sets T_4 and T_5 at locations 4 & 6 respectively. The presence of set T_4 at location 4 and its absence at all other locations may in some way be related to the lithological differences. The reason why some fracture sets develop at some locations and not at others is a difficult problem to investigate, as so many 'unknowns' influence fracture development. It is possible that at location 6 the occurrence

VARIATIONS IN FRACTURE PATTERNS ALONG STRIKE



— Bedding —·— Cleavage FA Fold Axis

FIGURE 10

of set T_5 which appears not to be related to the fold, may have inhibited the development of the later set T_4. This does not,however, explain why sets T_4 or T_5 are absent from locations 5 & 7.

Fracture set T_2 appears to be inclined at a higher angle to the horizontal going from north to south. This may be due to changes in the orientation of the principal stresses giving rise to these fractures or possibly to the absence of set T_4 at locations 5 - 7. It is possible that since at location 6 set T_5 is thought to have formed first, the orientation of this set affected the orientation of the later set T_2.

Both sets T_1 and T_3 show a slight change in orientation from north to south. At locations 4 and 5 the modal set T_1 fractures are vertical or dip steeply to the south, while at locations 6 and 5 they dip steeply to the north. This change in orientation is clearly related to the change in the direction of plunge of the fold.

Despite some minor changes in fracture patterns at the four locations it is seen from this analysis that the main fracture sets are related in orientation to the fold and do not change significantly in orientation along the fold. Any changes that do occur can be related to changing lithologies, changes in the direction of plunge of the fold, or the effect of earlier formed fractures on the orientation of fractures related to the fold.

LITHOLOGICAL CONTROL OF FRACTURE PATTERNS

At a few locations significant lithological changes occurred so that it was possible to investigate the effect of changing lithology on fracture orientations and frequencies. In general, fracture sets were better developed in laminated sandstones than the more massive, homogeneous rock types and the incompetent rock types. This observation is as would be expected, as it is generally recognised that rocks such as sandstones are more likely to undergo brittle failure than rocks such as siltstones (Harris, 1960). As bedding anisotropy is also likely to influence fracture development, fractures would be expected to be better developed in laminated sandstones.

At location 5 it was possible to determine fracture orientations in three different lithologies, a quartz arenite, laminated subarkose and a tillite. The contoured poles to fractures in each lithology are shown in fig. 11. Fractures were most abundant in the laminated subarkose and least abundant in the tillite (see plate 3c). The orientation of the fractures remains essentially the same in all lithologies, although some sets are restricted to certain rock types. For example, fracture set T_3 is not found in the laminated subarkose, while set T_4 is only found in the tillite. The relative high frequency of set T_3 in the tillite suggests some lithological control on its development.

Set T_4 is the only set at this location not approximately normal to bedding and this is significant since it is only present in the tillite in which bedding is absent. Set T_4 is orientated nearly vertical and parallel to the fold axis; it is thus very close in orientation to bedding in the other lithologies. This suggests that in rocks with well defined bedding, the bedding planes should be regarded as part of the fracture system. ?

Measurements were possible at location 13 in two lithologies, a massive quartz arenite and a fine grained laminated subarkose. Fractures were observed to be more abundant in the laminated subarkose. Three main fracture sets were recognised in the subarkose, two of which correspond to sets in the quartz arenite. As seen in fig. 11 there is a significant change in orientation of sets between the two lithologies. The development of well-defined bedding appears to exert a major control on fracture development.

VARIATIONS IN FRACTURE PATTERNS WITH LITHOLOGY

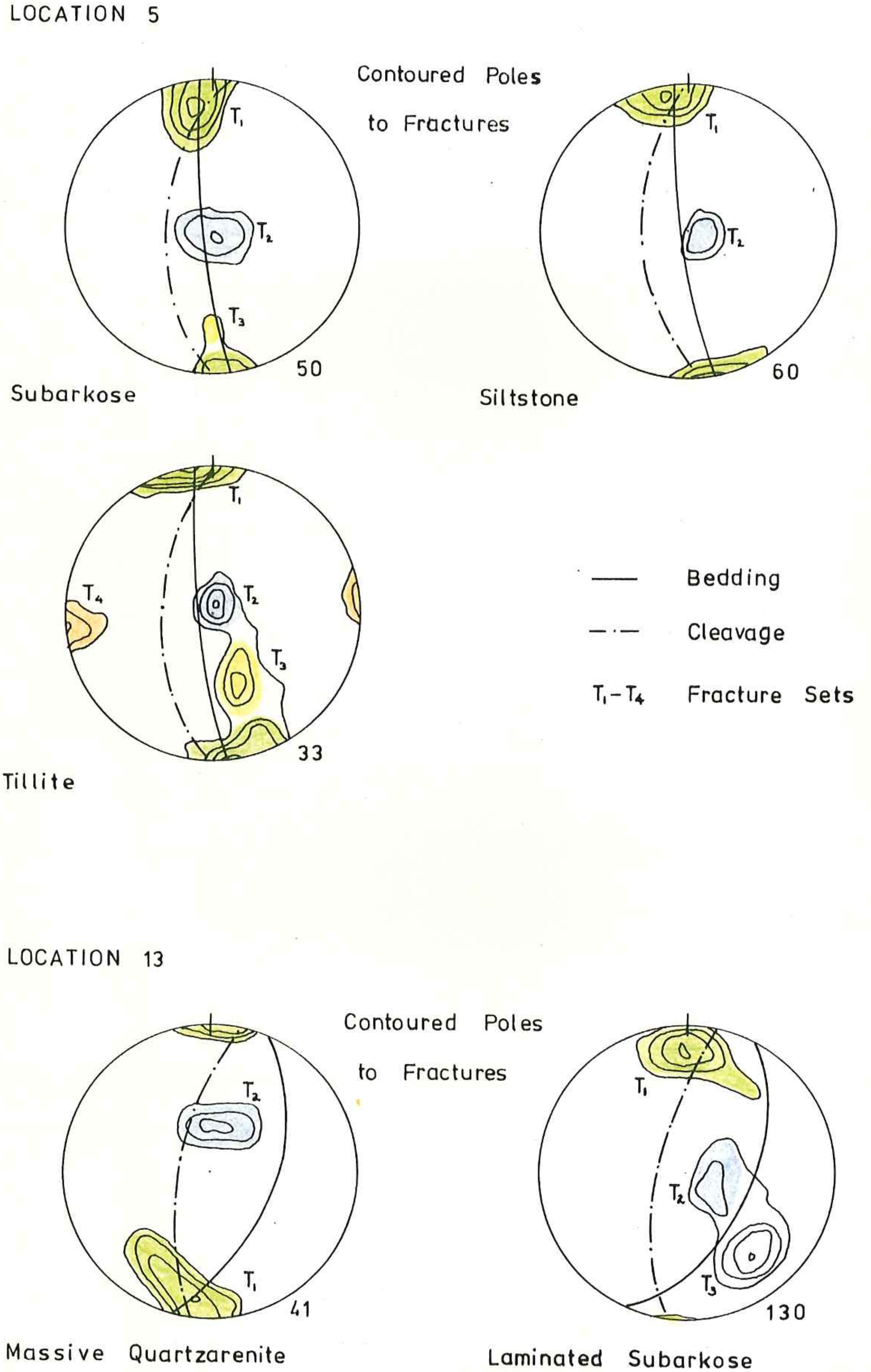


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FIGURE 11

THE REGIONAL FRACTURE PATTERN AND TECTONIC HISTORY

Within the portion of the Adelaide fold belt under study, folds strike essentially north-south with plunges of between 0 and 20^{o}. Most folds are concentric and asymmetrical, with axial planes dipping predominantly to the west, but to the east at locations 1 & 2. The area has only suffered from one period of deformation, the Delamerian orogeny of Cambrian-Ordovician age. The folds are the F_1 folds described by Offler & Fleming (1968). Faulting has occurred repeatedly from the Sturtian movements to the more recent Tertiary faulting. Most faults are normal, steeply dipping and orientated north-south. Present day tectonic activity is restricted to seismic activity, and has been described by Stewart, Slade & Sutton (1973) and McCue (1975). Most events are shallow and relatively low in magnitude. Earthquakes mainly occur in a zone close to the west boundary of the fold belt, the zone being oblique to fold trends. The reason for this distribution is not known, although an interpretation of seismic activity has been made by Stewart (1973) and Stewart & Mount (1973).

The observations and conclusions made from the study of fracture patterns across the Nalshaby anticline and along strike can now be combined and compared with the other locations, so that a regional interpretation can be made. The fracture patterns at locations 2 - 14 are shown in appendix 2, along with descriptions of local structure and fracture sets. A few points are worth noting:

(1) All fracture sets are developed approximately normal to bedding, except for a set that is approximately parallel to bedding and developed at locations 5 & 9.

(2) At nearly all locations 'ac & bc joints' are developed, 'ac' is usually dominant.

(3) Fracture sets occur at a number of locations, that could correspond to conjugate shear fractures similar to those developed at location 4. Shear movement where observed is always in the reverse sense. There is very little evidence for shearing along bedding planes.

(4) At locations 2, 5 and 8 fracture sets are developed that may be related to palaeocurrent directions, as determined at location 1. All of these sets appear unrelated in orientation to the folds.

(5) It is common to have vein quartz or syntectonic quartz fibres filling the 'ac and bc joints' as well as fractures that could be

related to palaeocurrents. Quartz fibres are generally orientated normal to fractures.

(6) Apart from all the fracture sets noted above a few local sets are developed that could possibly be related to Tertiary faulting.

The regional study of fracture patterns has shown that most fracture sets can either be related to folds as extension or shear fractures; or possibly to a palaeocurrent direction. From the analysis of fractures at location 1 the conclusion was reached that the fracture pattern was developed before and during folding. Although at other locations the timing of fracture formation cannot be determined with as much certainty, it appears likely that the fracture pattern was also established before and during the Delamerian orogeny. The presence of syntectonic fibres in fractures related to folds supports this view. The study by Wilkie (1974) of fractures in an area near Mt. Lofty also confirms that most fracture sets are related in orientation to folds. The main argument against the formation of fractures in folded rocks during folding or diagenesis has been that fractures could not form and would not survive at the depths at which folding takes place. Various attempts have been made by Griggs & Handin (1960), Secor (1965), Price (1966) and Hobbs et al (1976) to try to determine the maximum depth at which brittle failure will occur Depths determined vary between 200 and 6000 metres, depending on the rock type and stress conditions. Within the west side of the fold belt the depth to magnetic Archean basement is about 4 km. It is possible that fractures could survive in sandstone at this depth if the fluid pressure was great enough (Secor, 1965).

The conclusion that the main fracture sets did not form after the Delamerian orogeny, and that most fracture sets can be related to the folding has important implications on the tectonic history of the area. Various attempts have been made to interpret the curvature of the fold belt in terms of major strike-slip faulting (Katz, 1976) or by a major shear zone (Coward, 1976). If such faults or shear zones existed their presence should be reflected in the fracture pattern. Since fracture sets can either be related to folds or palaeocurrents it is very unlikely that any major fault or shear zones oblique to fold trends were active since the sediments were deposited. Glen et al (1977) has suggested that major faults or shear zones are not necessary to explain the configuration of the fold belt.

The only faulting that does appear to be associated with fractures occurred along fractures parallel to the palaeocurrent. Fractures that could be related to palaeocurrents occur at locations 1, 2, 5 & 8. The reason why these sets are only developed at these locations is unknown. The distribution of these fractures does not appear to be stratigraphically controlled, nor does it appear to be related to the intensity of deformation. The development of fractures related to palaeocurrents could depend on :

(1) Whether the palaeocurrent was oblique to the fold.

(2) Current strength.

(3) The type and texture of sediments.

(4) The water depth.

(5) The stresses active during folding.

(6) The depth of burial.

Seismic activity within the fold belt does not have any obvious relationship to fracture patterns as developed at the 14 locations studied. As the fractures are mainly thought to have formed before and during folding it is likely that these early planes of weakness controlled later faulting and possibly the seismic activity. The distribution of seismic activity within this area remains unexplained.

CONCLUSION

Fracture sets developed within the mid-north of South Australia are related to folds and sedimentary transport directions. Rock anisotropy plays a major role in controlling fracture orientations. The system of fractures developed before and during the Delamerian orogeny, with the history of fracture formation and the growth of syntectonic quartz fibres related to the folding process. A few minor fracture sets are found that could possibly be related to Tertiary faulting, but the fracture patterns show no evidence for major faults oblique to fold trends. No obvious relationship exists between fracture sets and current seismic activity.

The fracture sets related to folds comprise the extension fractures ('ac & bc') of assemblage 1 in fig. 2, and the extension and shear fractures of assemblage 2. The stress field active during folding is thought to consist initially of σ_3 parallel to the fold axis and σ_2 normal to bedding, with a later interchange between σ_1 and σ_3 as the folds developed.

Fractures related to transport directions formed either parallel or normal to palaeocurrents; these are the primary anisotropic directions established during deposition due to preferred grain orientations. Such fractures may have formed during late diagenesis or folding. They may be involved in faulting if they are oblique to folds.

At most locations fracture sets have a consistent orientation relative to folds. Changes in fracture patterns are the result of:

(1) Lithological changes.

(2) Variations in fold orientations.

(3) Effect of early formed fractures on the orientation and development of later fractures.

(4) Changes in palaeocurrents.

As most fracture sets show a consistent relationship to folds, prediction of fracture orientations should be possible if the bedding and fold axis orientations are known. Such predictions could be very useful in engineering projects such as dam and highway construction.

PLATE 1

EVIDENCE FOR FRACTURE DEVELOPMENT LOCATION 1

(a) A set T_1 quartz vein offsets an earlier set T_2 vein. Note normally there is no observable offset between these fractures as quartz fibres are generally normal to fractures.

(b) Normal fault (125/68W), with ¼ metre displacement, is parallel to set T_1 fractures. Location 8, Port Germein gorge.

(c) Dextral array (115°) of en-echelon sigmoidal quartz veins. The array is 16 cm. wide and shear displacement is 23 cm. at 1.5 γ. Assuming veins initially were orientated 25° to array.

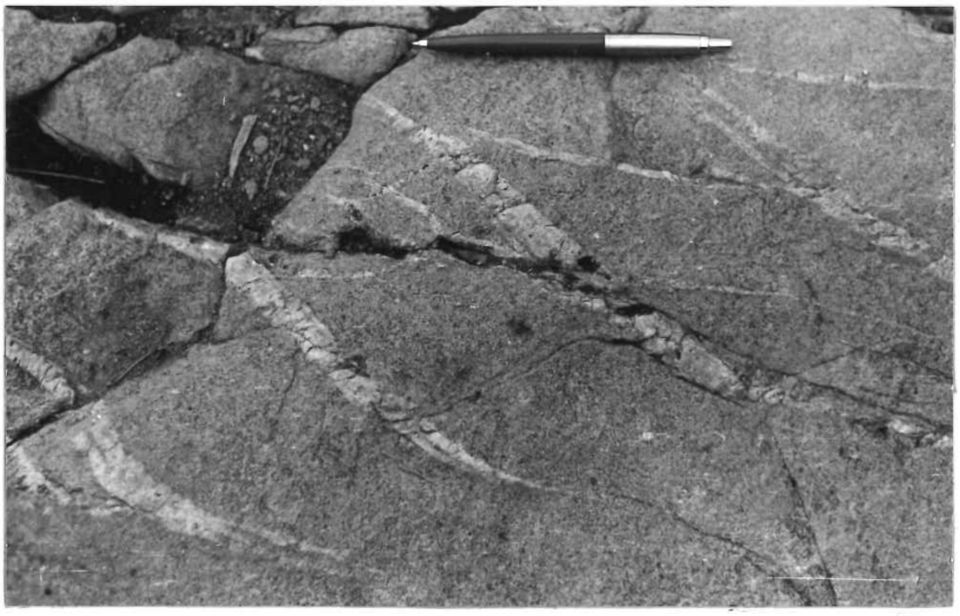

PLATE 2

PHOTOMICROGRAPHS, QUARTZ FIBRES FILLING FRACTURES

AND

INDENTATIONS IN A QUARTZ CLAST

(a) (left) Syntaxial, syntectonic quartz fibres in a set T_1 fracture, Port Germein gorge. Fibres are curved in a dextral sense. Cross Polars.

Note: (1) Boundaries of fracture are irregular and diffuse.

(2) Fibres are coarse with poor shape and optical continuity.

(3) Fibres have sutured and welded crystal faces.

(b) (right) Syntectonic quartz fibres in a set T_1 fracture, Port Germein gorge. Fibres consist of coarse crystals extending across the fracture, they have sutured crystal faces. Cross Polars.

(c) (left) Microfracture in an individual quartz clast is restricted to this clast and filled with quartz. Note welded clast contacts. Cross Polars.

(d) (right) Indentations in a single well rounded quartz clast. Cross Polars.

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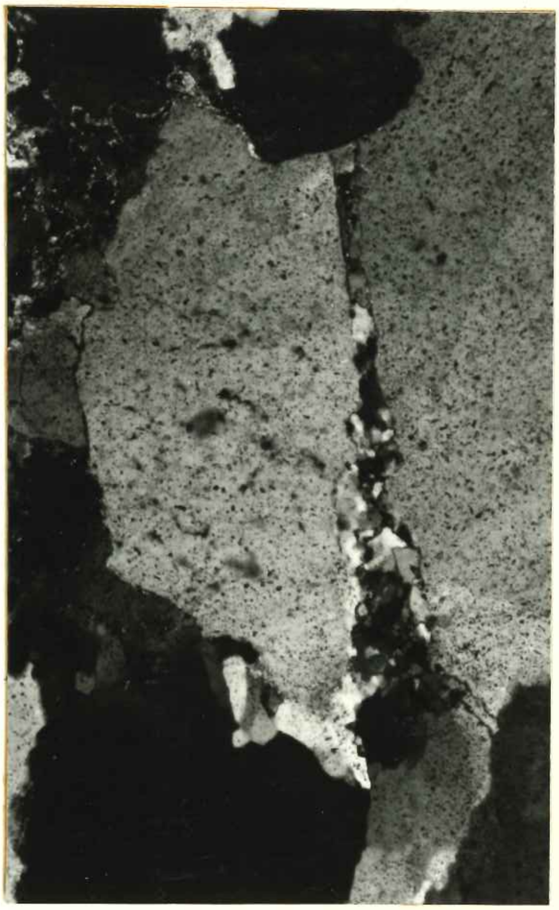
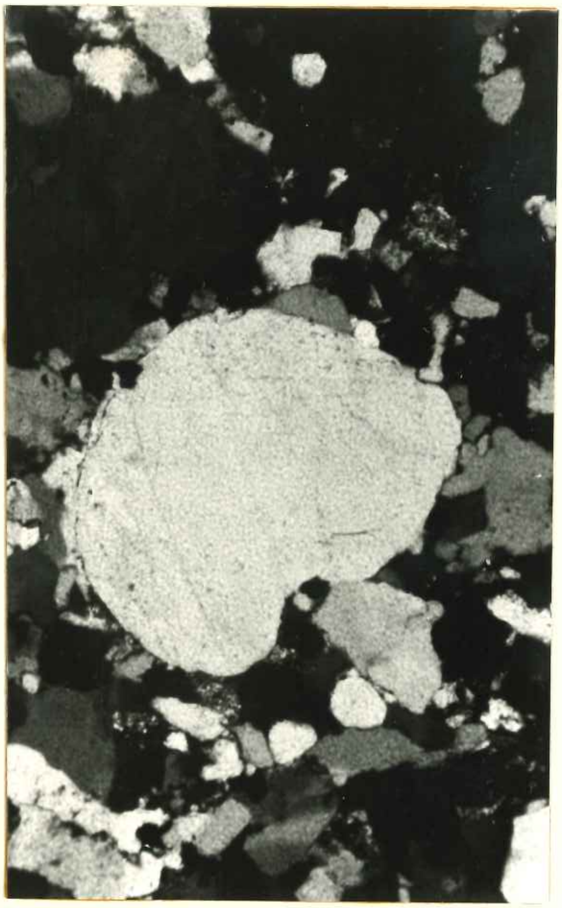



PLATE 3

EVIDENCE FOR FRACTURE DEVELOPMENT LOCATION 1, 5 AND 6

(a) A set T_1 quartz vein (144/80W) offsets veins in a sinistral en-echelon array (105^{o}) at location 4, Port Germein gorge. Angle between veins in array and array is 50^{o}.

(b) Fracture sets as developed at location 6:

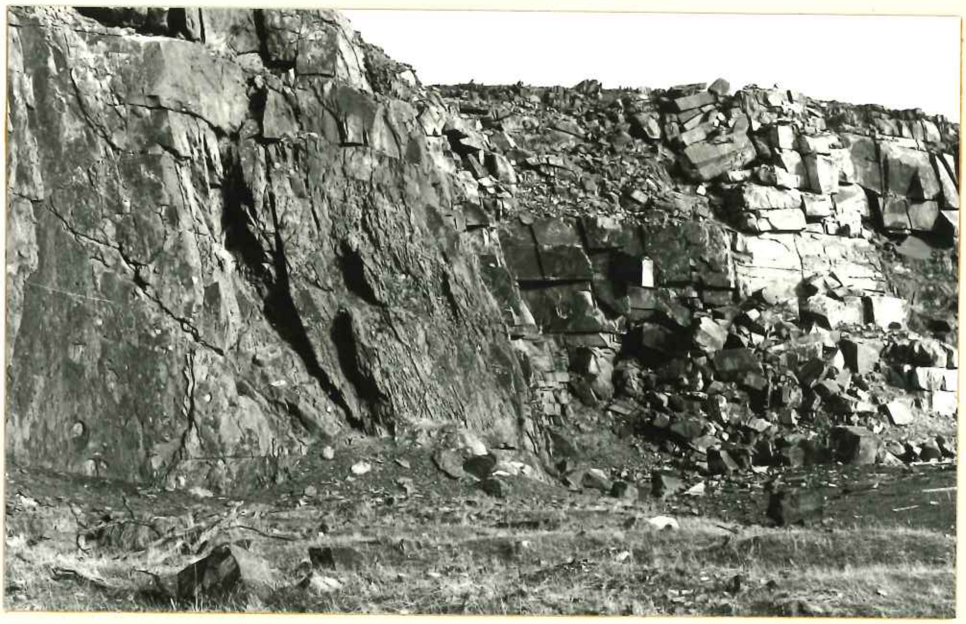
Set T_1 dips steeply to the right (north), not filled with quartz ('ac' extension).

Set T_2 shear fracture, dips about 35^{o} to the north, not filled with quartz.

Set T_3 horizontal quartz vein, has undergone dilation normal to fracture ('bc' extension).

Set T_5 quartz vein dips about 55^{o} south. Fracture is displaced in the reverse sense by set T_2. Dilation of set T_3 offsets T_2 veins.

(c) Difference in degree of fracture development in a tillite (left) and a sandstone (right) at location 5. Set T_3 fractures ('bc') are horizontal and better developed in the tillite. Bedding is overturned and dips steeply to the right (west).



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APPENDIX 1

PLATES 4 - 7

PLATE 4:	Fractures and en-echelon arrays, Port Germein gorge area.
PLATE 5:	Faulting and minor folding on the Nalshaby anticline.
PLATE 6:	Fractures at locations 4 and 5.
PLATE 7:	Fractures and plume structure at location 6.

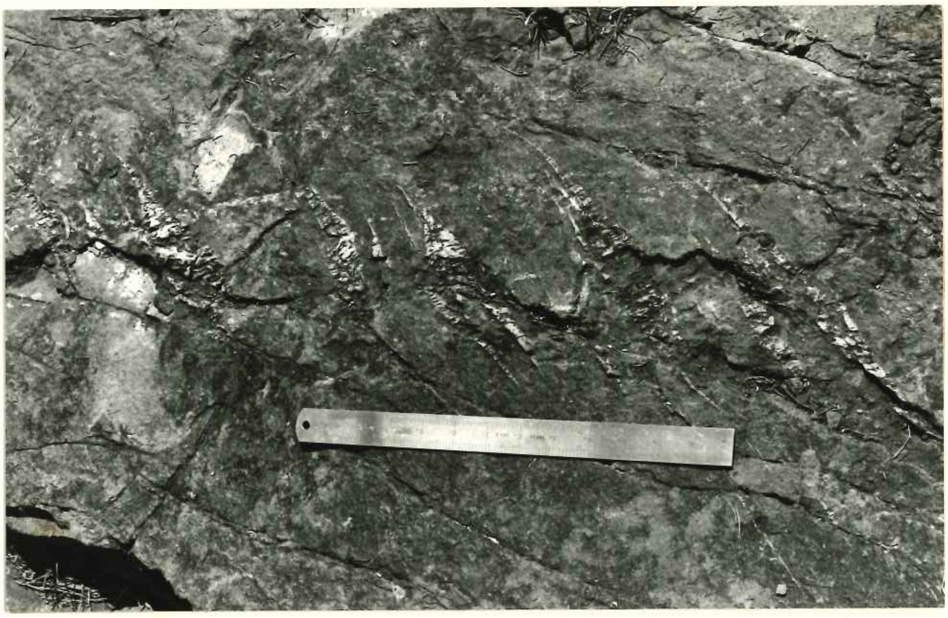
PLATE 4

FRACTURES AND EN-ECHELON ARRAYS, PORT GERMEIN GORGE AREA

(a) Set T_2 fractures at location 7 Port Germein gorge. Fractures dip steeply to the right (west), while bedding dips gently to the north.

(b) Dextral array (105°) with sigmoidal en-echelon quartz veins. Fractures have undergone considerable dilation. Location 5 Port Germein gorge.

(c) Sinistral array (143°) with non-sigmoidal en-echelon quartz veins. Set T_1 fractures are parallel to the shear zone. Location 6 Port Germein gorge.



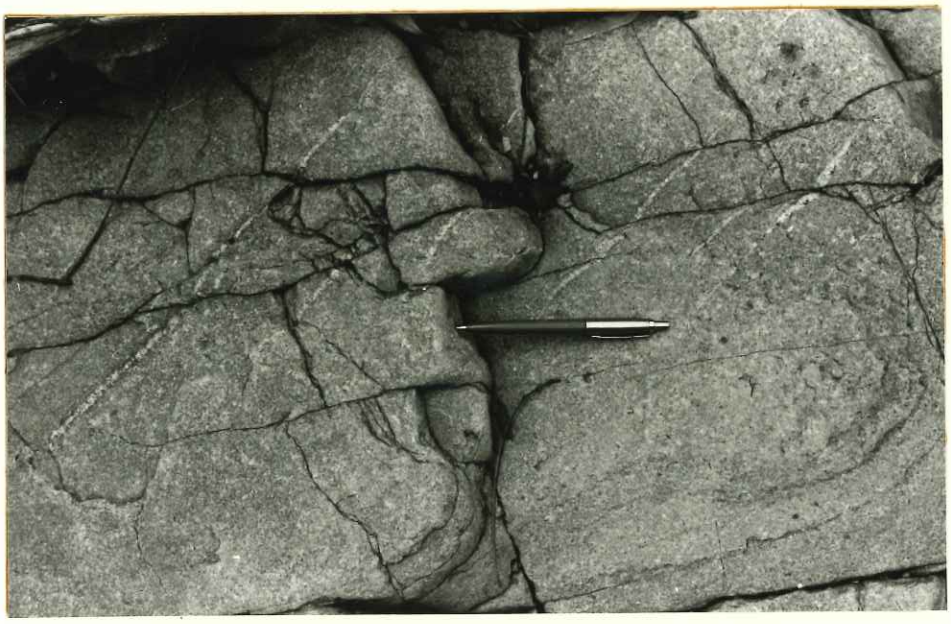


PLATE 5

FAULTING AND MINOR FOLDING ON THE NALSHABY ANTICLINE

(a) Brecciated zone (130/85W) 2 metres wide, Port Germein gorge Location 7.

(b) Concentric, gentle, symmetrical plunging fold location 2 (quarry 2). Plunge 15° towards 150°.

(c) Normal fault, dipping to the right (west) displaces an earlier fault dipping to the east, location 2 (quarry 1).

PLATE 6

FRACTURES AT LOCATIONS 4 AND 5

(a) Shear fracture set T_4 displaces extension fracture T_1 ('ac) with movement in the reverse sense at location 4.

(b) Fracture set T_3 ('bc') at location 5, shows best development close to present geomorphic surface. Bedding is vertical.

(c) Set T_4 fractures in a quartzite boulder in Appila Tillite location 5.

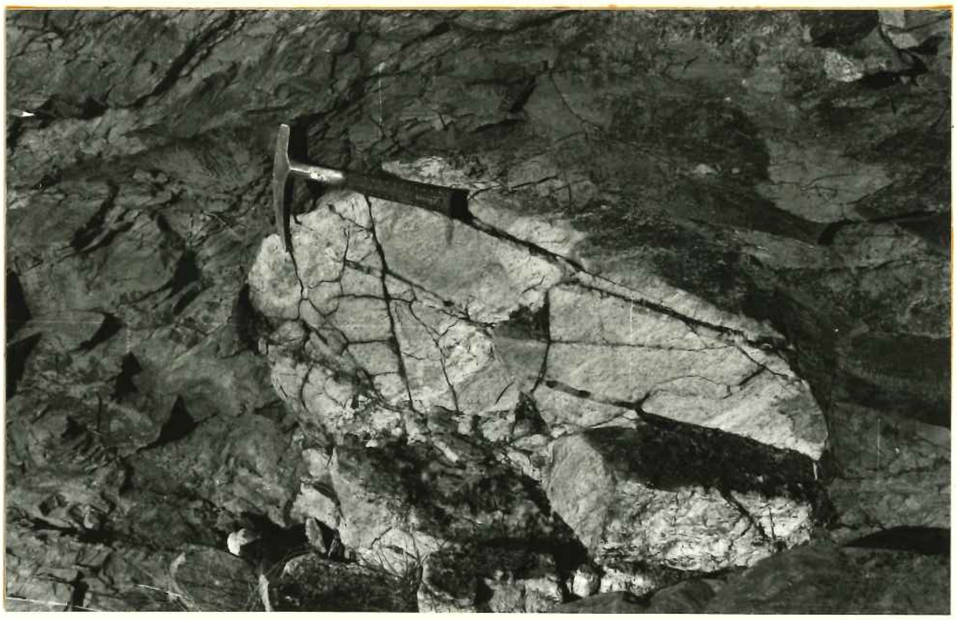


PLATE 7

FRACTURES AND PLUME STRUCTURE AT LOCATION 6

(a) Fracture sets T_1, T_2 and T_5 at location 6, on a bedding surface.

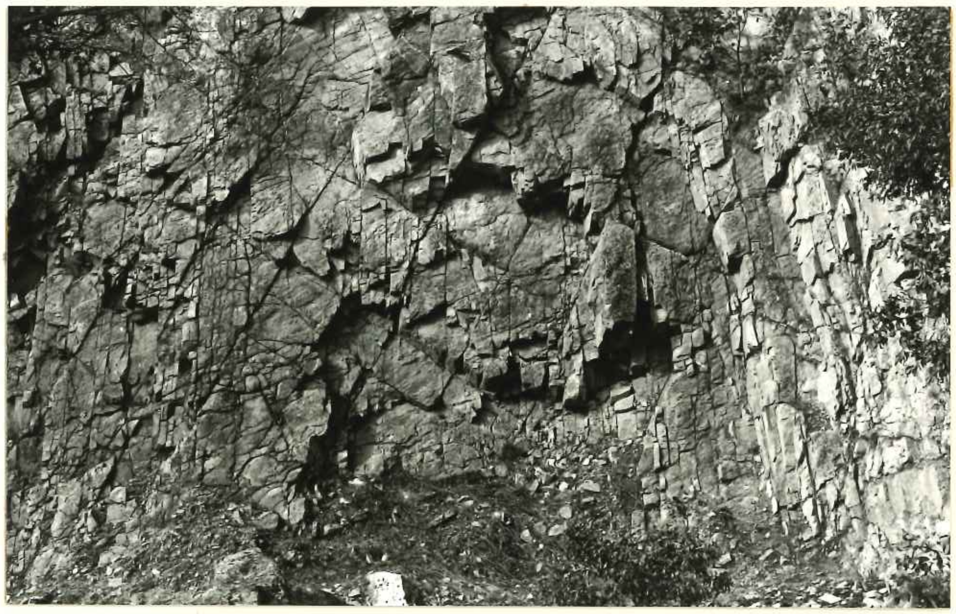
Set T_1 ('ac') is vertical.

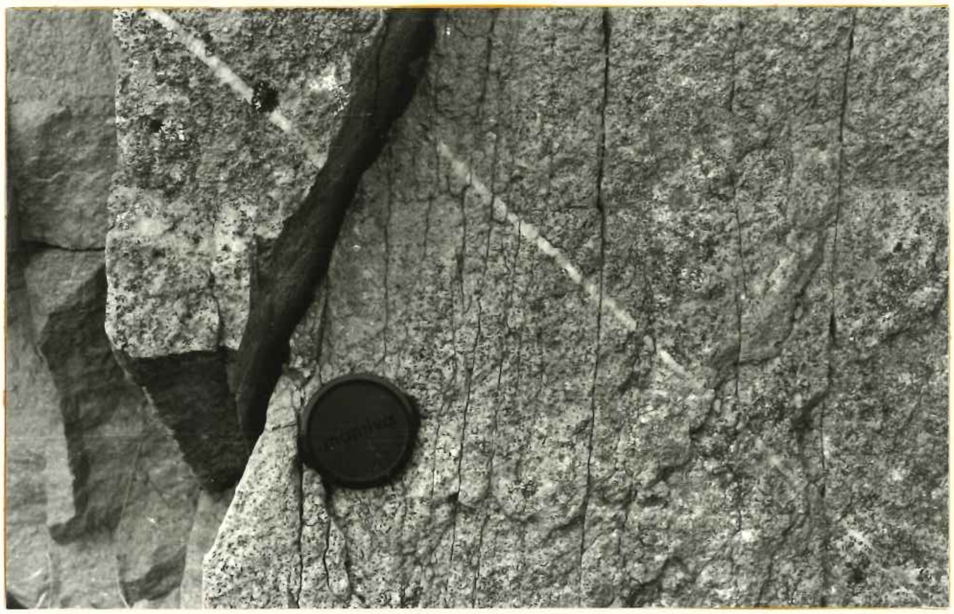
Set T_2 dips to the left (north).

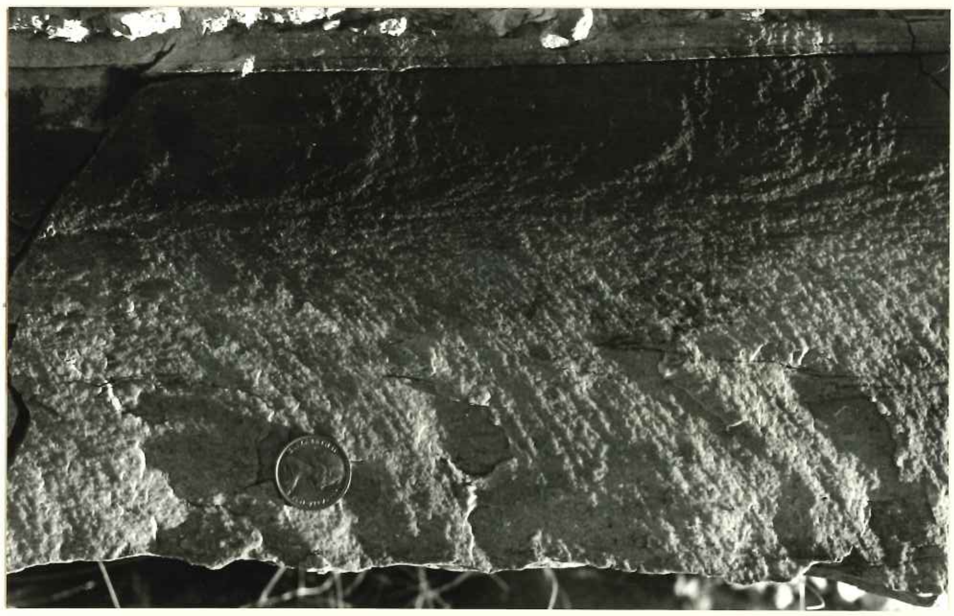
Set T_5 dips to the right (south).

(b) Set T_2 shear fracture displaces set T_5 quartz vein and set T_1 ('ac') extension fracture at location 6.

(c) Plume marking on fracture surface location 6. The fracture is not contained in any of the major sets.







APPENDIX 2

FRACTURE PATTERNS AT LOCATIONS 2-14

LOCATION 2 (QUARRY 1)

WARNERTOWN

Location:	Quarry operated by Andrews Pty. Ltd. 33^{o} 14' 0''S 138^{o} 10' 6''E
Bedding:	Variable 97/36W - 152/82W.
Structure:	West limb and nose of an asymmetrical anticline plunge 20^{o} towards 150^{o}, axial plane 164/60E.
Stratigraphy:	Emeroo Quartzite.
Lithology:	Feldspathic sandstone, heavy mineral laminations interbedded with pebbly sandstone and siltstone.
Faults:	Faults are very common within this quarry. Two dominent directions of normal faults are indicated, 140/60E and 155/72W. Observed vertical displacements vary between .5 to 3 metres. Displacement of one fault by another indicates that faulting initially occurred along 140/60E.
Fracture sets:	Since bedding orientations are very variable fractures were measured along six different lines along which the bedding orientation was reasonably constant. Two major fracture sets were found along each line, these two sets are approximately normal to each other and normal to bedding. Other minor fracture sets were found along individual lines. These localized sets may be associated with local faulting.

Set T_1 (extension fractures)

Most common fracture set within the quarry. The fractures are smooth and planar. Quartz extension fibres are commonly found filling fractures.

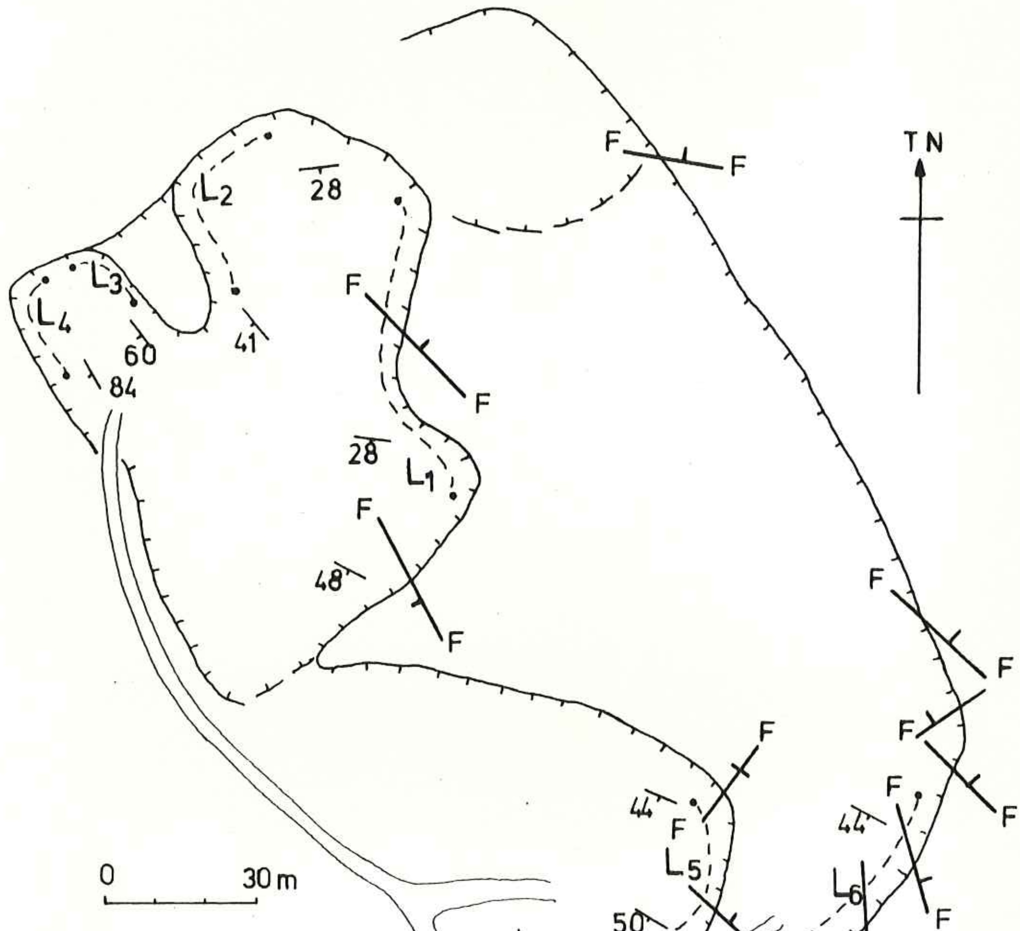
Set T_2 (extension fractures)

Moderately well developed fracture set. Quartz does not appear as filling in these fractures. A few fractures of this set have striated surfaces suggesting that their has been movement along these fractures subsequent to their formation.

QUARRY MAP

WARNERTOWN QUARRY 1 LOCATION 2

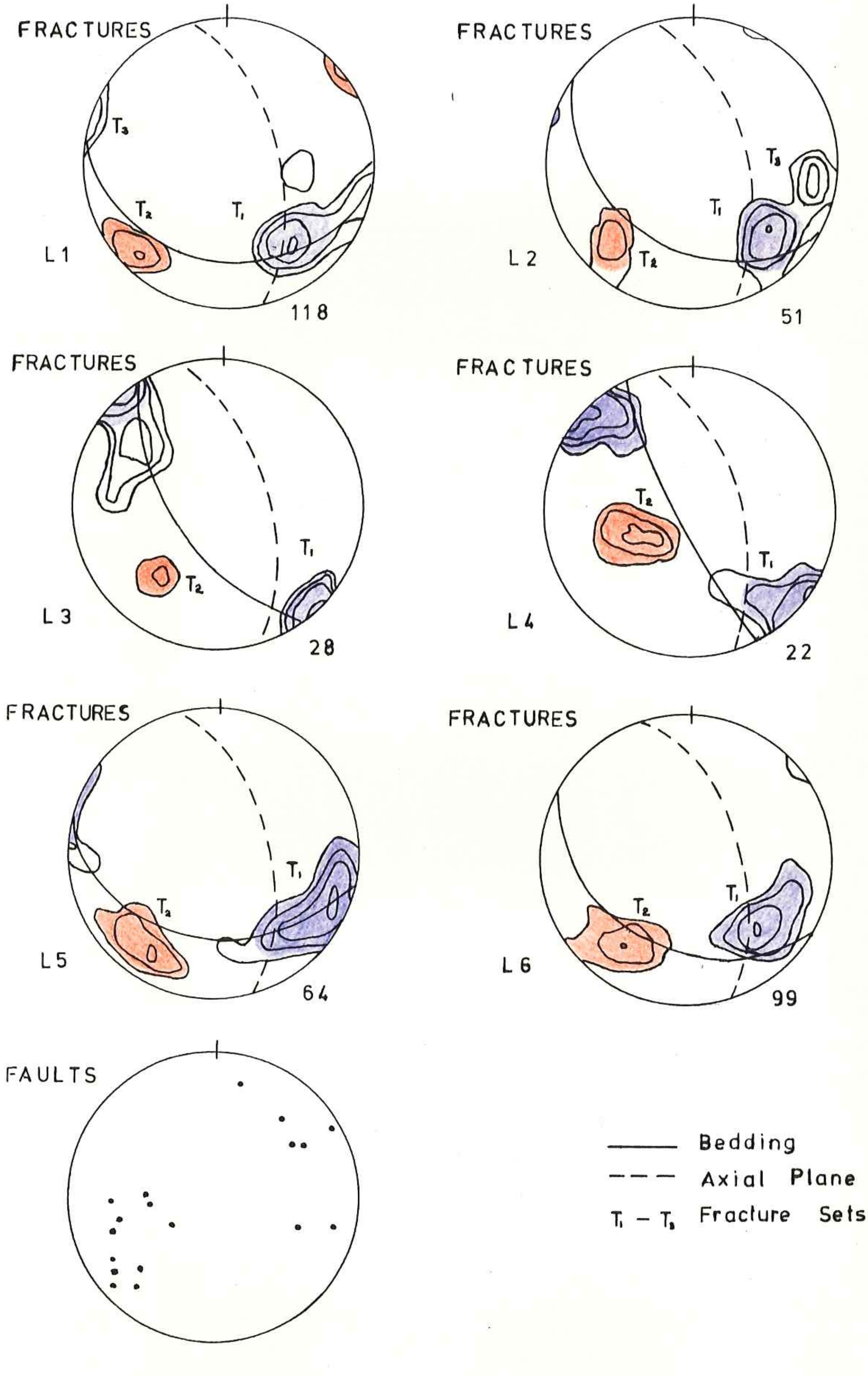
33°-14'-00" S 138°-10'-06" E



FRACTURE PATTERN

WARNERTOWN QUARRY 1 LOCATION 2

33°-14′-00″ S 138°-10′-06″ E



LOCATION 2 (QUARRY 2)

WARNERTOWN

Location:	Quarry operated by Andrews Pty. Ltd. 33^{o} 14' 0" S 138^{o} 10' 6" E
Bedding:	Variable 75/23S - 108/30S.
Structure:	Nose of an anticline plunge 20^{o} towards 150^{o}, axial plane 164/60E.
Stratigraphy:	Emeroo Quartzite.
Lithology:	Massive laminated feldspathic sandstones interbedded with grey siltstones.
Folds:	A number of small open folds were found within this quarry. These may be classified as concentric gentle folds.
Faults:	One normal fault (175/64E) was noticed. Vertical displacement is the order of 1 metre.
Fracture Sets:	Four major fracture sets were observed within the quarry. Three sets are nearly normal to bedding, while a fourth set is oblique to bedding.

Set T_1 ('ac' extension fractures)

Fractures of this set are the most common within the quarry.

The fractures are often filled with quartz in the form of extensional fibres.

Set T_2 ('bc' extension fractures)

Moderately well developed fracture set.

Quartz was not found as filling in fractures of this set. In a few cases striations were observed on fracture surfaces, these are thought to be the result of subsequent movement.

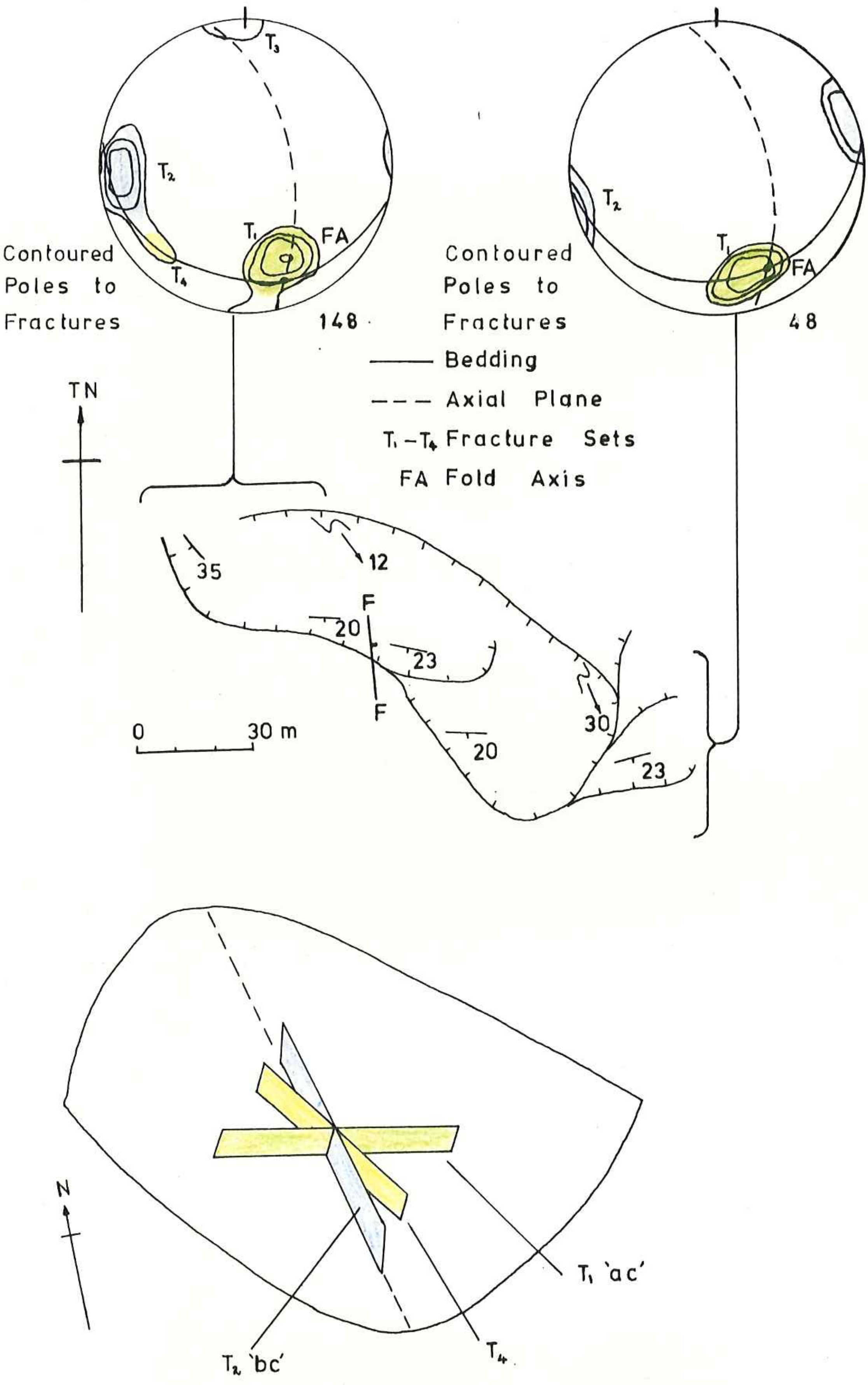
Set T_3 (? shear fracture)
Moderately well developed fracture set with irregular surfaces.
No quartz filling.

Set T_4 Poorly developed fracture set, no quartz filling.
Possibly associated with faults.

FRACTURE PATTERN

WARNERTOWN QUARRY 2 LOCATION 2

33°-14′-00″ S 138°-10′-06″ E



LOCATION 3

GEORGETOWN

Location: Georgetown Council quarry 33° 22' 0" S 138° 23' 0" E.

Bedding: 76/22N

Structure: Nose of symmetrical anticline, plunge 25° towards 020°.

Stratigraphy: ? Bungaree Quartzite.

Lithology: Massive grey feldspathic sandstone interbedded with thin bands of white siltstone.

Fracture Sets: Three major fracture sets were recognised all nearly perpendicular to bedding. No displacements were observed between sets.

Set T_1 ('ac' extension fractures)
Most common set, has good continuity, smooth and planar surfaces. Some fractures have a thin quartz filling.

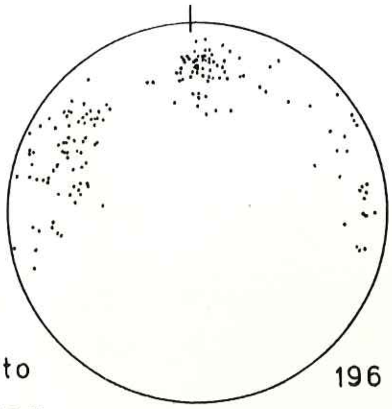
Set T_2 (? shear fractures)
Slightly less common, has good continuity, smooth and planar surfaces, no filling. Orientation of these fractures suggests that they are a shear set related to the fold.

Set T_3 ('bc' extension fractures)
Relatively poorly developed, irregular surfaces, no filling.

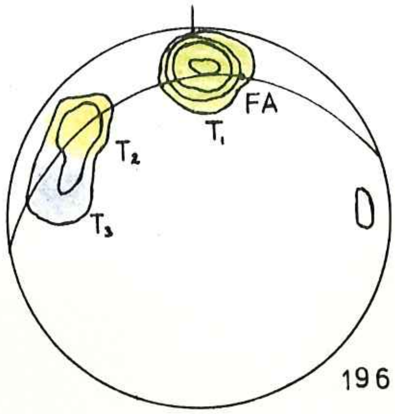
FRACTURE PATTERN

GEORGETOWN QUARRY LOCATION 3

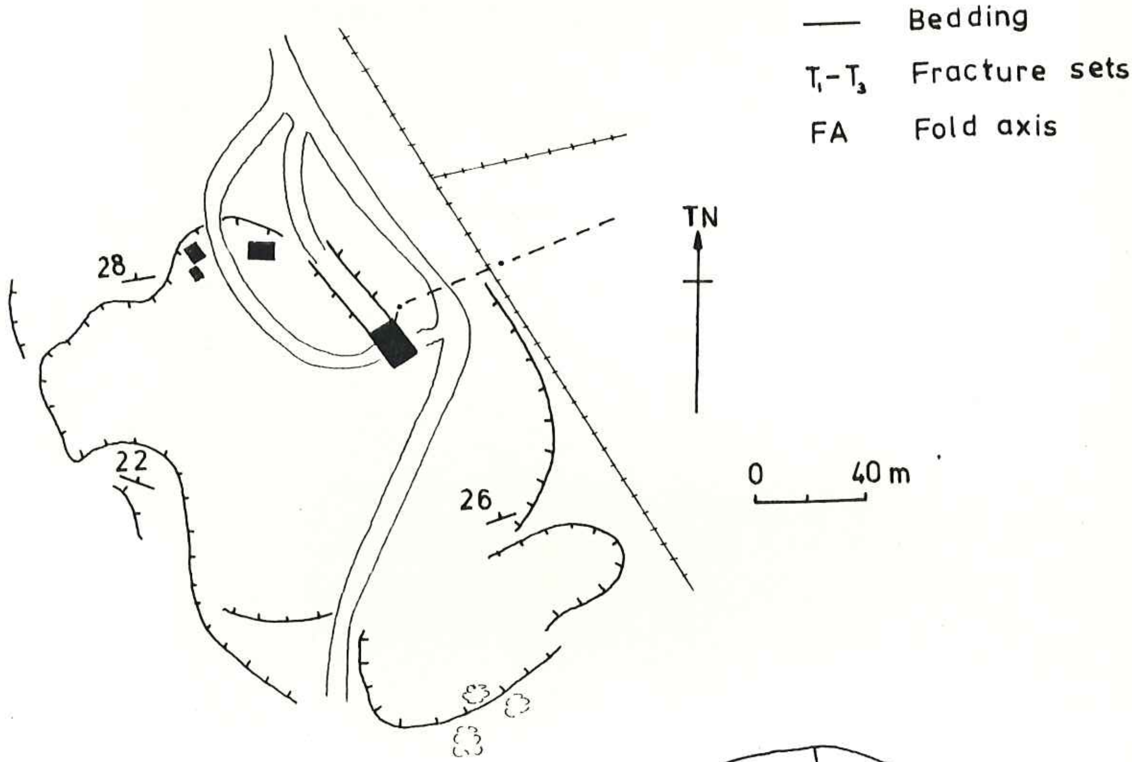
38°-22'-00" S 138°-23'-00" E

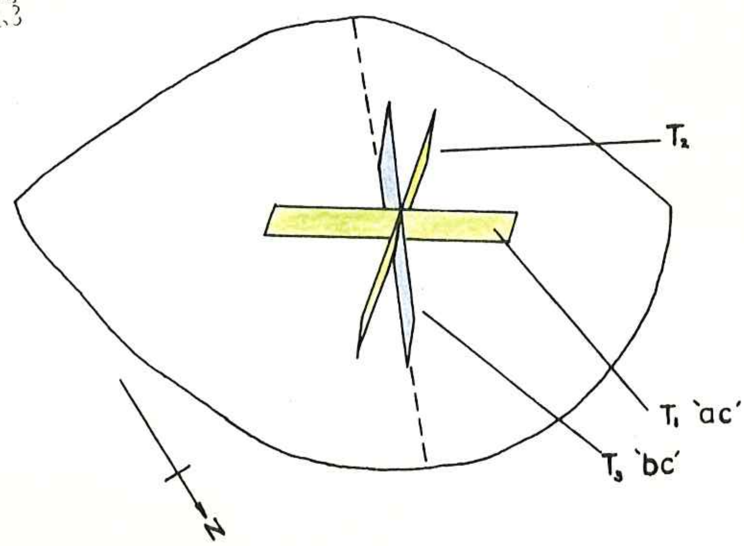


Poles to Fractures



Contoured Poles to Fractures





LOCATION 4

SPALDING

Location: Three small disused quarries
33^{o} 60' 30"S 138^{o} 36' 0" E

Bedding: Overturned 000/80W.

Structure: Overturned limb of a syncline with horizontal fold axis.

Stratigraphy: Leasingham Quartzite.

Lithology: Strongly weathered massive feldspathic sandstone, occasionally interbedded with red - black siltstone.

Fracture sets: Four major fracture sets were observed, all nearly normal to bedding.

Set T_1 ('ac' extension fractures)
Most common fracture set that has smooth planar surfaces.

Set T_2 (shear fractures)

Well developed set that is observed to displace set T_1 and quartz veins.

Set T_3 (shear fractures)

Moderately well developed, this set is also observed to displace quartz veins. Set T_2 and T_3 form a conjugate shear pair, movement on both sets is in the reverse sense.

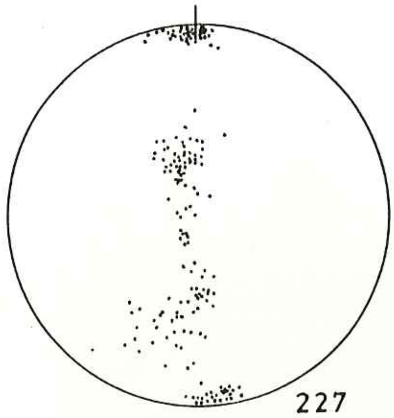
Set T_4 ('bc' extension fractures)
Poorly developed, these fractures are commonly filled with quartz, the veins may be up to 10 cm. wide.

FRACTURE PATTERN

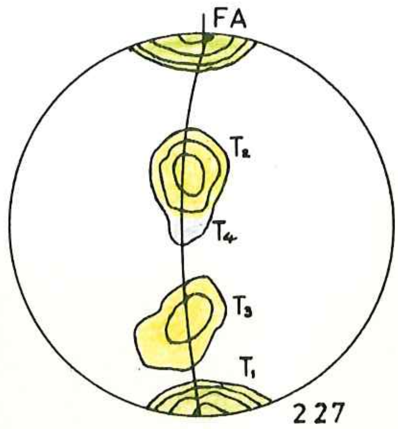
SPALDING QUARRY LOCATION 4

33°- 60′- 30″ S 138°- 36′- 00″ E

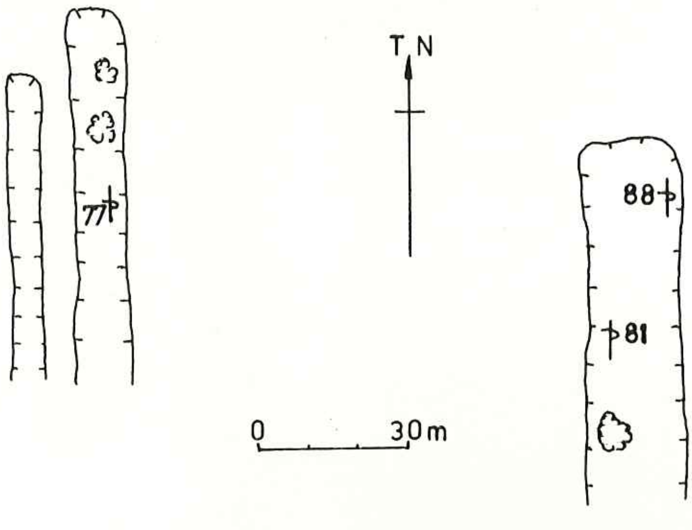
Poles to Fractures

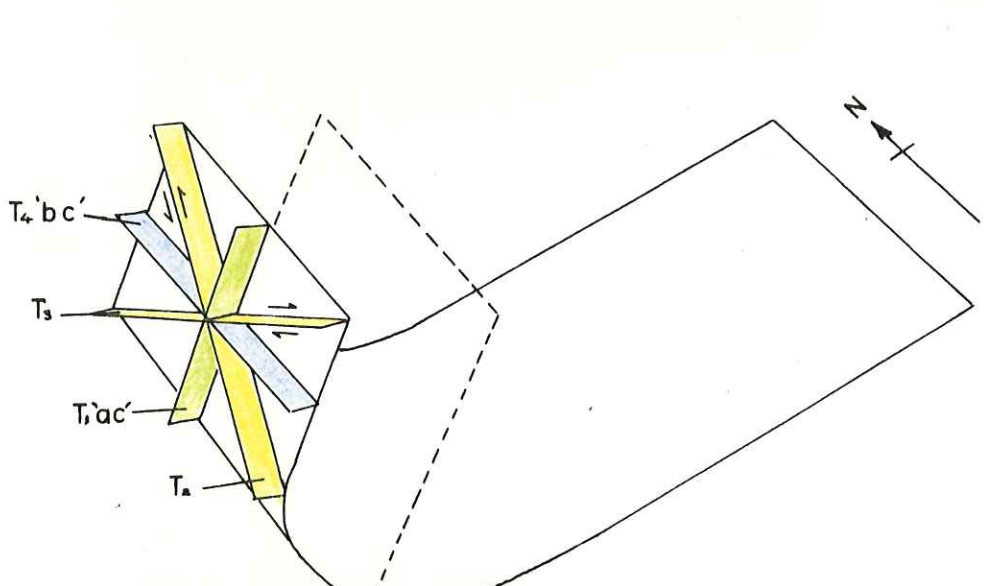


Contoured Poles to Fractures



——	Bedding
T_1—T_4	Fracture Sets
FA	Fold Axis





LOCATION 5

ANDREWS

Location:	Small disused quarry 33° 36' 6"S 138° 36' 54" E
Bedding:	Overturned 175/82W.
Structure:	Overturned limb of a syncline plunge 15° towards 355°.
Stratigraphy:	Gilbert Range Quartzite and Appila Tillite.
Lithology:	Massive subarkose, siltstone, grey shale and grey boulder tillite.
Cleavage:	As developed in shales and tillite dips 65° west.
Fracture Sets:	Four major fracture sets were observed, some sets were restricted or better developed in certain lithologies.

Set T_1 ('ac' extension fractures)
Well developed in all lithologies, with smooth planar surfaces. Quartz fills some of these fractures.

Set T_2 ('bc' extension fractures)
This set is also well developed in all lithologies The surfaces are smooth and planar. Quartz fills some of the fractures. This set shows its best development close to the present geomorphic surface.

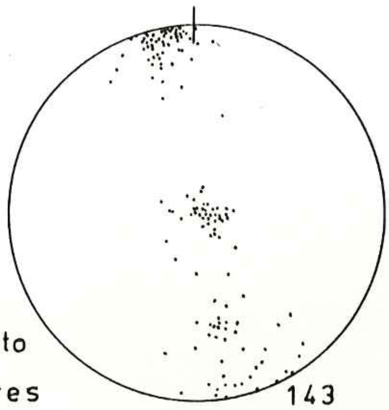
Set T_3 (? shear fractures)
This set is best developed within the tillite but also occurs within the massive subarkose. The surfaces tend to be irregular and fractures are not filled with quartz.

Set T_4 (extension fractures)
This set only developed in the tillite is not normal to bedding as are sets 1-3, but is nearly parallel to the bedding as developed in other lithologies. These fractures which are common within tillite boulders as well as in the matrix are smooth and filled with quartz extension fibres

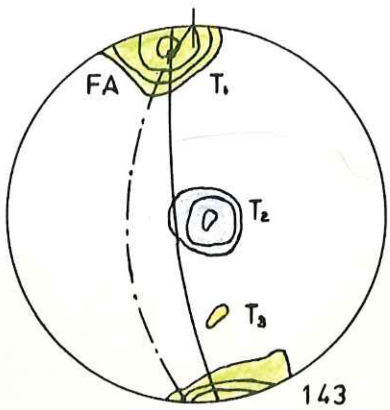
FRACTURE PATTERN

ANDREWS QUARRY LOCATION 5

33°-36′-06″ S   138°-36′-54″ E



Poles to Fractures



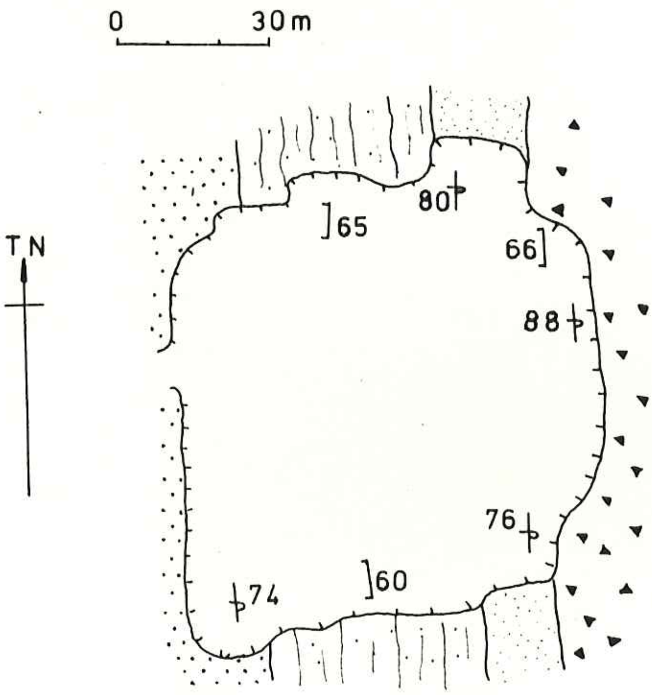
Contoured Poles to Fractures

—— Bedding

—·—· Cleavage

T₁ – T₃ Fracture Sets

F A Fold Axis

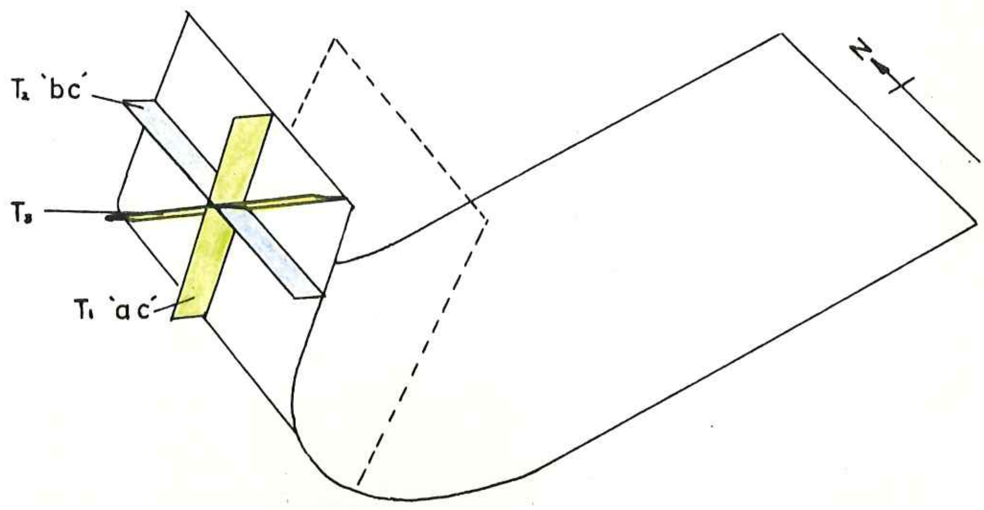


Tillite

Sandstone

Siltstone & Shale

Subarkose



LOCATION 6

BARINIA

Location: Small disused quarry 33^{o} 45' 36" S 138^{o} 38" 24"E

Bedding: Overturned 000/62W.

Structure: West limb of a syncline, plunge 10^{o} towards 185^{o}

Stratigraphy: Gilbert Range Quartzite.

Lithology: Massive subarkose.

Fracture sets: Four fracture sets were observed, all nearly normal to bedding.

Set T_1 ('ac' extension fractures)
Most common fractures, although they vary in frequency along the rock face. The surfaces are smooth and planar.
A few fractures are filled with quartz.

Set T_2 Fractures commonly filled with vein quartz, the width of veins varies between .1 and 2 cm. The dilation of these veins does not offset quartz in set T_1 fractures. This fracture set appears unrelated in orientation to the fold and may have formed before folding parallel to a palaeo-current.

Set T_3 (shear fractures)
Poorly developed fractures. Surfaces are generally irregular and no quartz is observed filling these fractures. Set T_3 fractures displace both set T_1 and T_2 fractures in a reverse sense.

Set T_4 ('bc' extension fracture)
Weakly developed fracture set, most fractures have been filled with quartz. Offsets between these quartz veins and set T_1 and T_2 veins indicates that quartz was introduced into set T_4 fractures after set T_1 and T_2.

LOCATION 7

SEVENHILL

Location: Clare Council quarry 33^{o} 53' 12" S 138^{o} 39' 12" E.

Bedding: Overturned 175/83W.

Structure: West limb of a syncline plunge 5^{o} towards 175^{o}.

Stratigraphy: Massive white feldspathic sandstone with yellow siltstones interbedded at regular intervals.

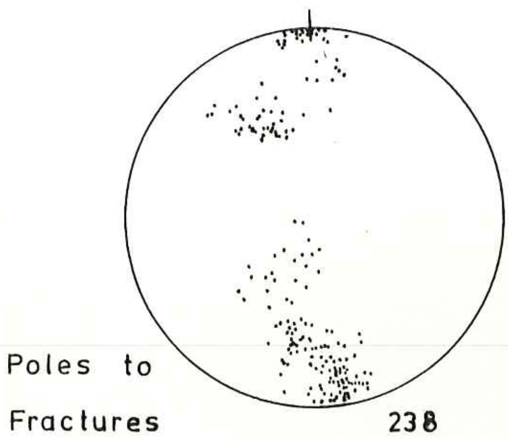
Fracture Sets: Three major fracture sets were observed all approximately normal to bedding.

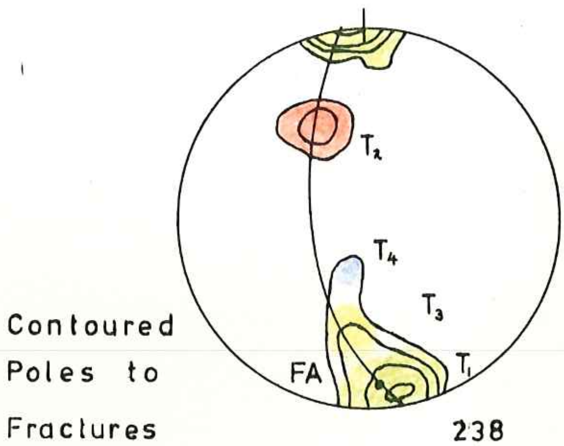
Set T_1 ('ac' extension fractures)
Most common fractures, smooth irregular surfaces. A few fractures have been filled with vein quartz. Although obvious shear movement has occurred on some of these fractures, this is thought to have occurred subsequent to the formation of the fractures.

Set T_2 (shear fractures)
This fracture set is not as well developed as set T_1 fractures, quartz was not found filling these fractures. Shear movement along set T_2 fractures is observed to displace set T_1 and set T_3 fractures. In all cases observed the movement along these fractures has been in the reverse sense.

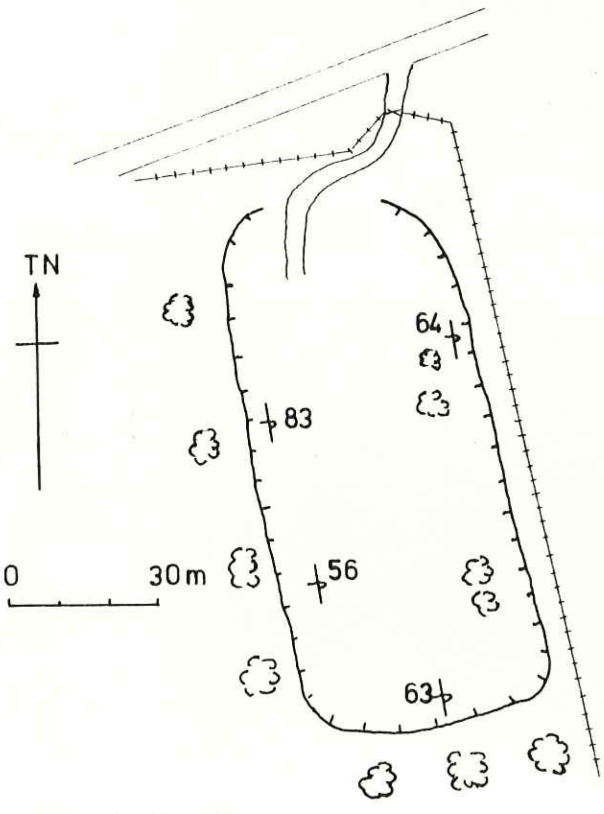
Set T_3 ('bc' extension fractures)
Since this fracture set is nearly horizontal it was very difficult to obtain a representative number of measurements. The fractures tend to be smooth and planar. Quartz veins occur slightly oblique (10^{o}) to this fracture set and are not represented as a separate fracture set on the contour diagram.

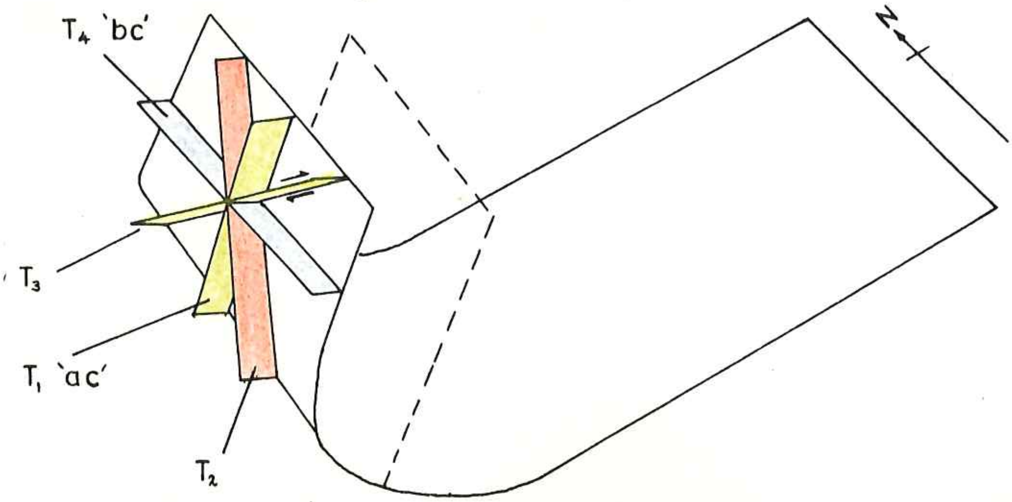
FRACTURE PATTERN
BARINIA QUARRY LOCATION 6
33°- 45'- 36" S 138°- 38'- 24" E





—— Bedding
T_1 — T_4 Fracture Sets
FA Fold Axis

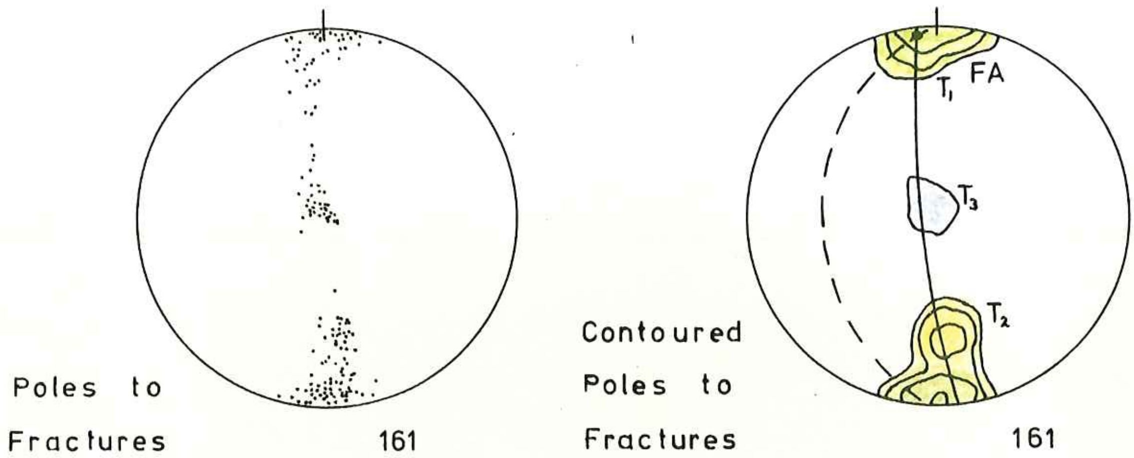




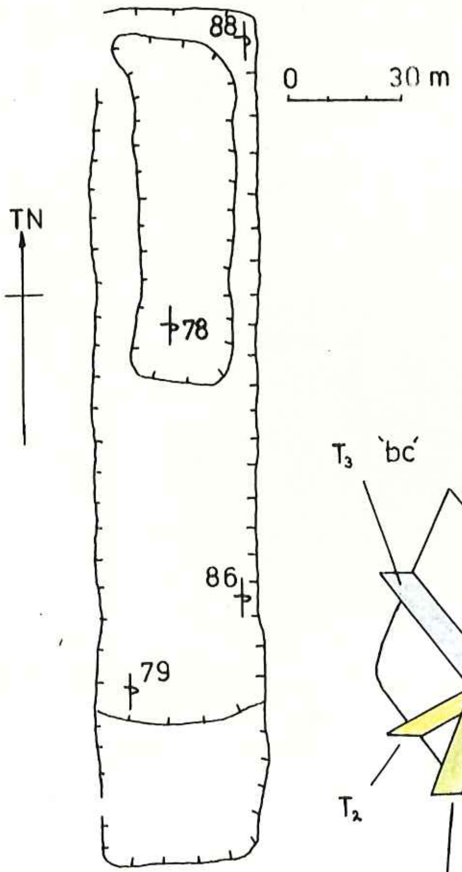
FRACTURE PATTERN

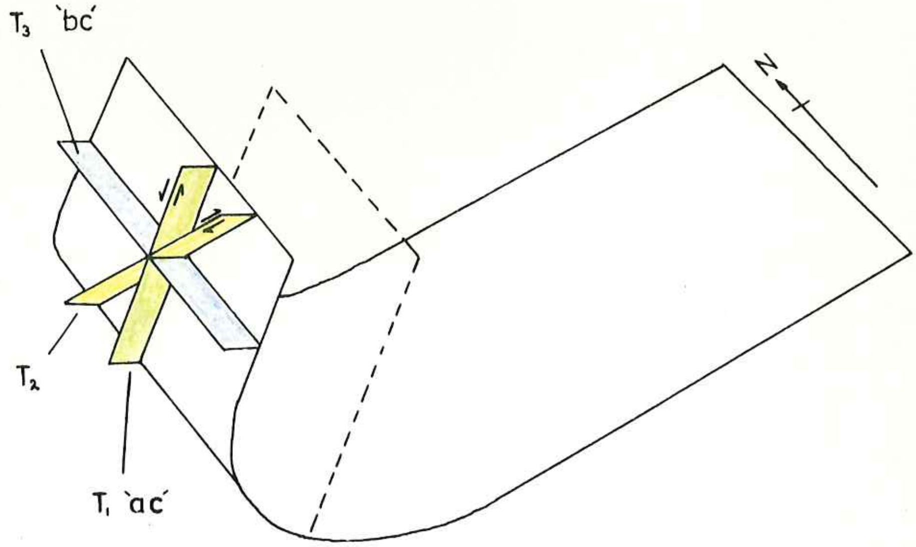
SEVENHILL QUARRY LOCATION 7

33°- 53'- 12" S 138°- 39'- 12" E



— Bedding
--- Axial Plane
T1 - T3 Fracture Sets
FA Fold Axis





LOCATION 8

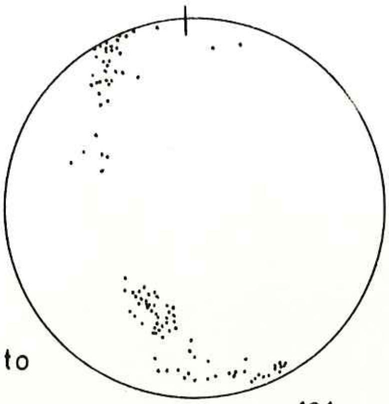
BLACK SPRINGS

Location:	Small quarry 33^{O} 53' 30" S 138^{O} 54' 30" E
Bedding:	162/58W
Structure:	West limb of an anticline plunging 25^{O} towards 180^{O}.
Stratigraphy:	Portion of the Appila Tillite of the Umberatana Group.
Lithology:	Feldspathic sandstone containing occasional quartzite pebbles and interbedded white siltstones.
Fracture sets:	Three major fracture sets were recognised at this location, all approximately normal to bedding.
Set T_1	(extension fractures) Very well developed has smooth planar surfaces often filled with quartz and iron oxides. The quartz is in the form of extensional fibres orientated normal to fractures. This fracture set appears unrelated in orientation to fold and may be parallel to a palaeocurrent direction.
Set T_2	Also well developed, but with variable frequency Quartz was found filling a few fractures of this set.
Set T_3	('bc' extension fractures) Relatively poorly developed, no quartz was found filling these fractures.

FRACTURE PATTERN

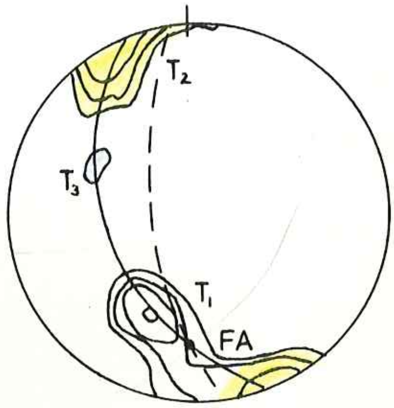
BACK SPRINGS QUARRY LOCATION 8

33°-53'-30" S 138°-54'-30" E



Poles to Fractures

121



Contoured Poles to Fractures

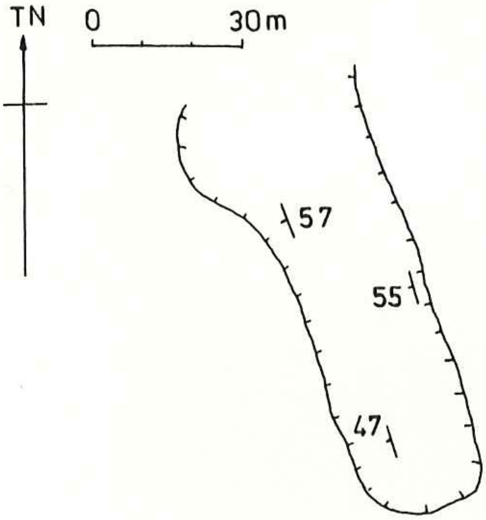
121

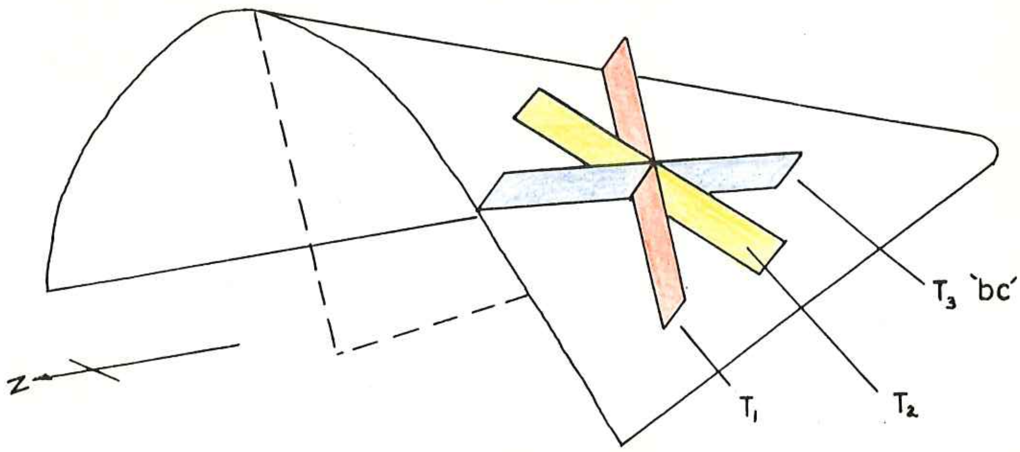
—— Bedding

- - - Axial Plane

$T_1 - T_3$ Fracture Sets

FA Fold Axis





LOCATION 9

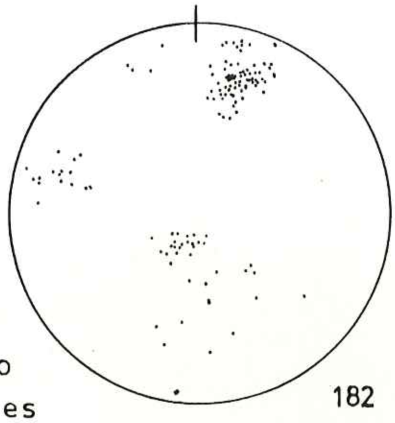
MANOORA

Location:	Small disused quarry 33° 59' 30" S 138° 48' 18" E
Bedding:	13/84E.
Structure:	East limb of an anticline plunging 20° towards 16°.
Stratigraphy:	Rhynie Sandstone at the base of the Burra Group.
Lithology:	Strongly weathered well laminated feldspathic sandstone, occasionally containing quartzite pebbles and interbedded with siltstones.
Fracture sets:	Three fracture sets are developed at this location, two approximately normal to bedding and a third weaker set nearly parallel to bedding. No displacements were observed between sets.
Set T_1	('ac' extension fractures) Most common set, smooth planar surfaces. These fractures are in many cases filled with quartz in the form of extension fibres orientated normal to fractures.
Set T_2	('bc' extension fractures) Not as well developed as set T_1. No quartz was observed in these fractures.
Set T_3	(extension fractures) This set, that is slightly oblique to bedding is generally poorly developed. The fractures commonly have been filled with extension fibres normal to fractures.

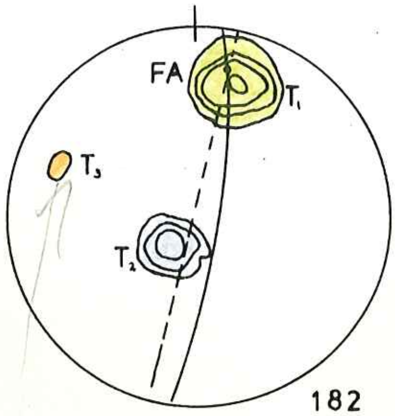
FRACTURE PATTERN

MANOORA QUARRY LOCATION 9

33°-59′-36″ S 138°-48′-18″ E

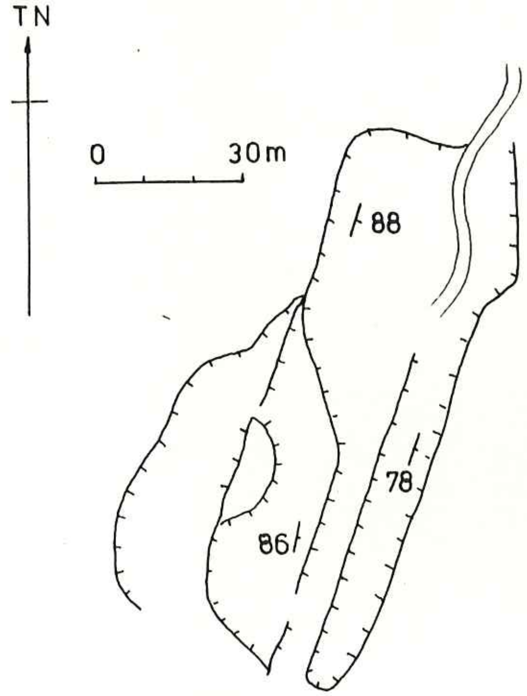


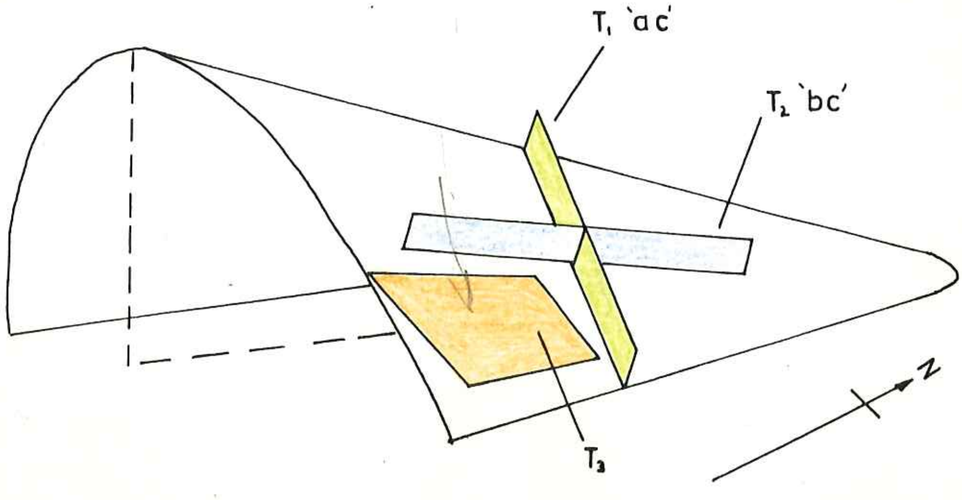
Poles to Fractures



Contoured Poles to Fractures

———	Bedding
- - -	Axial Plane
T₁ – T₃	Fracture Sets
FA	Fold Axis





LOCATION 10

MAGNUS HILL

Location: Road cutting at Magnus Hill 32^{o} 54' 42" S 138^{o} 16" 0" E

Bedding: 173/37W.

Structure: West limb of an anticline plunging 10^{o} towards 185^{o}.

Stratigraphy: Possible equivalent to Gilbert Range Quartzite.

Lithology: Grey quartzarenite with thin silty interbeds.

Fracture Sets: Two fracture sets were found at this location, set T_1 being by far the most common.

Set T_1 ('ac' extension fractures)

Planar smooth fractures that have variable frequency along the rock face. The separation between fractures is commonly the order of 5 cm. A number of fractures were observed to be filled with extensional quartz fibres; in a few cases these fibres were orientated parallel to the fracture, giving rise to a lineation on the fracture surface. It was occasionally observed that fractures of this set displaced bedding planes. Lineations on some set T_1 fractures suggests that there has been some movement along these fractures subsequent to their formation.

Set T_2 ('bc' extension fractures)

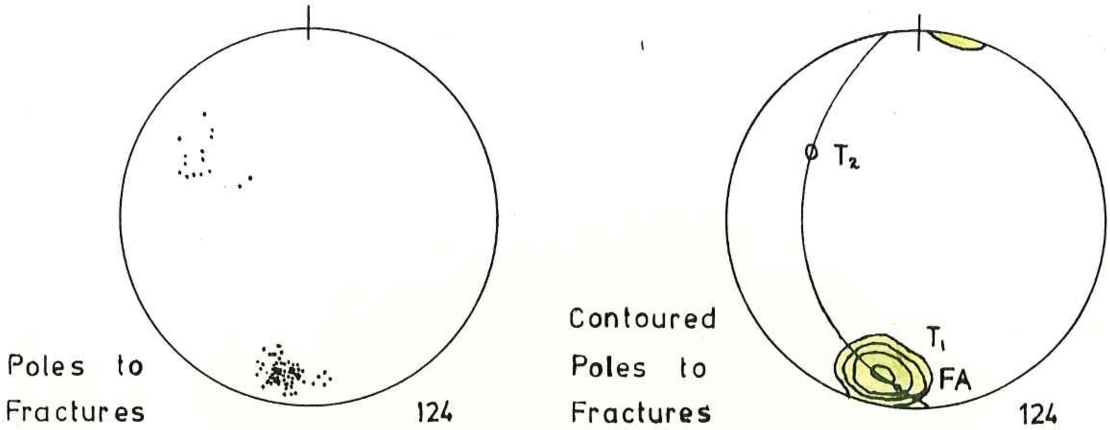
Poorly developed fracture set, this may be partly due to the orientation of the road cutting. Surfaces are smooth and fractures are usually filled with quartz.

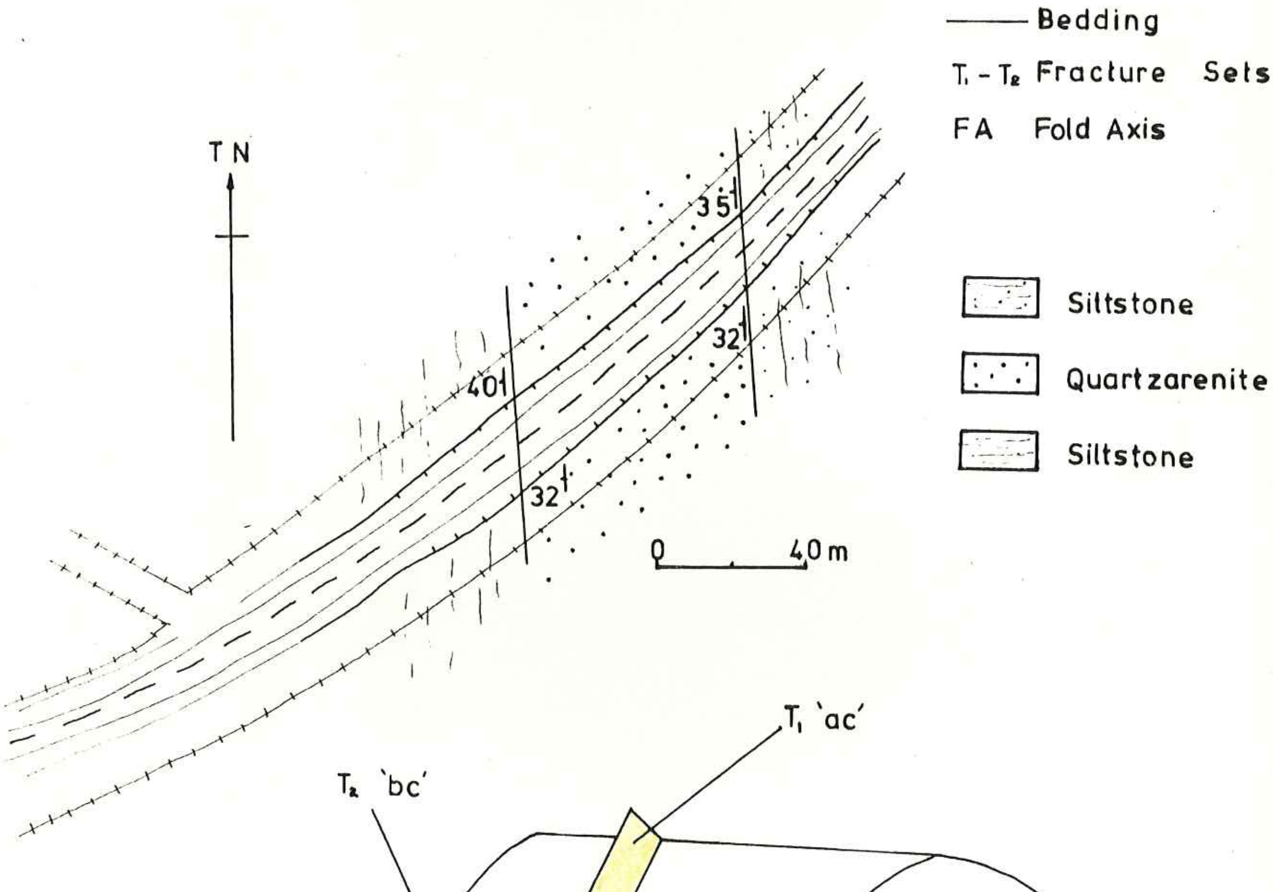
FRACTURE PATTERN

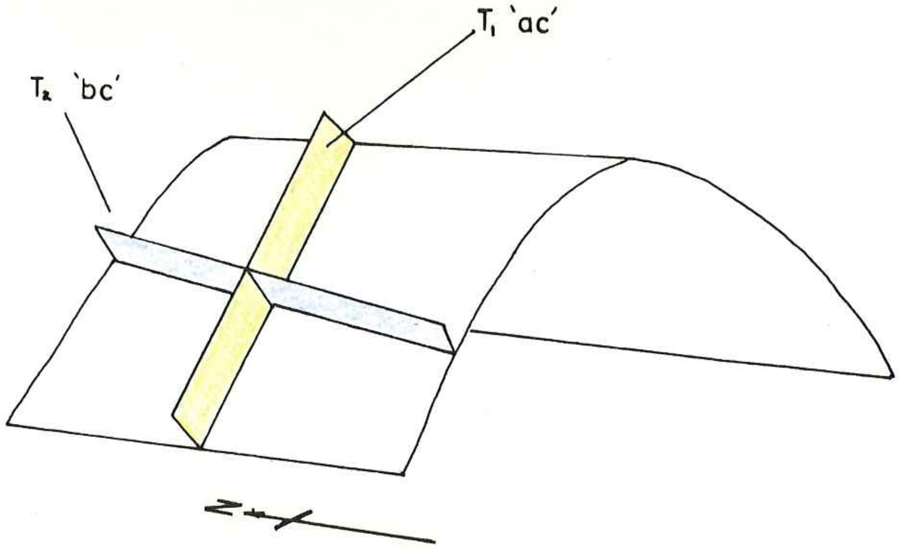
MAGNUS HILL ROAD CUTTING

LOCATION 10

32° – 54′ – 42″ S   138° – 16′ – 00″ E







LOCATION 11

JAMESTOWN

Location: Small disused quarry 33° 11' 48" S 138° 33' 6" E

Bedding: 164/71W.

Structure: West limb of an anticline plunging 30° towards 180°.

Stratigraphy: Gilbert Range Quartzite.

Lithology: Feldspathic sandstone interbedded between two siltstone units.

Fracture Sets: Three main fracture sets were observed at this location, all approximately normal to bedding.

Set T_1 ('ac' extension fractures)

Fractures of this set are the most common, although frequency varies somewhat along the rock face. In a few cases slickenslides were observed on fracture surfaces.

Set T_2 (shear fractures)

This fracture set is not as well developed as set T_1 fractures.

Surfaces are relatively smooth and fractures are not filled with quartz. One fracture of this set was observed to displace a quartz vein, movement was of the reverse sense.

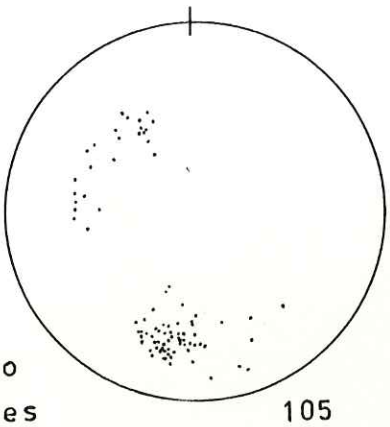
Set T_3 ('bc' extension fractures)

Poorly developed fracture set, this may in part be due to the orientation of the rock face. No quartz filled these fractures.

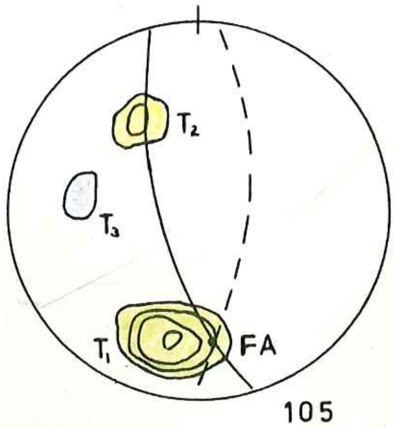
FRACTURE PATTERN

JAMESTOWN QUARRY LOCATION 11

$33^\circ - 11' - 48''$ S $138^\circ - 33' - 06''$ E

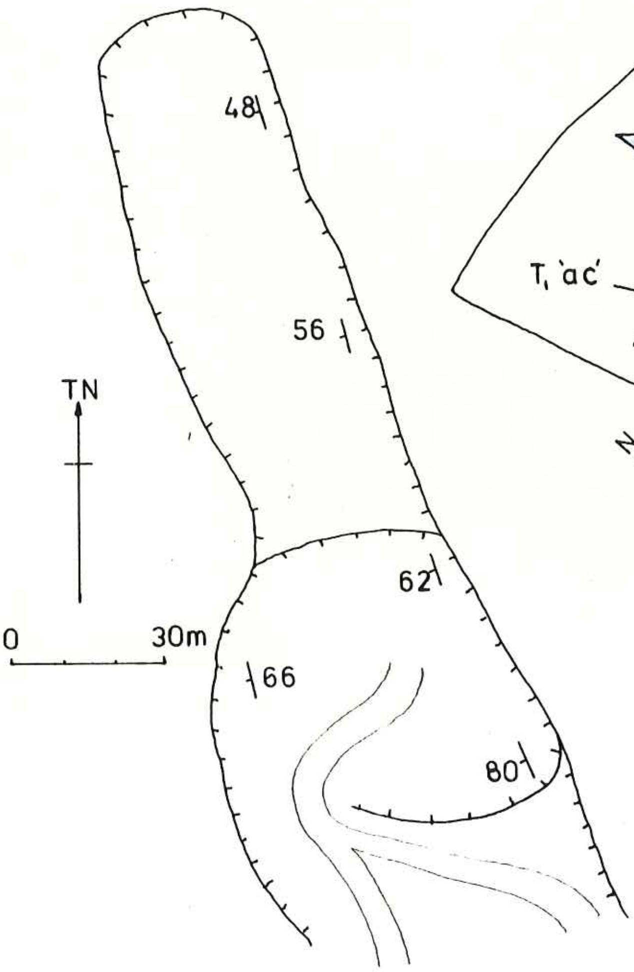


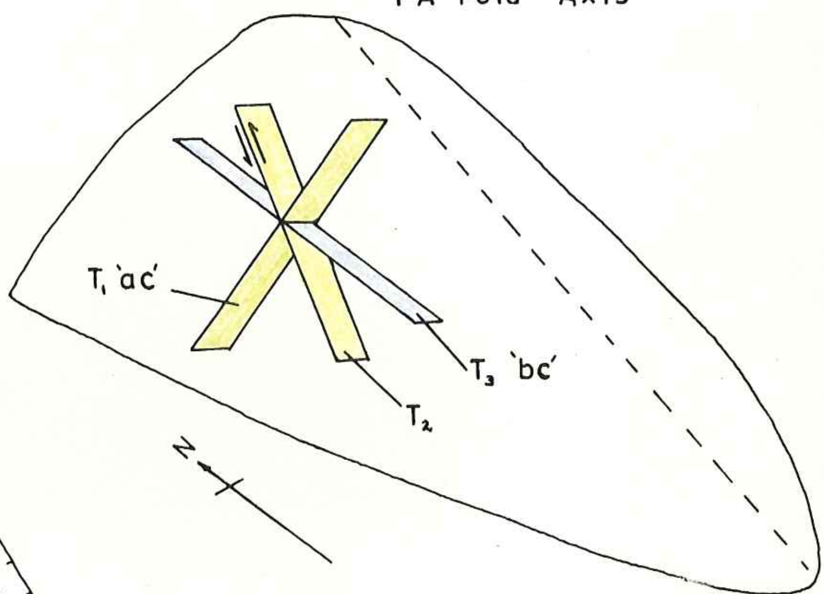
Poles to Fractures



Contoured Poles to Fractures

— Bedding
--- Axial Plane
$T_1 - T_3$ Fracture Sets
FA Fold Axis





LOCATION 12

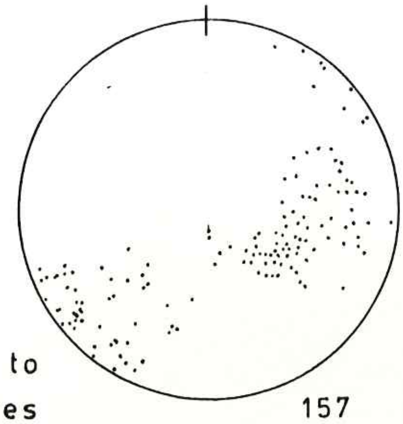
YONGALA

Location:	Small disused quarry 30^{o} 1' 36" S 138^{o} 42' 42" E
Bedding:	70/72E
Structure:	Nose of an anticline plunging 60^{o} towards 106^{o}.
Stratigraphy:	The stratigraphic position of these rocks is uncertain they are however contained within the Burra Group, possibly near the Skillogallee Dolomite.
Lithology:	Is variable consisting of grey siltstone, massive dolomite and fine sandstones.
Cleavage:	Poorly developed 87/86S.
Fracture Sets:	Four fracture sets were found within this quarry three of which are nearly normal to bedding and a third which appear normal to the axial plane. Calcite is found occasionally in fractures of each set and pyrolusite dendrites are common fracture surfaces.
Set T_1	('ac' extension fractures) Well developed set with irregular fracture surfaces.
Set T_2	('bc' extension fractures) In places well developed with in general irregular surfaces. Slickenslides are apparent on some fracture surfaces.
Set T_3	(? shear fractures) Moderely well developed, surfaces are smooth and planar.
Set T_4	(? shear fractures) Poorly developed fracture set orientated nearly normal to axial plane.

FRACTURE PATTERN

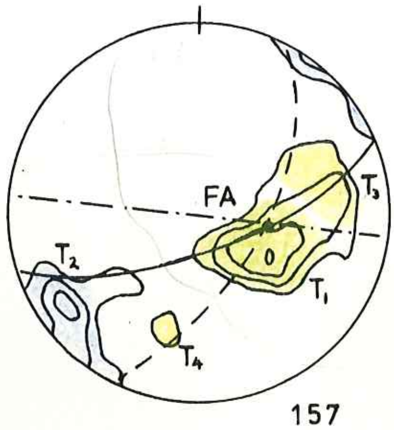
YONGALA QUARRY LOCATION 12

33°- 01′- 35″ S 138°- 42′- 42″ E



Poles to Fractures

157



Contoured Poles to Fractures

157

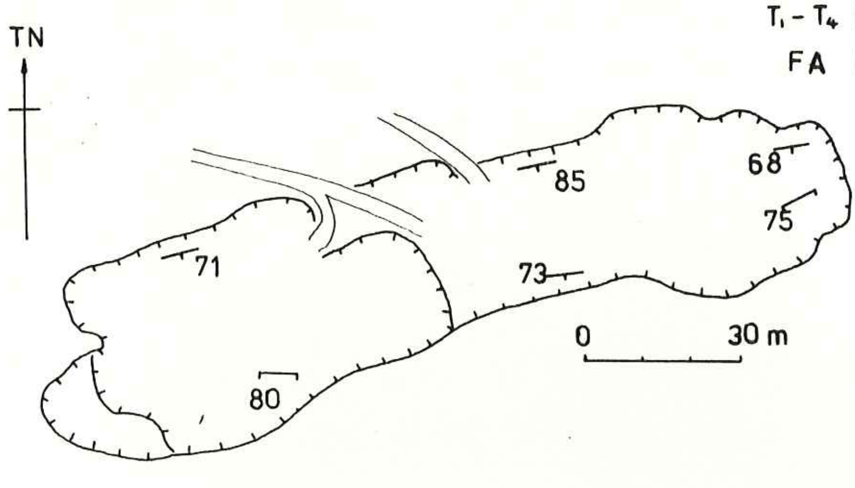
——— Bedding

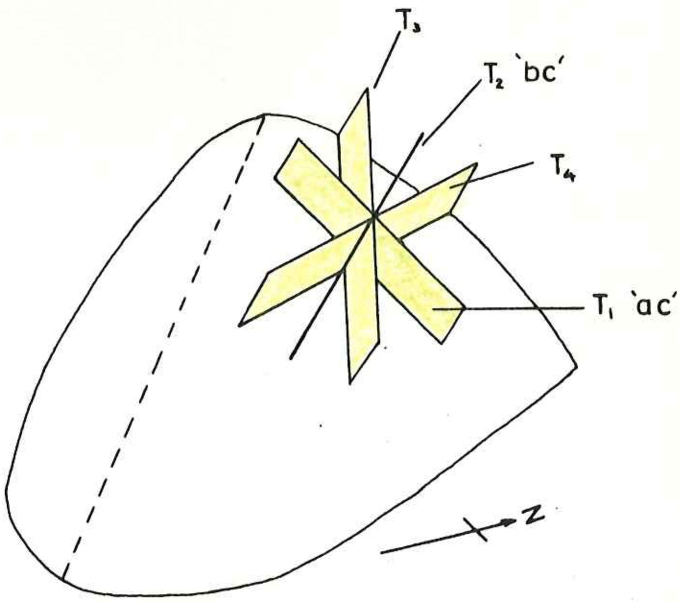
—·— Cleavage

- - - Axial Plane

T_1 - T_4 Fracture Sets

FA Fold Axis





LOCATION 13

BLACK ROCK

Location: Disused quarry 32° 48' 0" 138° 45' 30" E

Bedding: 22/54E.

Structure: East limb of a syncline plunging 15° towards 192°.

Stratigraphy: Minburra Quartzite of the Burra Group.

Lithology: Massive grey quartzarenite above which lies a finely laminated subarkose.

This location has been mapped by Russ 1966.

Fracture sets: The orientation of the fracture sets at this location are to some extent controlled by the lithology, so that it was necessary to take measurements of fracture orientations within both lithologies. Below only the fracture sets in the massive quartzarenite will be discussed. Pyrolusite dendrites are common fracture surfaces.

Set T_1 ('ac' extension fractures)

This is the most common fracture set, it has smooth planar surfaces in places extensional quartz fibres fill fractures.

These fibres are orientated normal to fracture surfaces.

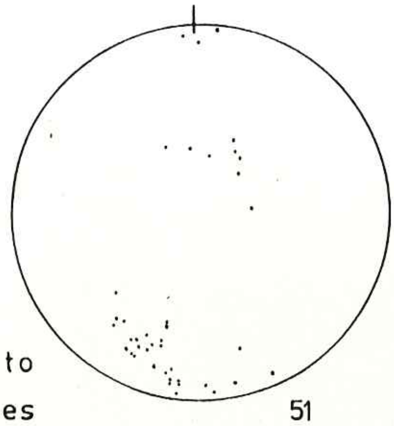
Set T_2 ('bc' extension fractures)

Also well developed fracture set with smooth planar surfaces, vein quartz is commonly found filling fractures.

FRACTURE PATTERN

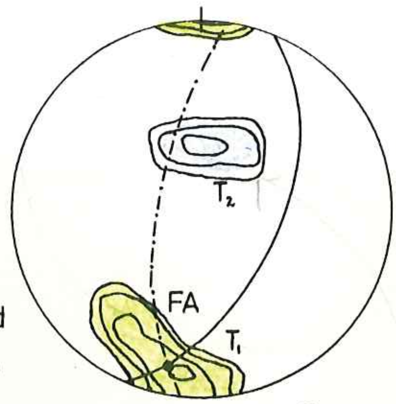
BLACK ROCK QUARRY LOCATION 13

32°-48′-00″ S 138°-45′-30″ E



Poles to Fractures

51



Contoured Poles to Fractures

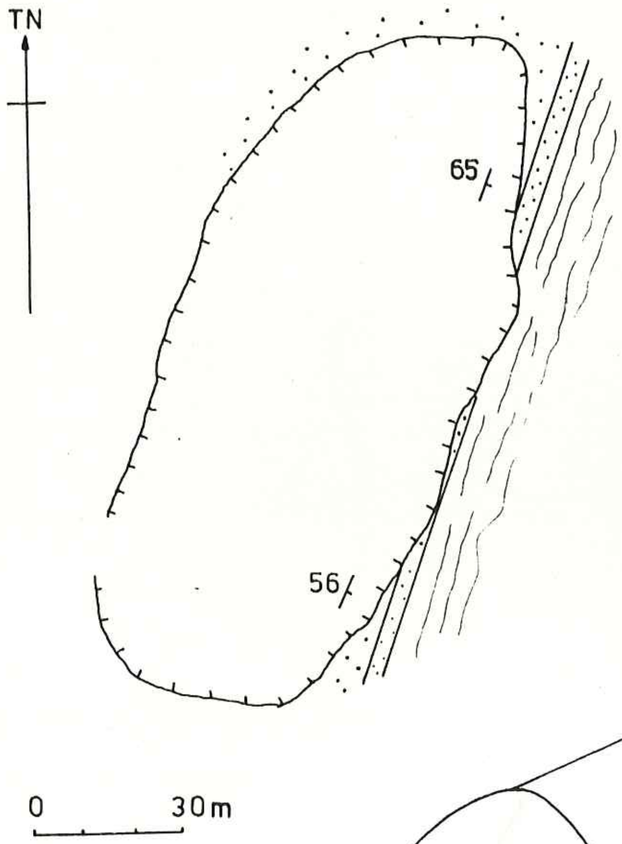
51

—— Bedding

—·—·— Cleavage

$T_1 - T_2$ Fracture Sets

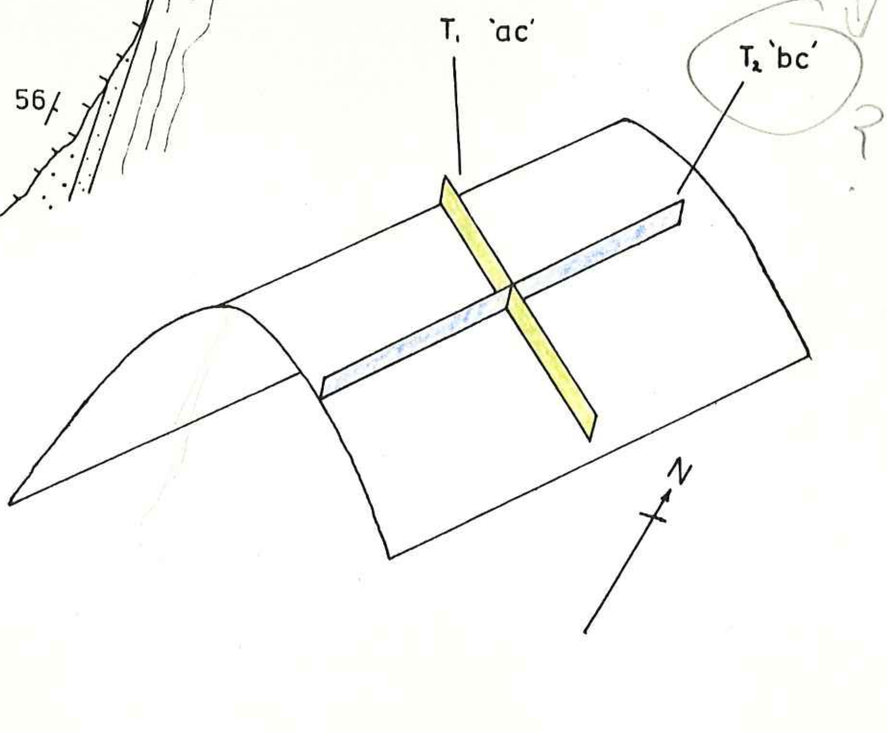
FA Fold Axis



Siltstone

Laminated Subarkose

Massive Quartzarenite



LOCATION 14

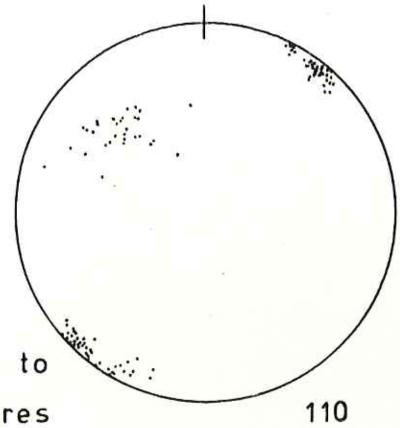
UCOLATA

Location:	Small disused quarry 32^{o} 58" 12" S 138^{o} 57'48"E.
Bedding:	36/56W
Structure:	East limb of a syncline plunging 0^{o} towards 028^{o}
Stratigraphy:	Grampus Quartzite of the Umberatana Group
Lithology:	Variable ranging from fine grained buff coloured feldspathic sandstone to siltstone with thin bands of dark shale at regular intervals.
Cleavage:	Well developed in the dark shales is orientated 24/69W.
Fracture Sets:	Two fracture sets are developed at this location both are filled with quartz. Both sets are approximately perpendicular to bedding and to each other. No offsets or displacements were found between the two fracture sets.
Set T_1	('ac' extension fractures) Most common fracture sets that have smooth planar surfaces. These fractures are filled with quartz and hematite. The quartz is in the form of extensional fibres, developed normal to fracture surfaces.
Set T_2	('bc' extension fractures) Smooth planar surfaces, filled with quartz, but no hematite. Quartz veins in this set are generally wider than set T_1 veins. The quartz is again in the form of extensional fibres normal to the fractures.

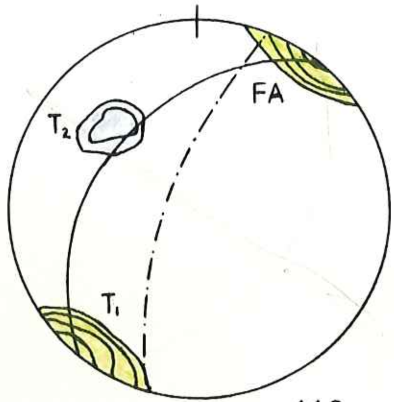
FRACTURE PATTERN

UCOLTA QUARRY LOCATION 14

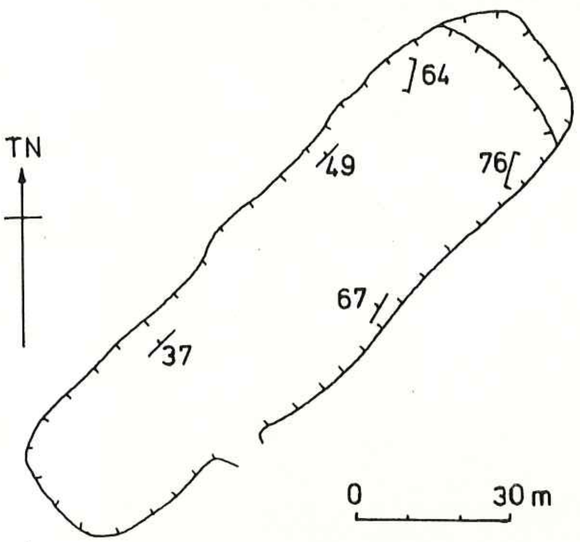
32°-58'-12" S 138°-57'-48" E



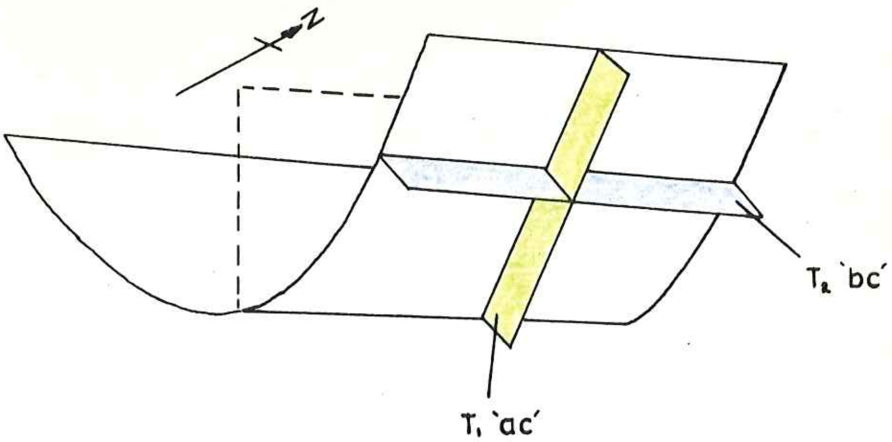
Poles to Fractures 110



Contoured Poles to Fractures 110



—— Bedding
—·—·— Cleavage
T1 - T2 Fracture Sets
FA Fold Axis



APPENDIX 3

ROCK AND THIN SECTION DESCRIPTIONS

Rock and thin section descriptions of specimens from locations 1-14, held under accession number 529 - by the Geology Department, Adelaide University. Rock names after Folk (1974).

Location 1

529/C10	Macro:	medium grained, well sorted feldspathic sandstone.
(Loc. 4)		Emeroo Quartzite Unit 3.
	Micro:	strongly weathered, well sorted, subarkose. 80% Quartz, subrounded - rounded. Indentations and sutured contacts are common. Strong undulose extinction. 15% Microcline. 5% Authigenic quartz overgrowths.
529/C20	Macro:	coarse, poorly sorted, feldspathic sandstone.
(Loc. 4)		Emeroo Quartzite Unit 3.
	Micro:	coarse, poorly sorted subarkose. Contains set T_1 fractures with quartz fibres orientated approximately normal to fractures. Fibres are curved slightly in a dextral sense and consist of coarse crystals extending across the fracture, no median line was observed.
529/C12	Macro:	Emeroo Quartzite Unit 3, medium grained, well
(Loc. 5)		sorted feldspathic sandstone.
	Micro:	texturally mature, well sorted subarkose. 70% Quartz, subrounded - rounded. 20% Altered feldspar. 5% Rock fragments 5% Authigenic quartz overgrowths.

Original grain shape is still present but contains evidence for pressure solution activity. Contains set T_1 fracture with quartz fibres, consisting of single crystals extending across the fracture. Fibres have undergone recrystallization and are coarser than the surrounding material.

529/C26 Macro: medium grained, strongly weathered feldspathic sandstone.

(Loc. 5) Emeroo Quartzite Unit 3.

Micro: well sorted subarkose.

85% Quartz subrounded - rounded, strong undulose extinctions.

10% Altered feldspar.

5% Authigenic quartz overgrowths.

A set T_1 vein 115/65W offsets a later vein 131/85W.

Quartz fibres consisting of single crystals with strong undulose extinction extend across the fractures. No median line was observed. Quartz fibres are coarser than the surrounding material and commonly have sutured crystal faces.

529/C15 Macro: Emeroo Quartzite Unit 3, medium grained, well sorted feldspathic sandstone.

(Loc. 6)

Micro: moderately well sorted submature arkose.

60% Quartz subrounded - subangular, strong undulose extinction.

30% Microcline.

5% Rock fragments.

5% Authigenic quartz overgrowths.

529/C18 (Loc. 11)

Macro: fine - coarse grained well sorted feldspathic sandstone.

Emeroo Quartzite Unit 3.

Micro: medium grained, moderately sorted lithic arkose.

60% Quartz, strong undulose extinction.

20% Microcline.

15% Rock fragments.

5% Authigenic quartz overgrowths.

Abundant evidence for indentation and pressure solution.

Contains a set T_1 fracture with single quartz crystals normal to fracture and extending across it. Contact between fracture and surrounding grains is irregular. Quartz fibres commonly have sutured crystal faces. No median line exists.

529/C25 (Loc. 15)

Macro: fine grained, well sorted sandstone. Emeroo Quartzite.

Unit 3

Micro: moderately well sorted, fine grained arkose. Set T_1 fracture offsets set T_2, quartz in fractures consists of extensional fibres orientated nearly normal to fractures. Some crystals have undergone secondary recrystallization and have irregular orientations.

529/C21 (Loc. 16)

Macro: iron stained siltstone, Emeroo Quartzite Unit 3.

Micro: well sorted, fine grained siltstone. Contains set T_1 and set T_2 fractures. Set T_1 veins are wider than set T_2 and do not contain extensional quartz fibres, but relatively large quartz crystals with no obvious optical preferred orientation. The boundary between fracture and surrounding material is irregular on the micro scale. Set T_2 fractures are filled with quartz fibres, normal to fractures consisting of single coarse crystals extending across the fracture. No median line exists.

529/C28 (Loc. 17)

Macro: moderately well sorted, medium grained, feldspathic sandstone. Emeroo Quartzite Unit 3.

Micro: well sorted, texturally mature subarkose. Indentations and quartz overgrowths are common. Set T_1 fractures are filled with coarse recrystallized quartz that does not appear to have any preferred optical orientation. Set T_2 fractures are filled with single quartz fibres extending across the fracture.

Location 2

529/D1

Macro: medium grained feldspathic sandstone. Emeroo Quartzite.

Micro: moderately well sorted, submature arkose.

50% Quartz rounded - subrounded.
35% Microcline
10% Rock fragments
10% Muscovite
5% Authigenic quartz overgrowths.

529/D3 Macro: fine - medium grained, well sorted sandstone.

Micro: fine grained, well sorted, mature arkose.
40% Quartz subrounded - rounded.
30% Microcline.
30% matrix clay.
Contains set T_1 fracture with coarse recrystallized quartz crystals, initially orientated normal to fractures.

Location 3

529/E1 Macro: strongly weathered, medium grained, feldspathic sandstone.
Bungaree Quartzite?

Micro: well sorted, mature quartzarenite.
Feldspar has been altered and removed.
Original quartz grain shape has been largely destroyed as a result of pressure solution.
Grains are strongly sutured and exhibit strong undulose extinction.

Location 4

529/G2 Macro: strongly weathered, medium grained quartzite.
Leasingham Quartzite.

Micro: strong undulose extinction and pressure solution activity.
The original grain shape has been largely destroyed as a result of pressure solution.

Slide contains a 'bc' fracture filled with extensional quartz fibres. Quartz are partly recrystallized and consist of single crystals extending across the fracture. No median line was observed.

Location 5

529/N1 Macro: fine grained, well laminated sandstone.

Micro: fine, well sorted, mature subarkose.

80% Quartz, equant grains sutured and pitted.

10% Microcline.

5% Authigenic quartz overgrowths.

5% Muscovite stringers, parallel to bedding.

529/N3 Macro: grey, poorly sorted tillite. Appila tillite.

Micro: poorly sorted, contains angular rock fragments and quartz in a fine micaceous quartzose matrix. Fragments and micas show a preferred orientation parallel to cleavage.

40% Subangular - angular quartz.

30% Muscovite stringers.

30% Fine quartzose matrix.

10% Rock fragments, mainly quartzites.

Location 6

529/K2 Macro: fine, well sorted feldspathic sandstone. Gilbert Range Quartzite.

Micro: fine grained, well sorted quartzite. The original grain shape has been almost completely destroyed as a result of pressure solution activity. Slide contains a set T_4 ('bc') quartz vein with coarse quartz crystals, some show preferred optical orientation normal to fractures, others have undergone recrystallization and have no preferred orientations.

529/K4 Macro: same as 529/K2.

Micro: fine grained quartzite. Contains set T_2 fracture filled with coarse quartz crystals that show a weak preferred optical orientation normal to fractures. The quartz crystals have sutured contacts and have undergone recrystallization.

<u>Location 7</u>

529/J3 Macro: strongly weathered, moderately well sorted, coarse - medium grained feldspathic sandstone. Gilbert Range Quartzite.

<u>Location 8</u>

529/I1 Macro: medium grained, well sorted feldspathic sandstone.

Micro: fine grained quartzarenite, quartz grains are strongly sutured, indentated and exhibit strong undulose extinction.

<u>Location 9</u>

529/H1 Macro: strongly weathered, micaceous, fine sandstone. Rhynie Sandstone.

<u>Location 10</u>

529/M1 Macro: strongly weathered, feldspathic sandstone. Gilbert Range Quartzite?

Micro: medium grained, grain supported quartz arenite. The original grain shape has largely been destroyed by pressure solution. Strong undulose extinction. Contains a set T_1 fracture with curved quartz fibres, composed of single crystals extending across the fracture. Surfaces of fibres are strongly sutured, and have strong undulose extinction, no median line was observed. Fibres are much coarser than the surrounding material.

<u>Location 11</u>

529/F1 Macro: fine grained massive feldspathic sandstone. Gilbert Range Quartzite.

Micro: fine grained, well sorted, mature subarkose. Quartz grains are strongly indentated and sutured. Contains a set T_1 ('ac') fracture filled with quartz, showing no obvious optical preferred orientation. Crystals of quartz are coarse and have undergone recrystallization.

<u>Location 12</u>

529/L3 Macro: massive fine grained dolomite, contains pyrite and chalcopyrite mineralization. Contains chert nodules.

529/L4 Macro: fine grained, well laminated grey - green siltstone.

<u>Location 13</u>

529/B2 Macro: buff coloured, well laminated, fine sandstone.

Micro: well laminated and sorted, fine grained subarkose. Framework and matrix supported.

50% Quartz subangular - subrounded.

30% Matrix.

20% Microcline Opaques - hematite.

Contains set T_1 ('ac') fracture with extensional quartz fibres orientated approximately normal to fracture surfaces.

529/B4 Macro: Pebbly conglomerate and well laminated sandstone.

Micro: coarse to fine grained feldspathic litharenite.

50% Quartz subrounded - rounded, strong undulose extinction.

25% Rock fragments dolomite and quartzose.

15% Microcline.

10% Authigenic quartz overgrowths and matrix.

529/B5 Macro: pebbly conglomerate passing into a sandstone. Minburra Quartzite.

Micro: poorly sorted, coarse litharenite. Containing well rounded elongate pebbles.

45% Quartz well rounded, strongly sutured, with strong undulose extinction.

30% Rock fragments, dolomite and quartzose.

20% Matrix and authigenic quartz overgrowths. Opaques - hematite.

<u>Location 14</u>

529/A1 Macro: fine grained, well sorted siltstone. Grampus Quartzite.

Micro: well sorted, texturally mature siltstone.

60% Quartz angular - subangular.

30% Muscovite stringers between quartz.

10% Fine quartzose matrix.

Contains set T_1 fractures with quartz fibres normal to fractures. Fibres consist of single crystals extending across the fracture. Fibres commonly have sutured crystal faces.

529/A3 Macro: fine grained well sorted sandstone. Grampus Quartzite.

Micro: moderately well sorted, fine grained subarkose. Contains set T_2 ('bc') fractures filled with extensional quartz fibres orientated normal to the fractures. Fibres consist of single crystals extending from either side of the fracture and meeting in an irregular median line. Crystal surfaces of fibres are sutured and exhibit strong undulose extinction.