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Interpretation of a set of faults across the hinge and a limb of a large-scale flexure in the Mount Isa district, Queensland, Australia, in terms of fractures related to the folding process

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Abstract—A revised interpretation of a number of faults across the hinge and western limb of a large-scale anticlinal flexure in the Mount Isa district has been made in terms of the faults following earlier-formed *bc* joints. Such joints often develop in weakly or moderately folded competent sediments, as a result of either tensile stresses that were active at a late stage during folding or the influence of residual stresses generated during tectonic uplift. The joints are oriented such that on a stereographic projection their poles plot parallel to the *a* axis of a fabric cross and at 90° to the fold axis (*b*). *bc* joints are thus approximately normal to bedding and contain the fold axis, and hence they fan around the axial plane of the fold containing them. Across the hinge and western limb of a steeply N-plunging large-scale F_2 flexure in the Mount Isa district, a number of faults at high angles to bedding fan about the axial plane. Making use of the fold geometry and local bedding orientation it is possible to predict the orientation of ideal *bc* fractures at locations within the fold. These predictions fit well with the observed fault pattern. The movement on the faults, although apparently complex, appears consistent with continued shortening perpendicular to an axial-plane cleavage during the D_2 deformation or as part of a later D_3 deformation.

INTRODUCTION

A MACROSCOPIC, steeply N-plunging anticlinal F_2 flexure is present in the area to the east of Mount Isa, southeast of Lake Moondarra (Winsor 1983, 1984). On a regional scale this fold is a large-scale, broad, asymmetric, N–S trending flexure, the western limb and hinge of which are well developed (Figs. 1 and 2), although the eastern limb is not. The fold (Fig. 1) with a wavelength of approximately 20 km, contains middle Proterozoic interbedded shales, siltstones, lithic sandstones, conglomerates (quartzites in Fig. 1) and the Eastern Creek Volcanics (volcanics in Fig. 1), of the Haslingden Group. These metasediments have been described by Mathias & Clark (1975). Unconformably overlying the Haslingden Group is the Mount Isa Group, comprising shales, metasiltstones and a basal quartzite.

Across the western limb and hinge of the flexure (Fig. 1) there are many N–S, NW–SE to NNW–SSE-trending faults oriented at a high angle to the local strike of bedding, although not necessarily normal to bedding. Most faults have sinistral displacements across them, although some, including the Moondarra and Armstrong Creek faults, and several minor faults, are dextral. The purpose of this article is to reinterpret the geometry and genesis of some of the faults shown in Fig. 1.

Smith (1969) proposed that a few faults (i.e. the Moondarra, Painted Rocks and Gum Creek faults) on the western limb and hinge of the flexure (Fig. 1) were initiated during sedimentation of the Myally Subgroup within the Haslingden Group. He noted that across these faults some stratigraphic units were absent or attenuated and that older stratigraphic units were more offset than younger ones, features possibly indicating growth-fault activity. Some faults that show signs of being folded were also interpreted by Smith (1969) as having originated penecontemporaneously. However, Smith did not attempt any detailed structural interpretation of the region, his model (Smith 1969) being mainly concerned with a syndepositional origin for the Mount Isa ore deposits. In a more recent investigation, Perkins (1984) has suggested a syntectonic origin of at least the copper ore body at Mount Isa. An alternative interpretation for the curvature of the Moondarra fault, and possibly the Gum Creek and Armstrong Creek faults (Fig. 1) is the effects of a second deformation (Winsor in press).

REGIONAL GEOLOGY

The folds and faults which affect the rocks of the Mount Isa district in the region to the east of the Mount Isa Fault Zone (Wilson 1972) have recently been interpreted by Winsor (1983, in press). Three folding events influenced the Lake Moondarra area, producing regional folds and associated cleavages. In developing a preliminary interpretation of the faults across the anticlinal flexure shown in Fig. 1, the assumption was made on the basis of geometrical arguments that the fold is a product of the second deformation (D_2). This conclusion is supported by the geometry of the fold (i.e. the N-plunging flexure is consistent with an F_2 fold using the criteria established by Winsor 1983) and the widespread occurrence of an S_2 cleavage (using the nomenclature of Bell & Duncan 1978), compared with the poor development of the S_3 foliation. Minor disharmonic F_1 folds of

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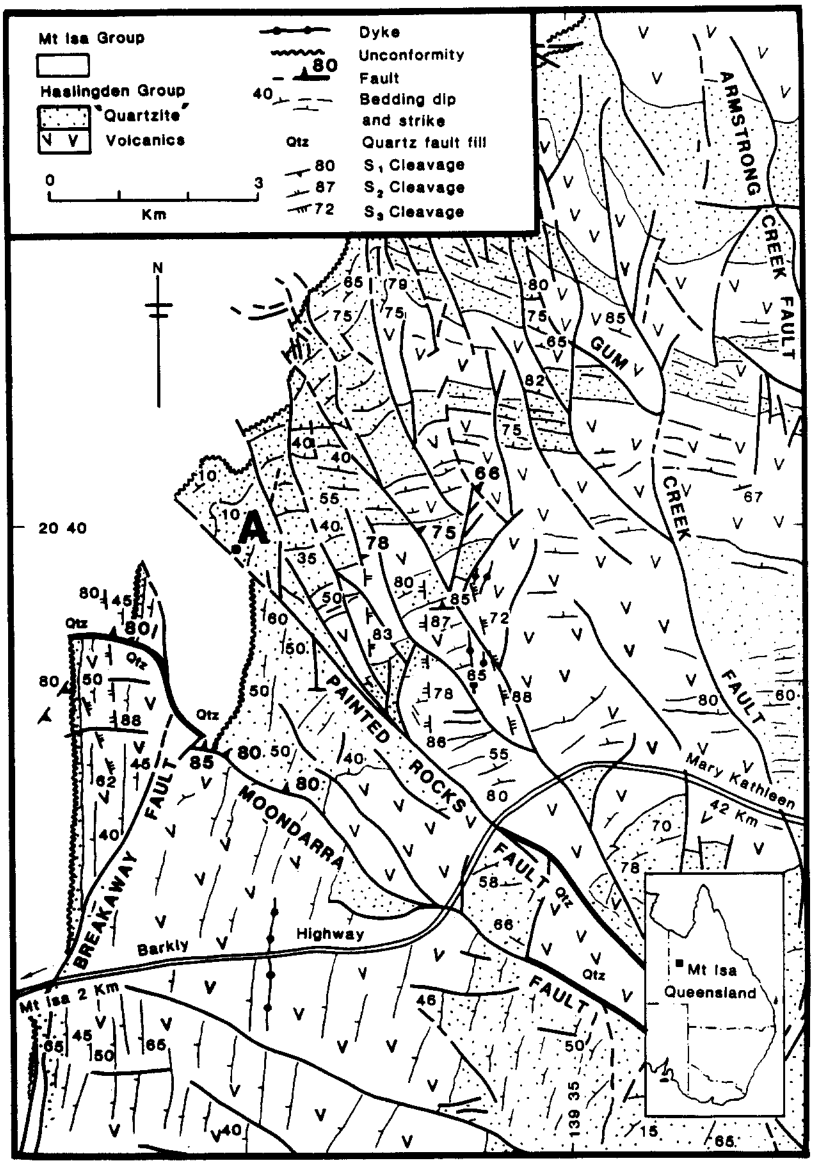

Fig. 1. Geology of the northwest section of a steeply N-plunging large-scale F_2 anticlinal flexure east of Mount Isa. Quartzite within the Haslingden Group comprises interbedded metasandstones, shales and metasiltstones (after Winsor 1983).

up to one metre in wavelength (Winsor in press), are however locally present. They have associated with them at specific locations throughout the region (Fig. 1), a fine continuous cleavage (Powell 1979), that is, a slaty cleavage, S_1. This cleavage, which makes a small angle with bedding, is defined by the preferred alignment of extremely fine micas and is regionally folded around the F_2 flexure illustrated in Fig. 1.

The second deformation (D_2) resulted in the development of the flexure shown in Fig.1 and other regional N–S trending folds. A fine continuous cleavage with generally a N–S orientation and slaty character (i.e. S_2) can be assigned to D_2.

The third deformation affecting the Lake Moondarra area produced NNW–SSE trending folds in bedding (S_0) and S_1, and a continuous cleavage (Powell 1979) of slaty cleavage character in hand specimen and thin section. The fabric type of the cleavages within the Lake Moondarra area has made interpretation of the structural history extremely difficult. In order to assign and separate S_2, S_3 and associated folds, use has been made of the relative timing of geometrically related syntectonic veins (Winsor 1983).

Subsequent to D_2 there was an interval when dilation occurred along the axial planes of F_2 folds in response to relaxation. This dilation allowed the emplacement of N–S trending dolerite dykes, some of which are illustrated in Fig. 1. Some dykes are offset by faults while others are not, so either the area was faulted before and after intrusion or there was more than one episode of dyke intrusion. The Moondarra fault is the only fault within the region (Fig. 1) across which there is clear evidence from the geometry of S_1 and S_2 over the fault, of movement prior to dyke intrusion (i.e. pre-S_2 faulting).

Examination of the deformation history within the Lake Moondarra area has revealed a complex interrelationship between the folding and faulting events. Some faults are infilled locally with milky quartz, cropping out as wide buck quartz ridges. The results of

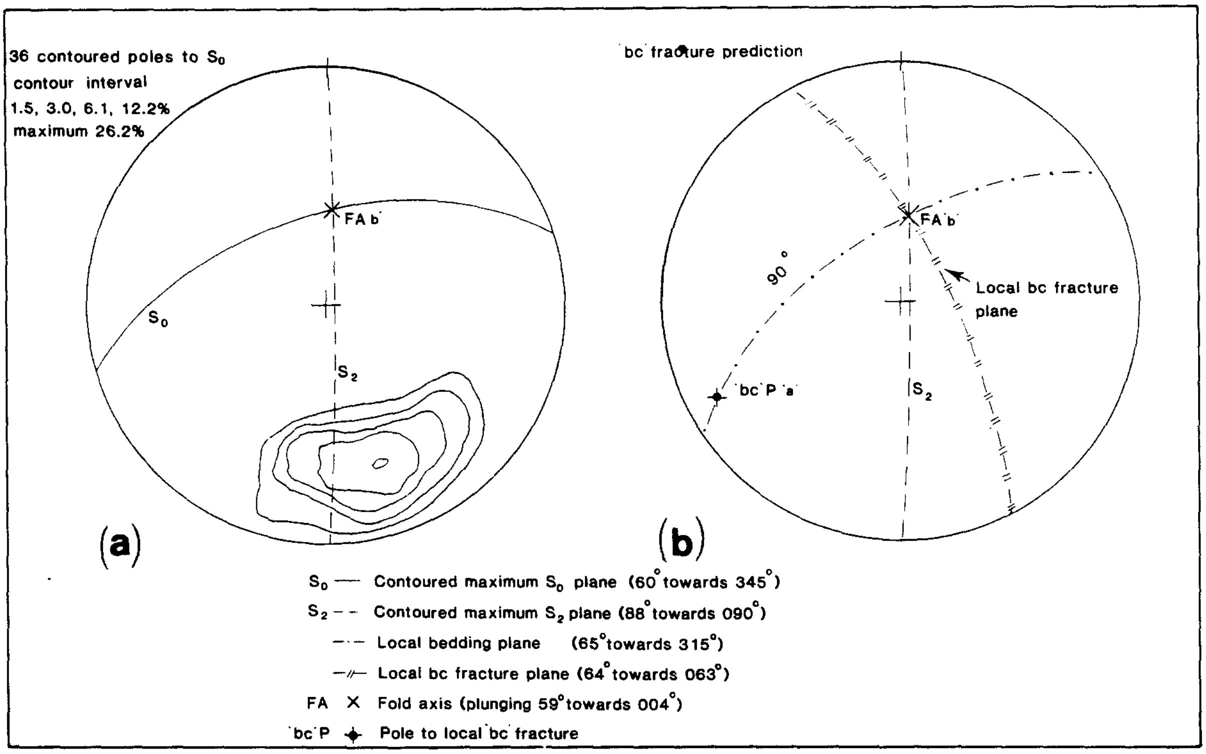

Fig. 2. (a) Contoured poles to S_0 within the hinge and western limb of the F_2 flexure. The orientation of the fold axis and the mean S_0 plane are also shown. (b) Geometrical method used to predict *bc* fracture orientations. Note that the *a* and *b* axes of the fabric axial cross are parallel to bedding, with *b* parallel to the fold axis and *c* normal to the bedding (Hancock & Atiya 1979). Thus the pole to a *bc* fracture, i.e. *bc*P, is parallel to the *a* axis (after Winsor in press).

oxygen isotope analysis of specimens of this quartz, suggest that the quartz moved into the fault zones by solution transfer (Durney 1972) via metamorphically derived water, the quartz originating (Winsor 1984) from the metasediments of the Mount Isa and Haslingden Groups. Fracture cleavage in some fault-fills is consistently parallel to S_2 in the adjacent country rock and locally fibrous quartz is also present, the fibres of which are parallel to L_2^2 and/or L_3^3. Therefore it is concluded that these faults were probably dilated and infilled synchronous with S_2 formation. The Moondarra fault is the only fault shown in Fig. 1 which has a wide zone of syn-S_2 quartz. The absence of a syn-S_2 quartz fill in the other faults, although they have a suitable orientation for dilation late- during D_2, suggests that they did not originate before D_2. The Painted Rocks fault is locally infilled with quartz that does not predate any of the cleavages and shows no signs of deformation, although it locally incorporates country rock fragments (i.e. generally irregularly shaped quartzite fragments from the Myally Subgroup).

Unlike the Moondarra fault, which is well exposed, most other faults in the region (Fig. 1) do not show much surface expression. The orientation of a few of these other faults has, however, been roughly determined, although the data are insufficient to produce meaningful stereographic plots. The faults, where exposed, have smooth planar surfaces dipping at moderate angles to the northeast (i.e. 66–78°, see Fig. 1), slightly gentler than the dip of the Moondarra fault (i.e. about 80°).

Slickensides represented by fibrous growths have been noted on the surfaces of a few of the faults shown in Fig. 1. Generally, these striations are oriented at a low angle to the northwest, indicating a component of strike-slip displacement. It is possible to determine the sense of fault movement from the stratigraphic offsets and for most faults there has been a component of sinistral strike-slip displacement. However, the Armstrong Creek fault, Moondarra fault, and a few minor unnamed faults immediately to the south of the former fault have undergone dextral displacement. Of the faults in the northeastern section of the map area shown in Fig. 1 that have moved dextrally most trend N–S to NNE–SSE, whereas most of the other faults (in Fig. 1) trend NNW–SSE to NW–SE. This evidence together with the change in bedding geometry across the flexure, suggests that most faults on the western limb of the structure have undergone sinistral strike-slip displacement, whereas those on the eastern portion of the flexure have moved dextrally. The distinction between the movement sense across the fold, however, is not easily interpreted as there is at least one fault other than the Moondarra fault on the western limb of the structure that has moved dextrally, while there is a NNE–SSW trending fault immediately to the west of the Armstrong Creek fault which has moved sinistrally.

The Moondarra fault, with a syn-S_2 buck quartz fault fill, shows signs of having undergone some sinistral strike-slip movement post-S_1 and pre-S_2. This timing is inferred because S_1, while maintaining a low angle to bedding, changes orientation across the fault; and S_2, with a constant orientation (Fig. 1), passes through the fault fill (Winsor in press). The Moondarra fault is considered older than most faults shown in Fig. 1. This fault's early development is supported by the following features: (1) the curvature in plan of the fault (Fig. 1); (2) the presence of S_2 with consistent geometry through the fault fill and locally fibrous fill (plus the results of oxygen isotope analysis indicating that it was derived from the surrounding country rocks syn-S_2 [Winsor 1984]) and (3) the occurrence of a wide buck quartz fault fill. Sedimentological evidence (Winsor in press) also supports the early formation of the Moondarra fault. Figure 1 shows that across this fault from north to south there is a dramatic thinning of the quartzite unit (i.e. the Myally subgroup) at the top of the Haslingden Group. The apparent thinning without an associated change in dip, suggests that the fault may have originated penecontemporaneously. This idea has been substantiated by the presence of a facies change within the Mount Isa Group along the northern section of the fault. Irregularly shaped boulders and pebbles of quartzite and volcanics have been noted within the Moondarra Siltstone, one of the oldest stratigraphic units of the Mount Isa Group, in the area just to the north of the fault. Elsewhere throughout the Lake Moondarra region the Moondarra Siltstone comprises an extremely fine-grained dolomitic siltstone or shale. Stratigraphically below the Moondarra Siltstone is a distinctly clean white meta-sandstone (the Warrina Park Quartzite), which marks the base of the Mount Isa Group and rests unconformably on the Eastern Creek Volcanics of the Haslingden Group. This unit also changes north of the Moondarra fault and becomes unclean and brown.

Although the Moondarra fault is the only fault shown in the area depicted in Fig. 1 with associated sedimentological evidence to support a penecontemporaneous origin, a number of other faults have related structural and sedimentological features which must be reinterpreted to accord with a new explanation for them. These features include: (1) the apparent abrupt termination of the faults where they enter the Mount Isa Group metasediments to the northwest; (2) evidence for greater fault displacement through the older stratigraphic sequence (Fig. 1) and (3) the occurrence of conglomerates in areas adjacent to the faults.

INTERPRETATION OF A SET OF FAULTS AT MOUNT ISA IN TERMS OF *bc* FRACTURES, WITH DISCUSSION OF PREVIOUS IDEAS

Smith (1969) interpreted the Moondarra, Painted Rocks and Gum Creek faults as having developed penecontemporaneously. He took the following features in order of decreasing significance as indicators of growth fault activity: (1) stratigraphic units which alter thickness across faults; (2) greater fault displacement in the lower portion of the stratigraphic column, where the final up-sequence termination of the faults may possibly be blind and (3) evidence for faults having been folded. Such features may accord with an episode of penecontemporaneous activity, but we should at least remove the effects of tectonic deformation before accepting them as conclusive. Clearly, variations in thickness of stratigraphic units across faults do not necessarily imply growth-faulting if the dip of bedding also changes, possibly from scissor fault movement or folding before faulting. Thus an increase in thickness of the upper Quartzite unit north of the Painted Rocks fault is marked by a decrease of the bedding dip, possibly because of scissor fault activity or F_1 folding.

A number of faults (e.g. the Painted Rocks fault) achieve greater displacements in the older stratigraphic sections and some end abruptly on entering metasediments of the Mount Isa Group to the northwest, but neither feature necessarily demonstrates growth movement. As suggested earlier, the increased fault movement through the older stratigraphic section may be a result of scissor fault movement. The apparent termination of the faults parallel to bedding could result from accommodation of shear strain within incompetent rocks of the Mount Isa Group. Also, the occurrence of conglomerates within the Myally Subgroup near some faults does not prove growth fault activity, as conglomerate horizons are fairly common within the Subgroup.

The Armstrong Creek, Gum Creek and Moondarra fault surfaces are locally curved (Fig. 1), possibly suggesting a degree of tectonic deformation. They may therefore have been affected by at least one of the regional folding events.

Numerous minor faults which extend for about 1–10 km and have a fairly high angle to bedding, are shown in Fig. 1. These faults have a similar geometry to those interpreted by Smith (1969) as having undergone penecontemporaneous activity, and must fit into any interpretation of the region. The Moondarra fault is accepted as penecontemporaneous, and the locally arcuate nature of the Gum Creek and Armstrong Creek faults indicates that they may have been deformed. Although more field data would be useful, a new interpretation based on available data is presented below.

The trend of the faults shown in Fig. 1 which have no associated evidence suggesting penecontemporaneous activity (i.e. all except for the Moondarra, Gum Creek and Armstrong Creek faults) geometrically follow the change in bedding across the western limb and hinge of the flexure (fanning about the axial plane). The strike of bedding changes through about 110° across the fold, while the trend of the faults fans through about 95°. This accordance, together with the rough parallelism of faults within the hinge of the flexure to the axial plane, suggests a geometrical relationship to the fold. The faults may therefore have the geometry of a set of joints developed due to tension release toward the end of, or after, a folding event.

The geometry and classification of fractures which may form in weakly or moderately folded rocks has been discussed by N. J. Price (1966), R. A. Price (1967), Stearns (1967) and Hancock & Atiya (1979). The geometrical and kinematic classifications used by these authors are much the same for joints developed across folds which plunge less than five degrees, in which fold axis and layer strike are nearly parallel. However, in a steeply plunging fold, such as that shown in Fig. 1, there are some differences in classifications. For this reason it would appear advisable to use a geometrical classification dependent on the orientation of bedding and the fold axis (e.g. Price 1967, Hancock & Atiya 1979). Within such a classification the axes of the fabric cross (*a*, *b* and *c*) are aligned such that the *ab* plane is parallel to bedding, *b* is parallel to the fold axis and *c* is normal to bedding (Hancock & Atiya 1979).

The geometrical types of joints, veins and fractures developed within a weakly folded terrain can be classified in terms of whether they are oblique to, or contain, one or more of the axes of the fabric cross. Fracture surfaces forming in weakly folded competent sediments are commonly parallel to the *ab* (bedding parallel), *ac* and *bc* planes. The *ac* surfaces are developed normal to bedding and the fold axis, while *bc* fractures form normal to bedding and *ac* fractures. Implicit in this form of classification is the observation that *bc* surfaces fan about an axial plane independent of the geometry of the plane of observation. During the formation of *bc* fractures the principal stresses are likely to be oriented such that the minimum principal stress is parallel to bedding and normal to the fold axis (i.e. σ_3 is parallel to *a*), while the maximum and intermediate principal stresses lie in the *bc* plane. According to Price (1966, pp. 148–153) *ac* and *bc* fractures may develop either during or after a folding event as a result of tensile stresses within a rock unit, depending upon the degree of ductile deformation. Using *a*, *b* and *c* as kinematic axes, Price (1967) has suggested that the formation of *ac* surfaces implies shortening in *a* and elongation in *b*, where *a* is parallel to the transport direction, *b* is normal to the transport direction. The formation of these fractures is possibly a result of release of residual stresses after folding or the action of tensile stresses within the extended portion of a fold during the deformation process. In the event that *ac* and *bc* surfaces form during folding, Price (1966) considered that they will subsequently develop into normal or wrench faults.

Geometrically, the faults found across the flexure shown in Fig. 1 appear to be consistent with the orientation of *bc* surfaces developed across the hinge and limb of the fold. This can be concluded because these faults, which are oriented at a high angle to bedding and approximately parallel to the axial plane in the hinge of the fold, appear to fan in a consistent fashion about the axial plane.

To test the idea that faults shown in Fig. 1 could be interpreted as *bc* fractures of the D_2 deformation phase, the ideal *bc* fracture orientations were determined using the geometry of bedding within the F_2 flexure (see Fig. 2a). The lack of exposure on the eastern limb made it necessary to establish the L_2^0 orientation by using the intersection of contoured maximum S_2 plane from Winsor (1983), with the contoured maximum S_0 plane across the flexure. For an ideal F_2 fold in this area, the fold axis plunges 59° towards 004° (Fig. 2). Although the flexure may have been deformed by the third folding event, the results of that deformation seem minor and localized (Winsor in press). Any discrepancy between the ideal *bc* fractures predicted and the geometry of the faults developed across the flexure (Fig. 1), should, if the faults are *bc* fractures, determine the truth of the assumption that the flexure is a D_2 structure.

Using local bedding and fold-axis orientations it is possible to determine on a stereonet, the geometry of *bc* surfaces at any location in a fold. This may be established by finding the stereographic position (*bc*P or *a*, Fig. 2b) 90° away from the fold axis (*b*) as measured stereographically along the cyclographic trace of the bedding plane (see Fig. 2b). The point thus determined will be the pole to the local *bc* surface, that is *bc*P or the *a* fabric axis. Using this technique it was possible to establish the geometry of ideal D_2 *bc* fractures across the flexure (Fig. 1). Minor variation in the dip of bedding in the fold may be a result of D_1 effects producing open gentle flexures. In order to apply a first-order correction for the influence of D_1, the strike of the local bedding was used to determine the ideal geometry of D_2 *bc* fractures. The bedding dip amount was thus altered so that the resultant orientation of the bedding plane intersected the pole of the fold axis.

The traces of ideal D_2 *bc* fractures at 35 points within the F_2 flexure are shown in Fig. 3. These traces are extended along fracture strike for 2.5 km about the point at which they were determined. Clearly, comparing Figs. 1 and 3 there is fair agreement between the strike of faults recognized and the fractures predicted, suggesting that most of the faults initially developed as D_2 *bc* fractures. This observation thus supports the earlier assumption that the flexure was essentially produced as a result of the D_2 deformation. Differences in geometry between Figs. 1 and 3 may be as a result of: (1) the influence of D_1; (2) minor fold readjustment due to D_3 or (3) changes in *bc* fracture orientation produced by refraction through different lithologies. In the region south of the Moondarra fault (compare Figs. 1 and 3), it is clear that the calculated bedding dips are steeper than those observed. This is probably because the plunge of the F_2^0 fold is gentler within this region. In order to predict *bc* fracture orientations for a particular fold in a multiply deformed terrain it is necessary to establish the fold axis orientation for each segment of the fold. However, in the present study the method gives a satisfactory approximation of the fault strikes across the flexure, despite the scarcity of data (cf. Figs. 1 and 3). In the area to the south of the Moondarra fault there are at least four minor E–W trending faults, which rather than having originated as D_2 *bc* fractures, probably represent *ac* fractures developed normal to bedding and the fold axis because their poles plot on a stereonet parallel to the fold axis, the *b* axis of the fabric cross.

Additional evidence supporting the *bc* interpretation of some of the faults developed across the flexure is provided by the examination of the geometry of 244 joints (Fig. 4) developed in a laminated quartzite within the Myally Subgroup at location A (Fig. 1) close to the Painted Rocks fault. Most of the fractures found here

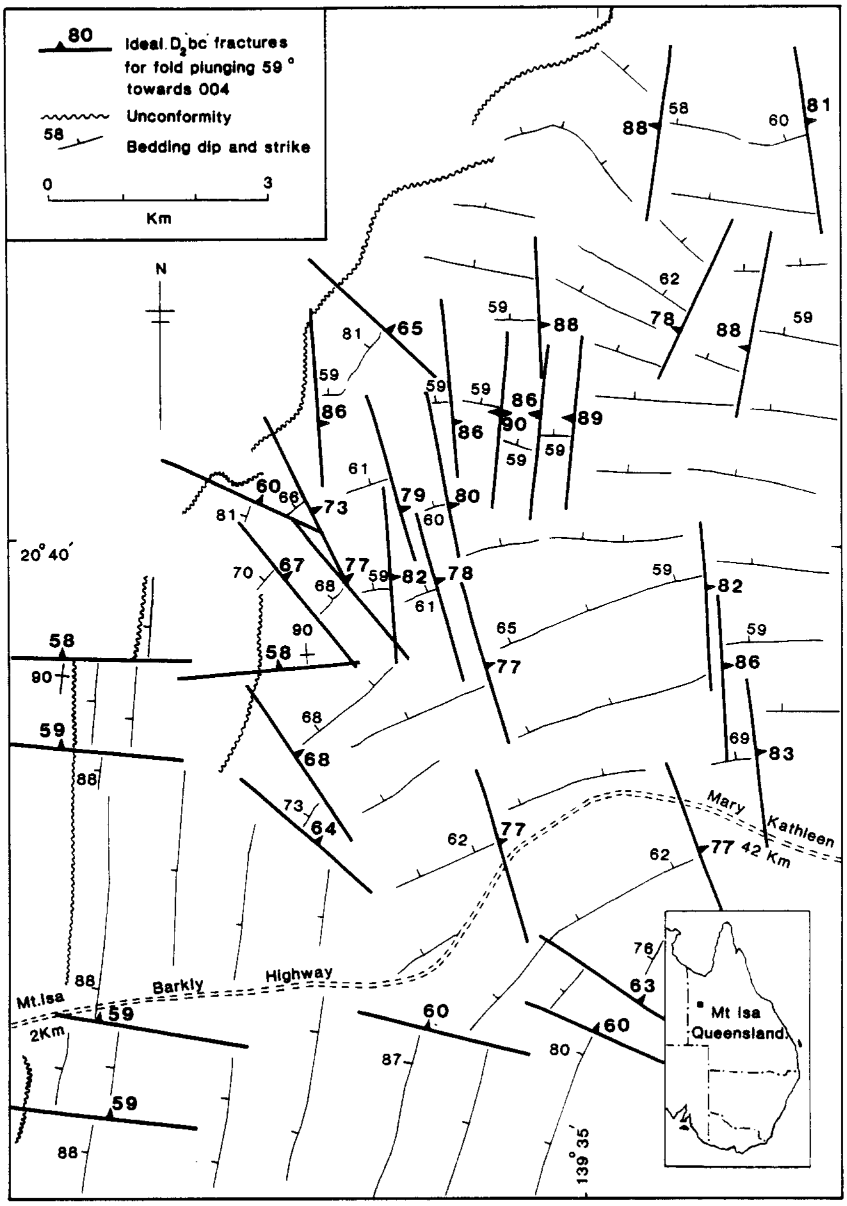

Fig. 3. *bc* fracture orientations predicted across the northwest section of the steeply N-plunging large-scale F_2 flexure east of Mount Isa. Bedding dips shown have been determined for an ideal F_2 fold plunging 59° towards 004°.

have smooth planar surfaces, but some are irregular, and a few have been dilated and filled with quartz. Although there is a wide scatter of joint orientations at this location most are normal to bedding. Geometrically, it is possible to distinguish two main sets of joints, one oriented about normal to bedding and the local L_2^0 orientation, that is *ac* joints, and another about normal to bedding with poles plotting 90° away from L_2^0, as measured along S_0. Clearly, at location A there is no major joint set parallel to the Painted Rocks fault, but the *bc* joints recognized are roughly parallel to the minor faults shown on Fig. 1 near location A. From the evidence contained in Fig. 4 it is clear that some *bc* joints which have not developed into faults are present in the Haslingden Group within the area shown in Fig. 1.

During discussion of the sense of fault movement across the flexure shown in Fig. 1, it was noted that most of the faults on the western limb and hinge moved sinistrally, while within the eastern portion of the flexure some had moved dextrally. Although this may suggest that the movement sense is symmetrical about the axial surface there are faults on the western limb which moved in the opposite sense to the majority. A symmetrical displacement sense about the axial plane is consistent with the idea that displacement occurred at a final stage of D_2, as a result of continued shortening normal to S_2, or perhaps late during D_3.

APPLICATION AND CONCLUSION

Faults developed across the hinge and a limb of a large F_2 anticlinal flexure in the Mount Isa district are interpreted as having originated as *bc* fractures (i.e. normal to bedding and parallel to fold axes). The development of such fractures is controlled by the orientation of bedding and the fold axis, knowledge of which enables the prediction of ideal fracture geometry. Any variations

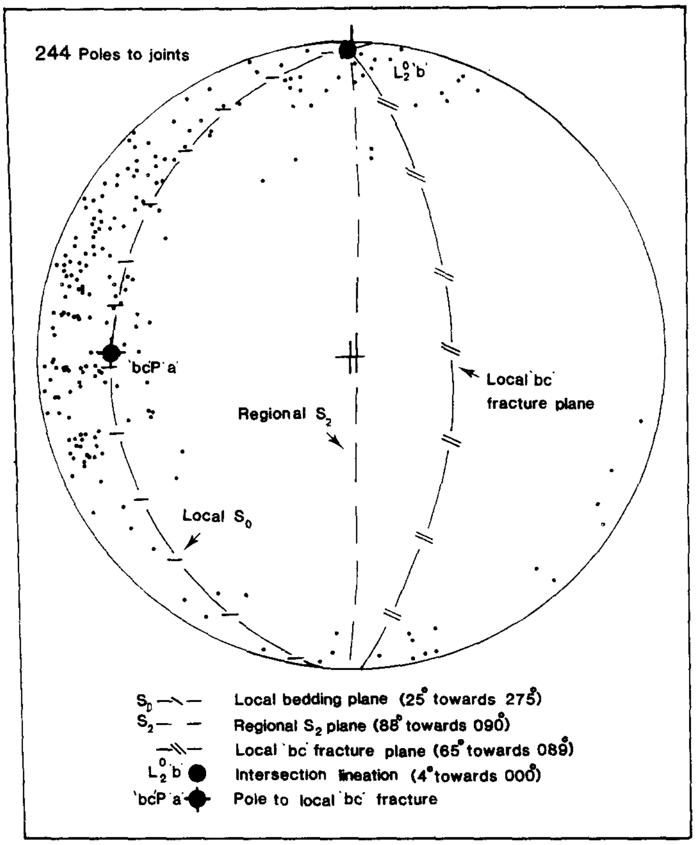

Fig. 4. Poles to 244 joints within a laminated quartzite at location A (Fig. 1). Showing local S_0 plane, contoured maximum S_2 plane and *bc* joint orientations.

between observed and predicted fracture patterns were probably caused by the first or third deformations.

The possibility of fracture prediction in weakly deformed competent sediments has potential application to engineering projects, such as road, dam, mine and quarry constructions. It is hoped that this brief article about the prediction of the presence of *bc* fractures will stimulate additional research concerning the application of geometrical constraints of fractures related to folds, particularly in multiply deformed terrains.

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