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The correlation of fracture directions with sediment anisotropy in folded rocks of the Delamerian fold belt at Port Germein gorge, South Australia

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Abstract—Fracture patterns have been analysed across an anticline within the Delamerian fold belt. All fractures have orientations normal to bedding and have been separated into sets geometrically related and unrelated to the fold. The preferred orientation of quartz grain long axes in thin sections is statistically normal to the crests of small-scale ripple marks and these two directions correspond to the orientation of two sets of orthogonal joints unrelated to the fold geometry. It is therefore suggested that the sedimentary structures may have had a controlling influence on the fracture orientations.

The presence of quartz fibres within fractures and consistent offsets between fracture sets allow time relations of fracture dilation to be determined. Dilation apparently occurred during or after folding. One set of fractures whose orientation correlates with the sedimentary anisotropy was dilated first and it is possible that these fractures were initiated before folding, possibly during diagenesis.

INTRODUCTION

IN A REGIONAL study of fracture patterns within the Delamerian fold belt (Winsor 1977), it was found that fractures normal to the fold axis (*ac* joints) are usually developed and fractures parallel to the fold axis are commonly developed (*bc* joints). At some localities additional fracture sets are developed. Sometimes these can be identified as shear fractures but in the Port Germein gorge area there is strong evidence that there is a relationship between extension fractures and primary sedimentary structures.

The Port Germein gorge provides a section through an anticlinal hinge where fractures could be studied across the fold within one stratigraphic unit. Fractures, recognised as discrete breaks not parallel to any visible fabric, were separated into a number of sets based on their orientation and morphology. Poles to fracture planes were plotted on equal-area projections and contoured with the aid of the computer program ORIENT (Bridges 1977). Interpretation of the fracture pattern revealed that some fracture sets could be related to the fold, while others showed no obvious geometrical relationship. The orientations of the latter sets suggested the possibility that they were initiated before the folding, and this led to an investigation of sediment anisotropy. This showed that primary preferred clast orientation was related to the directions of these fractures.

A direct relationship between diagenetically formed fractures and sediment transport directions was previously established by Diessel *et al.* (1967), Cook & Johnson (1970) and Moelle (1977), within an essentially flat lying fluvial sequence in the Sydney basin, New South Wales. One fracture set was observed to be parallel to the sedimentary transport direction with a complementary set normal to it. It is suggested (Moelle 1977) that these fracture sets formed during the final stages of diagenesis, with orientations controlled by the sediment anisotropy established when the sediments were deposited. The fractures are thought to have developed by brittle failure while under compactional load in a tensional stress regime.

Within deformed rocks only a few studies have been made relating primary rock fabrics to fractures. The 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. Despite this, 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 deformation. Bonhan (1957) studied petrofabrics and fractures across an anticline but could not find any relationship between micro- and megastructures. Reik & Currie (1974) in a study of the relationship between rock fabrics and fractures came to the conclusion that diagenesis and initial tectonic loading influenced the orientation of later formed fractures. The analysis of two soils by Lafeler & Willoughby (1971) confirmed that the most important anisotropy was parallel to the transport direction and that failure was most likely to occur in that direction. It is believed, however, that the present study is the first demonstration, in strongly folded rocks, of a specific control of fracture orientation by primary sediment anisotropy.

GEOLOGY OF THE PORT GERMEIN GORGE AREA

As shown in Fig. 1 the Port Germein gorge is located about 200 km north of Adelaide near the western margin of the Delamerian fold belt. This belt comprises shallow water clastic and carbonate sequences, deposited in what is commonly known as the Adelaide Geosyncline. They were deformed by the post-Cambrian Delamerian orogeny. Only one generation of

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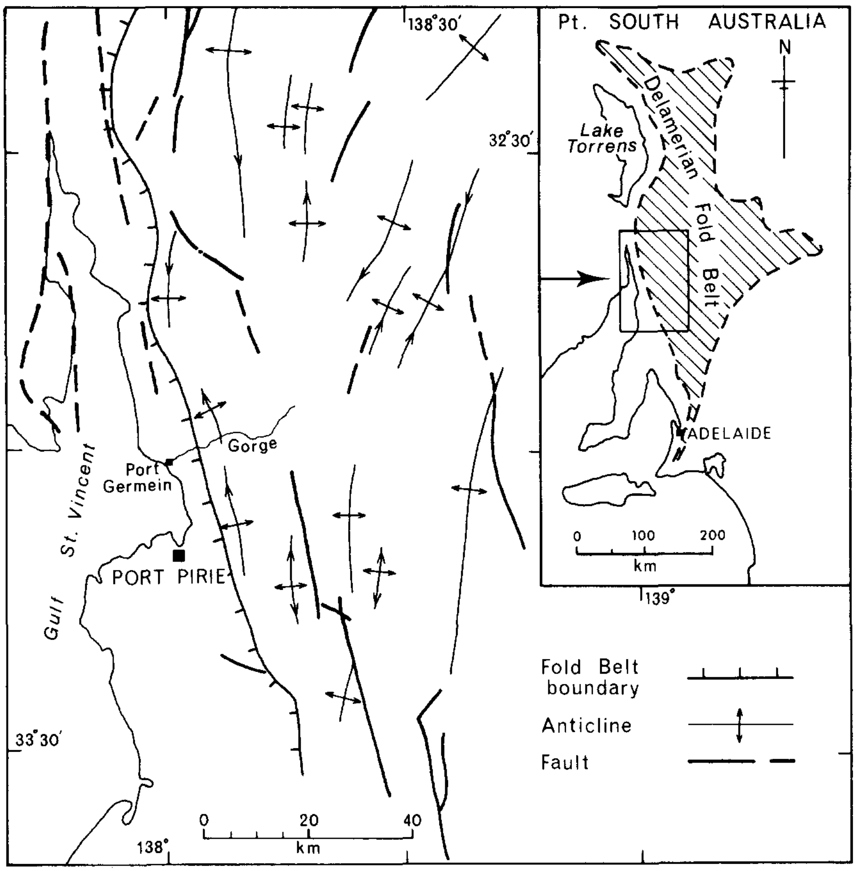
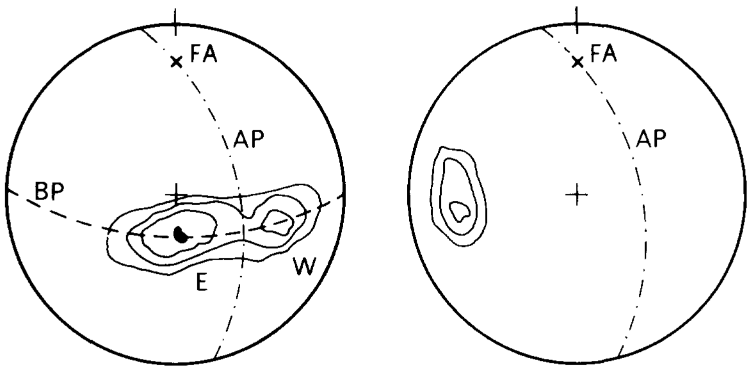


Fig. 1. Locality map.

tight folds is recognised. The macroscopic folds have a parallel style with gentle plunges. Cleavage is confined to the pelitic layers and the sediments have only been weakly metamorphosed to chlorite grade.

The structure within the gorge area consists of a broad inclined, plunging anticline. Contoured poles to bedding across the fold plot on a great circle (Fig. 2), the axis to which is the fold axis, plunging 360°/17°. Contoured poles to cleavage (Fig. 2), only observed in pelitic beds, can be used to draw a mean great circle which defines the axial plane of the fold. The axial plane has a strike of 170° and dip of 60° to the east. It intersects the fold axis. The trend of the axial plane conforms with the axial trace of the fold determined over a larger area (inset to Fig. 3).

The basal formation within the gorge area is the Emeroo Quartzite as defined by Mawson (1947). It



139 Contoured poles to bedding. 12 Contoured poles to cleavage.

FA : Fold Axis (plunge 17° to 00°) pole to great circle containing poles to bedding
AP : Axial Plane (170/60E) great circle to poles to cleavage
BP : Great circle containing poles to bedding
W : From west limb
E : From east limb
Contour interval 2, 4, 8, 16 %

Fig. 2. Basic structural data, Port Germein gorge.

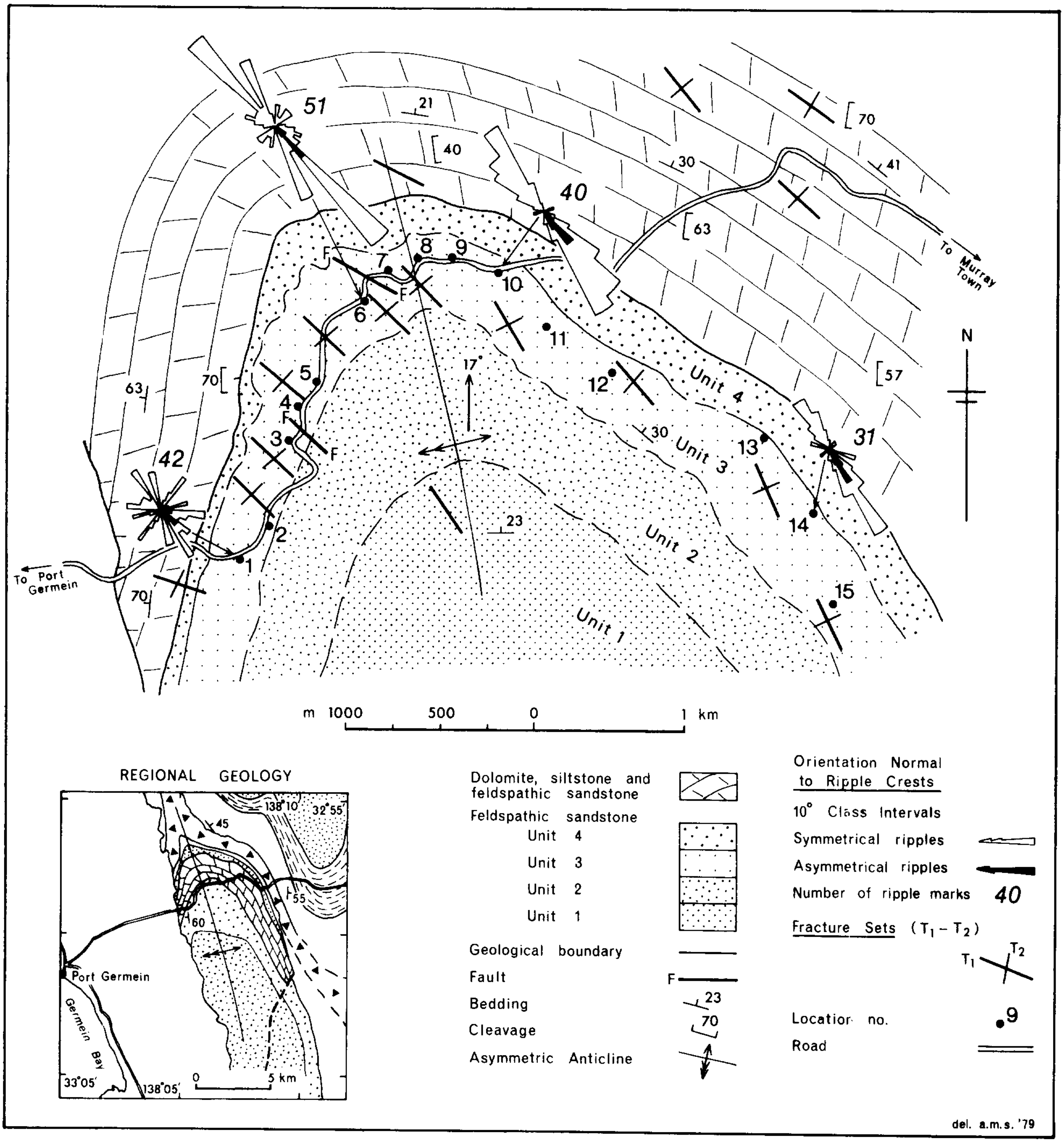


Fig. 3. Relation of sedimentary structures to T_1 and T_2 fracture sets. All data have been rotated using the method of Ramsay (1961) where the fold axis is restored to horizontal before the bedding is rotated around the strike. See text for further explanation.

belongs in the Burra Group of early Adelaidean (Torrensian) age. Four lithological units have been recognised within the Emeroo Quartzite which comprises feldspathic sandstones, siltstones and shales. The third unit is a competent unit consisting of fine to coarse grained, well sorted, feldspathic sandstone. Fracture orientations were sampled almost exclusively within this unit, because it is excellently exposed in the gorge and because the fractures cutting the unit are well developed and show consistent orientations.

DESCRIPTION OF FRACTURE SETS

The orientations of fractures were determined at the fifteen locations shown in Fig. 3. The contoured poles to the fractures at each location are displayed on equal-area projections in Fig. 4. They show that four major sets persist across the anticline. These sets are readily distinguished in the field on the basis of morphology and orientation. All four sets are approximately normal to bedding, and are described in order of frequency as sets $T_1 - T_4$.

Set T_1

This is the main fracture set, occurring at all locations. Fractures have smooth planar surfaces and are generally filled with quartz, commonly in the form of small crystals extending inwards from either side of fractures. In other instances extensional quartz fibres are present, commonly orientated normal to fractures.

Set T_2

The surfaces of these fractures are smooth and planar, with quartz generally filling them. This quartz is commonly in the form of extensional quartz fibres developed normal to fracture surfaces.

Set T_3

This set appears predominantly in the hinge of the fold. The surfaces of these fractures are irregular. No quartz was found filling them.

Set T_4

Fractures in this set are better developed on the limbs of the fold. Fracture surfaces are irregular with a continuity which is inferior to fractures in T_1 and T_2. Quartz was found filling these fractures. The quartz is in the form of extensional fibres developed normal to fracture surfaces.

Figure 5(a) shows the traces of fractures in sets T_1, T_3 and T_4 on a bedding surface at location 2.

GEOMETRICAL RELATIONSHIP BETWEEN THE FRACTURES AND THE FOLD

Sets T_3 and T_4

These sets are related spatially and geometrically to the anticline. Set T_4 fractures occur predominantly on the limbs of the fold while fractures of set T_3 occur mainly in the hinge. Poles to set T_4 fractures plot close to the orientation of the fold axis while poles to set T_3 fractures plot 90° from the fold axis as measured along a great circle representing the bedding. Figure 6 shows that the intersections of bedding with the modal orientations of set T_3 fractures at each location plot close to the fold axis.

Fractures with the orientations of sets T_3 and T_4 are commonly observed within natural folds (Hobbs *et al.* 1976, p. 294). Fractures developed normal to the fold axis on the limbs of folds (set T_4) have been called *ac* joints while fractures developed parallel to the fold axis in the extended portion of folds (set T_3) have been called

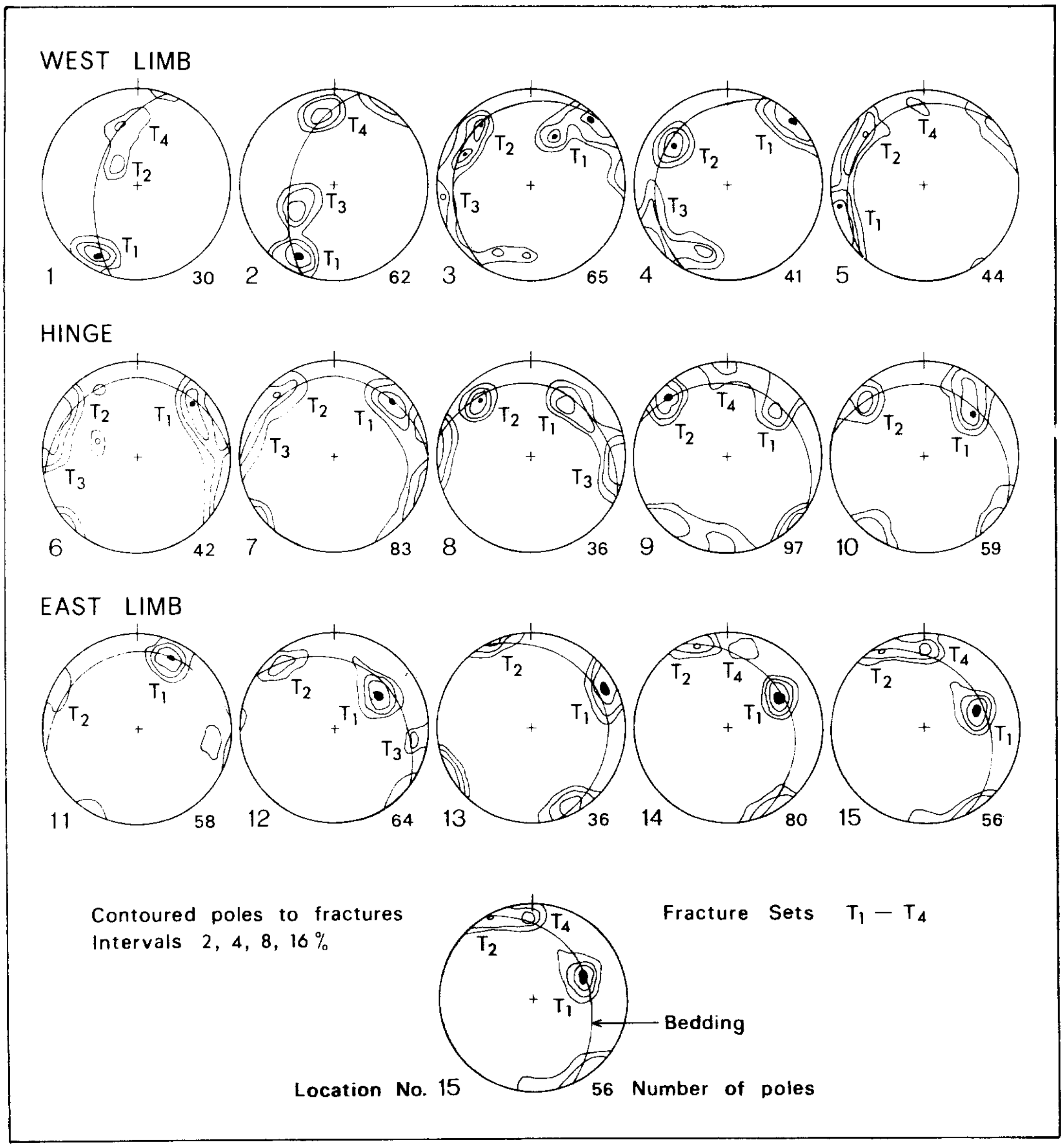


Fig. 4. Equal-area projections of contoured poles to fractures across the fold.

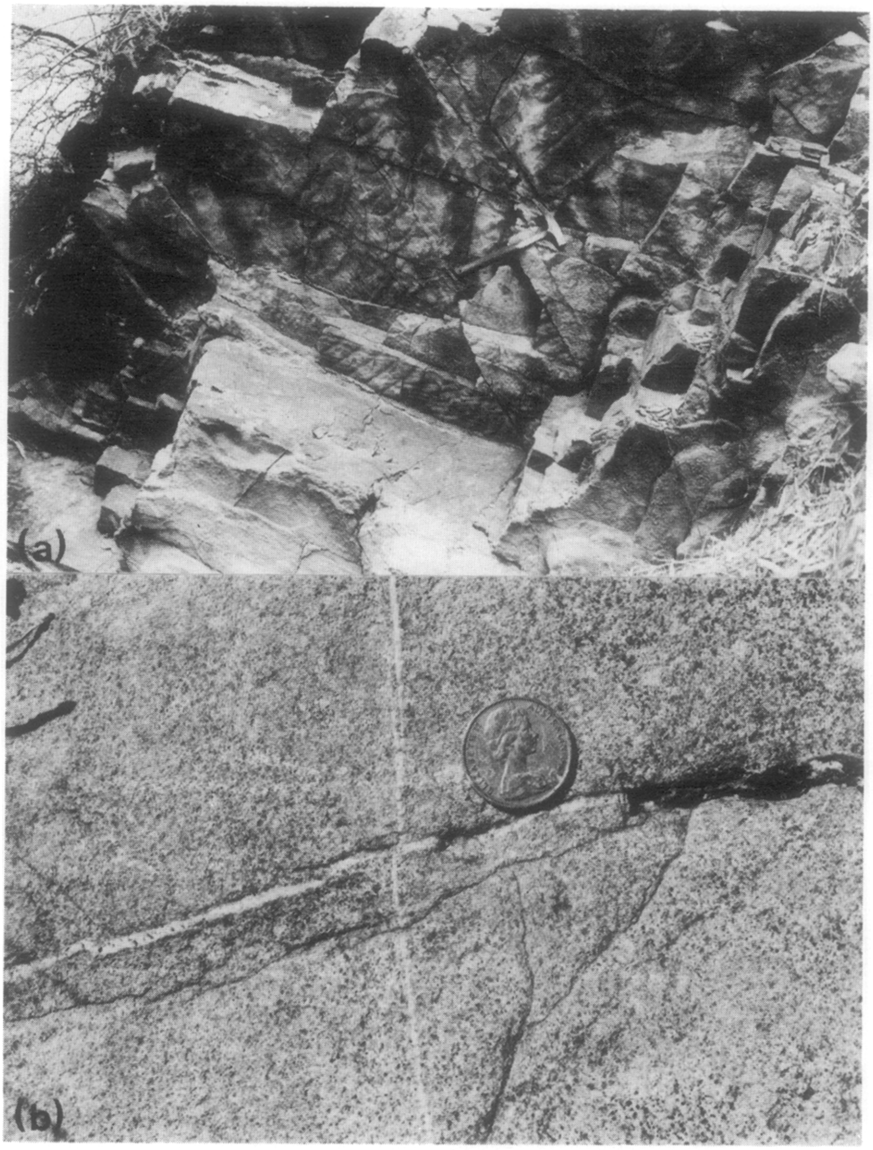


Fig. 5. (a) Set T_1 (normal to hammer handle), T_3 (gently inclined), and T_4 (steeply inclined) fractures on bedding surface at location 2. (b) Dilational offset of T_2 quartz vein (near vertical in photograph) by vein of set T_1.

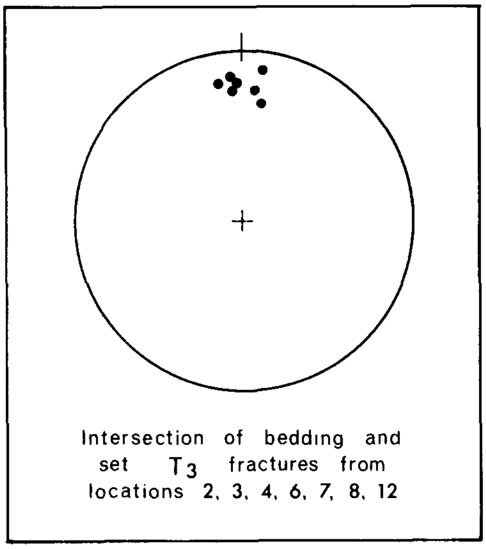


Fig. 6. Intersection of bedding and set T_3 fractures.

bc or longitudinal joints. Both of these fracture sets are regarded as extensional in origin. They are thought to have orientations controlled by the principal stress axes active during folding; although the fractures themselves may form after folding (Price 1966, pp. 148–153).

Sets T_1 *and* T_2

A genetic relationship appears to exist between these two fracture sets, as they are orientated approximately normal to each other and normal to bedding. However these sets do not appear to correspond to any of the five fracture assemblages which Stearns (1964, 1968) has found related to folds.

A possible relation to the folding is suggested by the observation that in the hinge of the fold (locations 6–10, Fig. 4), T_1 and T_2 are disposed approximately symmetrically about the fold axis. However, the fractures are extensional rather than shear fractures and the relationship is not maintained in the limbs of the fold. In both limbs, T_2 plots significantly closer to the pole of the *ac* joints (T_4) than would be required for a symmetrical relationship. Thus in the limbs the fractures are not symmetrically disposed about the axial plane. The strike of fractures in both sets also changes significantly across the fold. This variation is only slightly reduced when the bedding is restored to its orientation prior to folding, using the method described by Ramsay (1961). For example, T_1 has an average strike of 130–140° in the west limb of the fold, but of 140–150° in the east limb. Significant evidence concerning the origin of these fractures comes from their relation to sedimentary structures, and from the sequence of fracture development.

RELATIONSHIP BETWEEN FRACTURES AND SEDIMENT ANISOTROPY

In attempting to explain the orientations of set T_1 and set T_2 fractures, an examination was made of sedimentary structures to determine if they were related to these fractures. To determine the orientations of sedimentary structures it was necessary to rely on ripple marks that were classified as either symmetrical or asymmetrical. They possess wavelengths of approximately 8 cm and heights of 3 cm. The ripples occur on the tops of thick, parallel-bedded, flat-laminated sandstones, and probably reflect the waning stages of strong traction currents which deposited the underlying beds. Internal cross-laminations were rarely observed, but asymmetric current ripple types are closely associated with symmetrical ones and have similar orientations. It is therefore inferred that the statistical normal to the ripple crest orientation represents the dominant current direction. This conclusion is supported by evidence gained from the primary grain fabric which is given below. Within unit 3 the orientations of the normals to 164 ripple marks were determined from four locations across the fold, and were rotated so that the fold axis and bedding were restored to the horizontal (Ramsay 1961). Although there may be some error in determining absolute orientations there should not be any errors in determining the relative orientations of fractures and sedimentary structures. The results of rotation are shown in Fig. 3 along with the modal strikes of set T_1 and T_2 fractures after rotation.

As shown in Table 1, set T_1 fractures are normal to ripple crests and parallel to the inferred current direction, at locations 6, 10 and 14. At location 1 where ripple orientations are more variable (90–150°) the correlation between their directions and the fractures of set T_1 (110°) is weaker, but the general relationship is maintained.

The relationship between fractures and primary sedimentary structures is the same as that established by Moelle (1977). Fractures in set T_1 are normal to ripple crests while fractures in set T_2 are parallel to them.

Table 1. Ripple crest orientations and set T_1 fractures

Location	Ripple-mark data after rotation, Ramsay (1961)		Modal strike of set T_1 fractures after rotation, Ramsay (1961)
	Mean strike normal to ripple crests	Class interval, maximum 10°	
6	134°	130–139°	132°
10	137°	130–139°	138°
14	146°	140–149°	148°

Some evidence for a relationship between set T_1 and T_2 fractures and anisotropy on a microscale was obtained from three thin-sections cut parallel to bedding from specimens collected at locations 2, 6 and 11. The strikes of the long axes of quartz grains within thin-sections were determined relative to an azimuth after bedding had been rotated to the horizontal. The preferred orientation of 968 quartz grains of sizes between 0.2 and 3.0mm was determined by projection of the thin-sections onto a screen. The results are shown in Fig. 6. There is a definite preferred grain orientation parallel to set T_1 and set T_2 fractures.

There can be no doubt that the observed fabric is of sedimentary rather than tectonic origin. The preferred grain directions are neither parallel to or normal to the

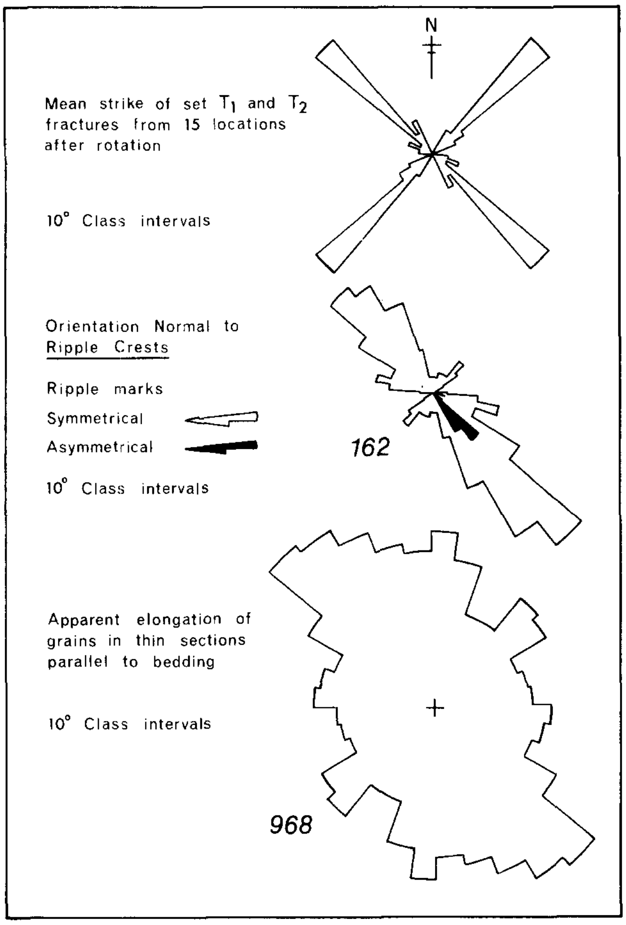


Fig. 7. Preferred orientation of quartz grains compared with orientation of normal to ripple crests, and of T_1 and T_2 fracture sets.

fold axis, and do not correspond to the cleavage orientation observed in the pelitic layers of other units (Fig. 2). Observation of the grain fabric in sections cut normal to bedding, showed that grains lie with their longer dimensions in the bedding plane.

Previous studies of sedimentary grain orientations have been summarized by Potter & Pettijohn (1963). Most studies have shown that the long axes of sand grains are aligned parallel to the transport direction. Shelton & Mack (1970) found a reasonable correspondence between grain orientations and palaeocurrent indicators. In the present analysis, grains show a clear preferred orientation normal to ripple crests, thus supporting the inference of current direction (Fig. 7). A weaker preferred grain orientation is also found parallel to ripple crests. This may be a result of grains having rolled in the direction of the current. The observed sedimentary fabric, although weak, clearly correlates with the orientations of fracture sets T_1 and T_2 and may control the latter orientations.

TIME OF FRACTURE DILATION

Quartz fibres are observed to fill fractures in sets T_1, T_2 and T_4. The fibres are commonly orientated normal to fracture surfaces, although some veins contain sigmoidal fibres. Richardson (1920) realized that veins containing fibres could not be explained by simple crystallization in fluid-filled cavities. Durney & Ramsay (1973) and Phillips (1974) have concluded that the growth of fibres occurs at the same time as the dilation of the fracture. Durney & Ramsay (1973) describe fibres of this type as syntectonic, with the direction of growth controlled by the orientation of the least principal stress at the growth surface. The fibres filling fractures of sets T_1, T_2 and T_4 are believed to be syntectonic (i.e. fibre growth occurred during folding).

Consistent offsets of a dilational nature (Hobbs *et al.* 1976, p. 292) have been observed between the veins of fracture sets T_1, T_2 and T_4. Because of the nature of these offsets they can be used to establish the relative timing for the dilation of fractures. It is observed that both set T_2 and set T_4 veins are offset by set T_1 veins (see Fig. 5b). Also set T_2 veins are offset by set T_4 veins. Thus the order of dilation of fractures is; firstly dilation of set T_2 fractures, secondly dilation of T_4 fractures, and thirdly dilation of T_1 fractures. As fractures of set T_3 have not been filled with quartz, it is postulated that these fractures formed after the other sets. This may have been during, or more probably, after folding.

The order of quartz fibre growth is believed to be related to a systematic variation in extension directions, and presumably to a similar variation in the minimum principal stress direction. As indicated in Fig. 8, the extension direction was orientated NW–SE for the

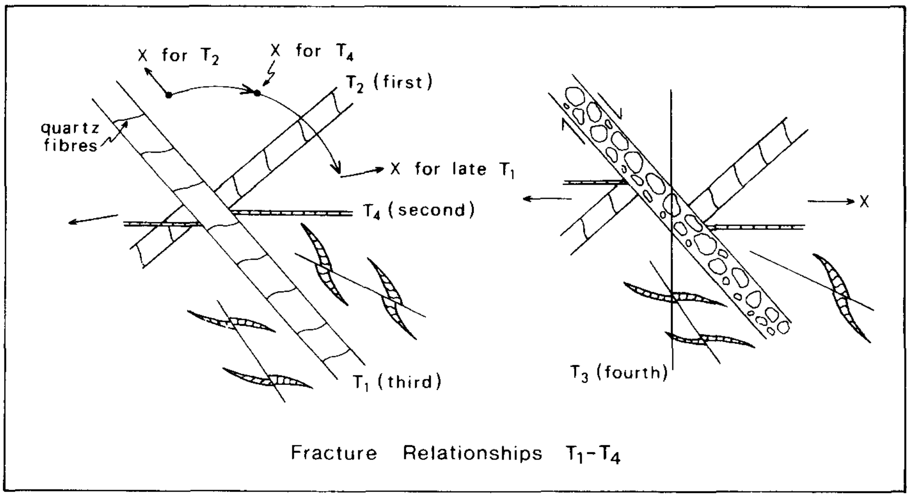


Fig. 8. Fracture relationships T_1–T_4.

formation of T_2 fractures. It then rotated progressively in a clockwise direction. Thus it was N–S for the dilation of the T_4 (*ac*) fractures. The rotation of the extension direction is illustrated by the curved form of the quartz fibres filling some fractures. Usually the fibres filling T_1 and T_2 fractures are straight and normal to the fracture but in some cases the fibres in the central parts of the filling are curved in a clockwise direction. Thus the fibres in T_2 fractures rotate towards being parallel with fibres in the *ac* T_4 fractures which were next to form.

It is notable therefore that although the T_1 and T_2 fractures are apparently related to the sedimentary fabric their dilation was separated by dilation of the T_4 (*ac*) fractures which are clearly related to the folding. Dilation of the T_1 fractures occurred before that of the T_4 fractures but the two dilations are of approximately the same age. Initial formation of set T_1 and T_2 fractures, as distinct from their dilation, may however have occurred before folding, possibly during diagenesis as postulated by Moelle (1977). In any event, as suggested above, their attitude is apparently controlled by sedimentary anisotropy.

ARRAYS OF EN ECHELON QUARTZ VEINS

That the rotation of extension directions is a reflection of the rotation of stress directions is indicated by the development of shear zones containing en echelon sigmoidal and non-sigmoidal quartz veins. Sinistral arrays appear predominantly in the west limb of the fold, while dextral arrays are more common in its hinge zone. Sinistral shear zones have a mean orientation of 148° with veins orientated at 115°. Dextral shear zones have a mean orientation of 111° with veins orientated at 141°. Thus the angle between the shear zones is only 37°, while the angle between shear zones and the veins within them is 30°. Beach (1975) suggests that in these situations fractures in arrays originate as shear fractures; the arrays forming as a result of progressive deformation in established shear zones.

In the present instance the fractures in the shear zones are considered to be shear fractures since veins in the array of one zone are parallel to the complementary shear zone. There is no consistent relationship between shear zones and extension fractures. The T_1 fracture direction everywhere lies between the two shear directions although it may be subparallel to either. The shear zones are therefore not related to the formation of the T_1 fractures.

Thus the shear zones are consistent with a maximum principal stress direction which acted close to the direction of T_1 and normal to the extension direction, this suggests that they may have been formed at approximately the same time as the dilation of T_1 fractures. In support of this inference is the observation that they are cut by dilated T_1 fractures, but not by older T_2 and T_4 fractures.

As the extension direction and stress directions continued to rotate in a clockwise direction, the T_1 fractures became subjected to dextral strike-slip movement before the formation of the T_3 (*bc*) fractures. It seems likely, therefore, that during at least the later stages of the development of the fracture systems, the intermediate principal stress remained vertical while the maximum and minimum principal stresses rotated. This may mean that the dilation of the fracture systems occurred mainly after the folding, since during the folding it is likely that the intermediate principal stress was close to the horizontal.

It is notable in this context that the principal faults observed are subparallel in average orientation (130°/75°W for 40 faults) to the average orientation of fractures in set T_1 (139°/80°W). The faults have only small displacements of up to 2 m and are of normal or dextral strike-slip type.

CONCLUSIONS

It has been recognised that two sets of fractures (T_3 and T_4) are spatially and geometrically related to the folding. They correspond to *ac* and *bc* joints which elsewhere are usually thought to have orientations controlled by the principal stress axes active during folding, although they may form after folding (Price 1966, pp. 148–153).

The other two sets (T_1 and T_2) are the principal concern of this paper. They are not related to fold geometry but show an excellent correlation with primary sedimentary anisotropy: one set is parallel to the inferred palaeocurrent direction and the other set is normal to it. This correlation strongly suggests that the orientations of these sets of fractures were controlled by the sedimentary anisotropy.

It is not possible to determine conclusively when the fractures were initiated but the timing of their dilation and filling with quartz has been established. Dilation of the T_2 fractures occurred first, but T_4 fractures (related to the folding) were dilated before T_1. The dilation of all the fracture sets may have occurred during folding but the evidence that the intermediate stress was vertical during the later part of the dilation history suggests that dilation may have occurred after folding. The T_3 fractures are not filled with quartz and are interpreted as having been initiated after the dilation of the other sets.

The order of initiation of the fractures need not be the same as the order of their dilation. The spatial and geometrical characters of T_3 and T_4 fracture suggests that they could not have been initiated before folding. They were formed during or possibly after folding and T_3 fractures were certainly initiated after T_4 fractures.

The correlation of the other two sets of fractures, T_1 and T_2, with the sedimentary anisotropy may be better explained by postulating that these fractures were initiated before folding possibly during diagenesis. The only evidence directly supporting this proposition is the observation that T_2 fractures were the first to be dilated and filled with quartz.

The introduction of quartz into the early formed fractures has ensured their survival and they provided important planes of weakness along which later faulting has occurred.

It was possible to arrive at the conclusions presented in this paper because good exposures in suitable units are available around the macroscopic fold hinge. This local evidence for control of fracture systems by sedimentary anistropy is therefore reported in the hope of stimulating similar studies in critical localities elsewhere.

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