Regional-scale foliation reactivation and re-use during formation of a macroscopic fold in the Robertson River Metamorphics, north Queensland, Australia

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Abstract

The rocks defining a macroscale antiform (25 km²) in the Proterozoic Robertson River Metamorphics have been affected by four deformations of distinctive style, with the fourth deformation, D₄, being responsible for formation of the macroscale geometry of the fold. Redistribution of progressive shearing strain, due to strain partitioning during progressive D₄ deformation, resulted in the accommodation of D₄ shearing strain along S₂ differentiated crenulation cleavages that had been synchronously rotated into favourable orientations. On the antiformal limbs this commonly resulted in reactivation of S₂ because shearing during D₄ was in a sense that was antithetic relative to that on the bulk scale of the fold. Continued D₄ deformation caused unfolding of D₂ crenulations, resulting in straightening of sigmoidally folded S₁ and its rotation toward the axial plane of the synchronously forming macroscopic D₄ fold. In zones where the sense of shear during D₄ was the same as that operating on the bulk scale of the fold (i.e. synthetic), D₄ shearing strain was accommodated dominantly by the favourably oriented, approximately axial-planar S₁ fissility. In zones where the progressive shearing component of D₄ deformation was relatively more intense, the S₂ cleavage was also rotated into parallelism with S₄ and was also re-used, as opposed to reactivated. Detailed microstructural analysis, particularly of porphyroblast-matrix relationships, combined with field observations have resolved the processes operating during folding and reveal that, despite the intensity of D₄ deformation, a separate cross-cutting S₄ cleavage has rarely been produced at either the meso- or microscale. Similar processes have probably operated at all scales in other orogenic belts.

1. Introduction

1.1. Scope of the study

In this paper a detailed field and microstructural petrological study of a macroscopic fold (Fig. 1) are used to demonstrate the following: (a) that the processes of deformation partitioning have been important in the production of structural geometries at all scales; (b) the importance of porphyroblast–matrix microstructures for resolving problematic macroscale fold and foliation geometries that have been produced as a result of deformation partitioning; (c) that shearing strain accommodated by favourably oriented, pre-existing foliations has dominated to a large degree over formation of any new foliation axial-planar to the synchronously developing fold; and (d) that
detailed microstructural work can resolve the relative importance of antithetic shear and synthetic shear on pre-existing foliations.

This paper uses the standard techniques of geometric analysis (e.g., Hobbs et al., 1976; Hopgood, 1980; Laajoki and Tuisku, 1990) in conjunction with porphyroblast–matrix microstructural relationships (e.g., Bell et al., 1986; Jamieson and Vernon, 1987; Vernon, 1989; Gibson, 1992; Johnson, 1992; Davis, 1993) to evaluate data from field locations and over 700 spatially oriented thin sections. The geometries of structures produced during the complex deformation history are first described and interpreted. These interpretations are then used to provide a solution for macroscale strike-trend line geometries for foliations of each event. Implications for analysis of foliation strike-trend line geometries and for structural processes operating at all scales during folding are then discussed.

1.2. Definition of strain-related terms used in this paper

Deformation partitioning. This term is used as defined by Bell (1981), where partitioning of strain in a progressively deforming rock mass is broadly viewed as zones which accommodate progressive
shortening strain and zones which accommodate progressive shearing strain. Strain can be further subdivided into regions undergoing: (1) no strain; (2) dominantly progressive shortening strain; (3) progressive shortening plus shearing strain; and (4) progressive shearing-only strain.

**Bulk strain.** This term is used as defined by Means (1994) and as used by Bell (1986). When strain is partitioned, the regional or bulk strain is the sum of the partial strains (terminology after Means, 1994) contributed by domains at a lesser scale. In this case the term bulk refers to the scale of the macroscopic antiform described herein. The bulk strain can be further considered in terms of bulk shear strain and bulk shortening strain. In this paper the bulk shear sense relates to the sense of shear operating at the scale necessary to form the macroscopic antiform.

**Synthetic /antithetic shear.** As deformation progresses, strain is redistributed, particularly the progressive shearing component. This heterogeneously distributed progressive shearing strain operates in a synthetic and an antithetic sense (terminology after Weber, 1976). The sense of the bulk shear operating to form the macroscopic antiform is defined as synthetic. Hence, a synthetic sense of shear for the northwest-plunging antiform (and associated antiformal parasitic folds) described herein is that which operates (subparallel to the axial plane) in a sinistral sense on the southwest limbs, and a dextral sense on the northeast limbs, when the folds are viewed in profile section. For the same antiformal structures, antithetic shear operates in the opposite sense.

**Reactivation.** Reactivation is used as defined by Bell (1986), and is a result of the redistribution of strain. Reactivation involves the operation of progressive shearing in an antithetic sense relative to the bulk shear and can be accommodated by pre-existing structures at a considerable angle to the axial plane of the synchronously forming fold.

**Re-use.** This term is used as defined by Davis and Forde (1994), and refers to the accommodation of progressive strain by pre-existing foliations during a subsequent deformation. This occurs in a sense that is synthetic relative to the bulk shear operating to form the macroscopic antiform.

### 2. Rocktypes and geometry of bedding

The Robertson River Metamorphics represent a major subdivision of the Proterozoic Georgetown Inlier, which comprises an area of approximately 100,000 km$^2$ in north Queensland, Australia. The regional geology of the Georgetown Inlier has been summarized by White (1962) and Withnall et al. (1980). The Robertson River Formation contains the Robertson River Metamorphics, which consist of a suite of multiply deformed phyllites, pelitic schists, amphibolites, quartzites and rare calc-silicate gneisses. The metamorphic grade is generally amphibolite facies and is associated with well defined isograds (e.g., FitzGerald, 1974). Extensive porphyroblast development, with well-developed inclusion trails, is typical.

Within the Robertson River Formation, Black et al. (1978) dated five deformation events, spanning a period from 1574 Ma to 300 Ma, which they considered to be temporally discrete and regional in extent. T.H. Bell (pers. commun., 1993) has recognized at least one subsequent event. However, these events cannot be reliably correlated with those in the area presented herein due to regional-scale strain partitioning, which has caused variation in the intensity of fabric development between this area and that of Black et al. Furthermore, examination of approximately 120 oriented thin sections from several traverses across the Robertson River Metamorphics to the south suggests that there may be additional events to those recognized by Black et al. (B.K. Davis and S.A.J. Hewson, unpubl. data). Based on the structural timing of the most extensively developed porphyroblast assemblages in both areas, my $D_4$ is tentatively correlated with their $D_2$, thereby giving it an age of approximately 400 Ma via their Rb–Sr whole-rock analysis.

All rocks within the area of study lie within the andalusite zone. Rocktypes are amphibolite units belonging to the Cobbold Dolerite, pelitic schists,
Fig. 2. Strike-trend lines of bedding as resolved from field mapping and aerial photographs. Note that at this scale the Cobbold Dolerite (stippled) displays poorly defined folding in places but the geometry of most bedding strike-trend lines is independent of this. Note the well defined girdle produced by poles to bedding, which indicates a moderately northwest-plunging fold axis. Equal-area net with contouring at 2 standard deviations.

and quartzites (Fig. 1). Porphyroblasts are represented by andalusite, staurolite, garnet and biotite. Strike-trend lines of bedding (Fig. 2) define a macroscopic fold with a steeply dipping, approximately NW–SE axial plane. A plot of total poles to bedding defines a girdle that indicates a moderately NW-plunging fold axis (equal-area net in Fig. 2). Continuous strike-trend lines for bedding cannot be constructed across many regions of the area because of faulting and cross-cutting units of the Cobbold Dolerite, which intruded during the subsequent D₃–D₄ deformation history.

3. Deformation history

Four distinct deformation events, D₁–D₄, have been recognized in the study area presented herein, based on overprinting relationships between structures produced. Porphyroblast–matrix microstructural relationships indicate growth of
Fig. 3. Photomicrograph and line diagram of common microstructural relationships. The $S_2$ differentiated crenulation cleavage runs diagonally across the photo from lower-right to upper-left and is defined by mica-rich differentiation zones containing biotite porphyroblasts (shaded). The $S_2$ differentiation zones display microscale crenulation by $D_4$. Staurolite ($St$) has grown along $S_2$ during $D_4$ and has preserved some $D_4$ crenulations of $S_2$. $S_1$ between the $S_2$ mica microlithons in the matrix was originally sigmoidally folded but has been straightened out and re-used by $D_4$, thereby forming a composite $S_1$-$S_4$ foliation. Note that $S_1$ is now in an orientation that is approximately axial-planar to the $D_4$ microfolds. $Gt$ is garnet. Partly polarized light. Long edge of figure is 14 mm. Location: 143°028'46", 18°41'56".
the porphyroblast assemblage during D₃ (Fig. 3; see below). The D₂ and D₄ deformations produced cleavages that are distinctive in style in both outcrop and thin section (Figs. 3 and 4) across the area. These marker cleavages allowed resolution of the deformation history and problematic trends in S₁ and S₂ (see below). The D₃ event was very weak and only locally produced a crenulation cleavage. The D₄ event produced complex geometries in the strike-trend line patterns of pre-existing foliations. Consequently, the importance of the D₄ event is emphasized by discussing it separately and in terms of the geometries of bedding and the S₁, S₂ and S₃ foliations.

4. The first three deformations, D₁–D₃

4.1. Description and interpretation of D₁ structures

D₁ produced a schistosity, S₁, that is variable in intensity and style across the area. This variation is largely a function of lithology and the style of S₁ is consistent within individual lithologies despite the effects of overprinting deformations.
Rare crenulation hinges within some porphyroblasts and areas of low post-D1 strain indicate that S1 was originally a differentiated crenulation cleavage.

Interpreted strike-trend lines for S1 are shown in Fig. 5 and generally define broad-scale folds separated by extensive, sporadically located zones of non-folded, approximately NW-SE-trending S1. The equal-area net of S1 for the folded zones (net A in Fig. 5) defines a broad discontinuous girdle, indicating folding of S1 about a northwest, moderately plunging axis. The zones of non-folded S1 are a result of subsequent deformation (mainly D4), and contouring of the equal-area net for

Fig. 5. S1 foliation strike-trend lines. Stippled regions are areas where S1 has been rotated into an orientation parallel to the S4 axial plane of the macroscopic fold. These zones have partitioned synthetic D4 shear and the foliation in these is an S1-S4 composite foliation. Net (A) is a plot of total S1. The maxima are a result of the dominantly steep northwest–southeast-trending re-used S1 (now composite S1–S4), whereas the modification into a girdle is due to S1 that has been folded by D4 but not re-used. Nets (B) and (C) show separation of total S1 data into axial-planar composite S1–S4 and S1 that has been folded by D4, respectively. Net (D) shows L0 data. Equal-area nets with contours at 2 standard deviations.
these produces a maximum indicating a steep NW–SE orientation. The significance of this pattern is discussed below.

Outcrop folds and S₁-bedding vergence relationships show D₁ folds of S₀ to be open to tight with wavelengths and amplitudes from a few centimetres to a few tens of metres. Facing relationships are unknown due to a lack of younging criteria. The distribution of L₁⁰ (terminology after Bell and Duncan, 1978) shows a maximum defining moderately northwest-plunging orientations (net D in Fig. 5).

4.2. Description and interpretation of D₂ structures

D₂ produced the most pervasive foliation in the field area, S₂, which is easily correlatable across the whole study area. S₂ is a crenulation cleavage that is commonly differentiated (Fig. 3). S₁ is preserved as inclusion trails within biotite, garnet, staurolite and andalusite (e.g., Fig. 6) and S₂ inclusion trails are almost always continuous with matrix S₂. As with S₁, the strike-trends of S₂ have been deformed into broad folds, the continuity of which is interrupted by approximately NW–SE-striking zones of non-folded S₂ produced during subsequent deformation (Fig. 7). A plot of total S₂ produces a well defined girdle (net A in Fig. 7), the axis of which plunges moderately to the northwest, subparallel to the axis of folded S₁ and S₀. Non-folded S₂ structures strike NW–SE and are steeply dipping.

Intersection lineations between S₂ and S₀ (L₀²) define a broad maximum in the northwest quadrant of the equal-area net (net B in Fig. 7). This concentration of data is a function of northwest-striking S₂, attenuated bedding on the limbs of the macroscopic fold and the similar dips and dip directions of S₂ and S₀ in the macroscopic fold hinges. Intersection lineations between S₂ and S₁ (L₁²) also produce a maximum defining moderately northwest-plunging orientations (net C in Fig. 7). This is largely a function of the dominantly NW-striking non-folded S₁ intersecting S₂ that was folded during subsequent deformation.

Fig. 6. Photomicrograph of section approximately parallel to the profile plane of the macroscopic fold. A composite S₂–S₄ foliation is developed in the matrix (parallel to the short edge of the photo) and dips steeply to the southwest. The original character of the S₂ cleavage, prior to modification by D₄, is shown as sigmoidal crenulation of S₁ inside garnet porphyroblasts. S₁ in the quartz-rich regions, which define original matrix D₂ crenulation hinges, has been rotated into subparallelism with S₂–S₄ in many places. Partly polarized light. Long edge of photo is horizontal and 14 mm.
4.3. Description and interpretation of \( D_3 \) structures

The third deformation is restricted to uncommon open crenulations of \( S_1 \) and \( S_2 \) in outcrop and in thin section. The small number of measurements (Fig. 8) hinders compilation of a reliable strike-trend line diagram of the same detail as for \( S_1 \) and \( S_2 \). However, the \( S_3 \) pattern fits well with the pattern resolved for \( S_2 \) (Fig. 7) when the two are overlain, and suggests that it is probably similarly complex. An equal-area plot of \( S_3 \) for the study area (net A in Fig. 8) indicates that \( S_3 \) is dominantly gently dipping. \( D_3 \) crenulations of the \( S_2 \) differentiated crenulation cleavage have been observed as inclusion trails within staurolite porphyroblasts.

5. The fourth deformation, \( D_4 \)

No new structural fabrics attributable to \( D_4 \) were recognized in the field. However, in thin
section D₄ has produced microscale kink-like crenulations (Fig. 3) with a steeply to subvertically dipping, NW–SE-trending axial plane (Fig. 9). These crenulations are most notable as overprinting effects of the S₂ differentiation zones (Fig. 3). The pervasive nature of structures associated with D₄ shearing strain is reflected most notably by the microscale geometries of deformed S₁ and S₂, and in the field as zones of reoriented S₁ and S₂ cleavages, which now strike northwest–southeast. During D₄ deformation S₁, including originally sigmoidally folded S₁ in the hinges of D₂ differentiated crenulations, has been straightened out and rotated into an orientation parallel to the axial plane of D₄ crenulations (Figs. 3 and 10) and the macroscopic fold. Consequently, zones of intense D₄ shear are characterized by straightened NW-trending S₁ (Fig. 5) that have been re-used during D₄ shearing in a sense that is synthetic for the macroscopic fold. That is, for re-used S₁ foliations on the southwestern limb of the macroscopic fold, microstructural geometries indicate sinistral D₄ shear on S₁ in plan view.

Similarly, shearing strain associated with re-use of S₁ on the northeast limb accommodated dextral D₄ shear.

Shear sense during D₄ is best demonstrated by examining S₁ and S₂ porphyroblast–matrix geometries and observing the direction of curvature of matrix S₁ and S₂ away from the porphyroblasts (e.g., Fig. 4). Also, decrnelulation of matrix S₂, due to reactivation adjacent to porphyroblasts containing unreactivated S₂, is a good indicator of local shear sense. Bell and Johnson (1992) suggested that the asymmetry of differentiated crenulation cleavages could be used as shear sense indicators. In this study, the Bell and Johnson method was tested to interpret shear senses from such asymmetries. Comparison with porphyroblast–matrix geometries in the same thin sections showed excellent agreement.

 Reactivation (Bell, 1986) of the S₂ differentiated crenulation cleavage was a major process during D₄ deformation. This involved decrnelulation and reorientation of S₁ within D₂ crenulation hinges as a result of antithetic D₄ shear

![Fig. 8. S₃ strike-trend lines for the study area. Equal-area net with contours at 2 standard deviations.](image)
strain, which was partitioned along the $S_2$ differentiation zones. However, in some zones of intense progressive $D_4$ deformation $S_2$ has been re-used, as opposed to reactivated, because it has been rotated into the $S_4$ orientation and has accommodated synthetic $D_4$ shearing strain (Fig. 11). In these zones $S_2$ is parallel to $S_4$ and the axial-planar cleavage to the macroscopic fold is a $S_2$--$S_4$ composite foliation.

The recognition of extensive zones of re-used and reactivated cleavages provides a solution to pre-$D_4$ strike-trend line patterns. By treating the northwest–southeast zones of re-used $S_1$ and $S_2$ foliations as separate entities, equivalent to com-

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**Fig. 9.** Strike-trend lines for axial-plane data for the macroscopic fold. Measurements are a combination of $S_4$, composite $S_2$--$S_4$ (plotted as $S_2$) and composite $S_1$--$S_4$ (plotted as $S_1$). Some locations show more than one measurement, commonly with slightly different orientations. This is due to measurements being taken at closely spaced outcrops, which have been given the same field location on the map. Net (A) is for measurements of $D_4$ microfold axial planes only. Stereo net (B) is for total $S_4$, $S_2$--$S_4$ and $S_1$--$S_4$ and shows the dominant steep northwest–southeast orientation of the axial plane. Lengths of dip bars are inversely proportional to dip value as in Figs. 2, 5, 7, and 8. Equal-area nets with contours at 2 standard deviations.
posite S$_1$–S$_4$ and S$_2$–S$_4$ cleavages, respectively (e.g., Meneilly, 1982; Williams, 1985; Tobisch and Paterson, 1988; Gibson, 1992; Davis and Forde, 1994), during construction of strike-trend lines, realistic patterns were resolved. In these solutions, boundaries were initially drawn around zones of re-used foliations that were identified from microstructural work. Within these zones strike-trend lines for the re-used foliations were constructed in isolation to foliation measurements outside the boundaries. The external foliation measurements were then used to construct independent strike-trend lines across areas where foliations had not been re-used. Truncation of these external strike-trend lines against the zones of re-used foliations, which essentially represent a cross-cutting foliation produced during subsequent deformation, produce the solutions shown in Figs. 5 and 7.

The original geometries and orientations of S$_1$ and S$_2$ are important for determining which foliation undergoes reactivation and which one undergoes re-use. In general, the orientation of S$_1$ was most favourable for re-use during D$_4$ shear. This is supported by the development of relatively more extensive zones of re-used S$_1$ relative to re-used S$_2$ (compare Figs. 5 and 7).

**Growth of porphyroblasts and their relative timing.** Within the Robertson River Metamorphics porphyroblast growth was originally interpreted as being a result of the regional D$_2$ event (Bell and Rubenach, 1983). However, they recognized that their S$_1$ was locally preserved in some porphyroblasts as a differentiated crenulation cleavage (T.H. Bell, pers. commun., 1986). Consequently, it can be inferred that earlier deformations were present prior to D$_1$ but could not be resolved from subsequent events due to the generally high intensity of D$_1$. Davis (1986) interpreted growth to have occurred in the D$_4$ event of his deformation history and consequently correlated this event (e.g., Fig. 3) with the D$_2$ event of Bell and Rubenach (1983). However, at this stage it is still uncertain how the foliations correlate between this area and that mapped by Bell and Rubenach (1983) because of the variation in intensity of deformations between them.

No evidence for diachronous porphyroblast growth relative to deformation was noted. In both areas the sequence of progressive porphyroblast

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Fig. 10. Photomicrograph and line diagram of composite S$_1$–S$_4$ foliation. D$_4$ deformation has straightened S$_1$ and D$_4$ shear has been partitioned along it such that it folds and commonly cross-cuts S$_2$. The S$_1$–S$_4$ cleavage is axial-planar to D$_4$ microfolds of the S$_2$ differentiation zones. Plane polarized light. Long edge of photo is 14 mm.
growth, in decreasing order of age, was biotite, garnet, biotite, staurolite, andalusite.

6. Discussion

Fig. 12 summarizes the microstructural geometries observed on the southwest limb of the macroscopic D₄ fold and relates them to progressive D₄ deformation responsible for the development of the fold. Porphyroblast growth is depicted in Fig. 12 for garnet and staurolite only as these consistently preserve well-developed inclusion trails. These geometries indicate that the processes operating during D₄ folding represent interaction between reactivation and re-use of pre-D₄ foliations, including bedding (cf. Phillips and Key, 1992).

Shortening in the initial stages of D₄ deformation would have deformed the S₂ differentiated crenulation cleavage into open folds. Early porphyroblast growth, indicated by garnet in Fig. 12B, occurred at this time. With continued deformation the deformation pathway conceivably followed two routes.

Route 1. In the limb regions of D₃ folds the S₂ cleavage was rotated into an orientation favourable for accommodating the progressive
shearing component of reactivation in a sense that was antithetic relative to the bulk shear producing the macroscopic D_4 fold (Fig. 12D). Staurolite growth then occurred and preserved an orientation of S_2 that was rotated relative to that in the garnets. In the staurolite porphyroblasts the hinge regions between S_2 differentiation zones are commonly slightly thinner and tighter than those in the garnets. This is interpreted to be a result of the localization of subsequent D_4 shearing strain along on S_2 (e.g., Fig. 11), which caused dissolution of quartz from between the mica microlithons (e.g., Bell et al., 1986; Hammond, 1987; Williams, 1994). S_2 continued to be rotated toward the S_4 axial plane while accommodating reactivation, thereby causing unfolding of earlier
formed D₄ folds (Figs. 12D and 12E). Continued D₃ shortening also synchronously rotated S₁ into the S₄ orientation and D₄ was then accommodated by shear along S₃ (sketch to left of Fig. 12D). Locally, where shear on S₁ dominated, S₂ acted as a passive marker and zones of shearing strain accommodated by S₁ cross-cut it.

On F₂ short limbs, antithetic shear associated with reactivation would have been relatively less important than synthetic shear parallel to S₄. Rotation of S₂ necessarily meant synchronous rotation of S₃, commonly into an orientation parallel to S₄. This led to formation of a composite S₁–S₄ cleavage (e.g., Figs. 12E and 12G) in areas where antithetic shearing associated with reactivation was relatively less intense than synthetic shearing during D₄ re-use of S₁. On the long limbs of F₂ folds, minor D₄ re-use of S₁ would have occurred in the strain shadows of porphyroblasts where shear during reactivation was unable to operate (Fig. 12E).

**Route 2.** In zones of relatively more intense D₄ deformation, synthetic shear dominated and only minor antithetic reactivation shear occurred during rotation of both S₁ and S₂ toward S₄. Whether strain partitioning caused synthetic D₄ shear to be initially accommodated by S₁ or S₂ depended on their original orientations. For example, if S₂ was originally in a closer orientation to S₄ than S₁, then S₂ would have initially been re-used by D₄. Continued shear on the S₂–S₄ composite cleavage then rotated the S₁ cleavage into sub-parallelism with S₄ also, and produced a composite S₁–S₂–S₄ fabric axial plane to the D₄ fold (Figs. 12F and 12H). Bedding on D₄ fold limbs was also an actively shearing surface during the processes of both re-use and reactivation (Fig. 13; e.g., Wilkins, 1993). The presence of D₂ crenulation hinges in porphyroblasts within phyllosilicate-rich zones containing intense bedding-parallel cleavage indicates that this geometry is not the result of the D₂ crenulations forming only in the quartz-rich layer.

The importance of foliation re-use during D₄ can be appreciated by noting the pervasive nature of D₄ across the whole area. Fig. 9 is a combined plot of S₄ and pre-D₄ foliations that were re-used by D₄. The pre-existing orientations of these surfaces, combined with local increase in intensity of D₄ strain, were important factors in determining which fabrics accommodated D₄ shear. Although areas of foliation re-use cover much of the fold, individual areas generally contain only one re-used foliation, thereby suggesting that the pre-folding orientation of the fabric that was subsequently re-used was the dominant control. However, in zones of intense D₄ strain all pre-existing surfaces, including bedding, have been rotated into S₄ and re-used.

### 6.1. The role of lithological variation

Lithological variation clearly controls strain partitioning and localization at all scales (e.g., Bell, 1986; Alsop, 1993, 1994). The finely laminar nature of the graphitic schist horizons in the area was important for accommodating large components of progressive shearing strain, particularly that associated with reactivation (see below; Fig. 13). A consequence of this is the preservation of crenulations, which have been destroyed in the matrix due to intense shearing along bedding, as inclusion trails. Conversely, partitioning of variable amounts of the progressive shearing component of deformation along different lithological horizons has resulted in the preservation of cleavages in layers that were not reactivated or re-used. This is interpreted to be a result of (a) variations in competency and phyllosilicate content, and (b) switching of zones of progressive shearing component of deformation along different lithological horizons has resulted in the preservation of crenulations in rock containing relative thin alternating beds of highly variable phyllosilicate content, well-developed cleavage refraction has resulted. This has produced a geometry where an apparent crenulation cleavage has developed parallel to laminar bedding (e.g., Bell, 1986, fig. 13). Phyllosilicate-rich beds, which have accommodated intense shearing strain, are
commonly planar at the scale of tens of centimetres and display intense bedding-parallel foliations. Adjacent beds that are relatively phyllosilicate-poor, experienced less shearing strain and locally preserve pre-D_4 cleavages at a moderate angle to bedding (Fig. 13).

Geometries that demonstrably developed due to the controls of lithology are best seen at the micro- and mesoscale. However, map-scale geometries of S_0 suggest that these controls operated at the scale of many 100's of metres also. In Fig. 2 the bedding strikes immediately adjacent to the equal-area net show orientations that are consistently anticlockwise of the interpreted strike-trend lines. The strike-trend lines have been interpreted from aerial photographs and the geometry shown is possibly due to preservation of early (pre-D_4 reactivation) bedding geometries internal to lithological boundaries that have been reactivated by bedding-parallel shear. That is, the measured strikes were possibly taken from folded horizons, which were internal to the layer boundaries that accommodated relatively more intense D_4 shearing strain. Consequently, the zones where strike measurements were taken, are interpreted to have experienced relatively less shearing strain and preserved their early D_4 geometries. This explanation conceivably applies to the similar geometries displayed by the S_1 and S_2 cleavages in Figs. 5 and 7.

6.2. Implications of large-scale foliation "reworking"

The structural history and processes operating during folding could not have been resolved without conducting the detailed microstructural study in conjunction with strike-trend line analysis (e.g., Reinhardt and Rubenach, 1989; Lang and Dunn, 1990; Johnson, 1992; Davis and Forde, 1994). Microstructural examination proved very important for identifying the effects of D_4. Without microstructural work, zones of what appeared to simply be intense S_1 or S_2 in the field, could not be reliably identified as composite structures produced mainly in D_4. Consequently, initial field mapping suggested that, despite the production of a macroscopic antiform, D_4 did not produce any easily recognizable mesoscopic structures in the field. The orientations of fine-scale, generally microscopic, S_4 cleavages (e.g., Figs. 3 and 10) could only be reliably resolved by measuring them in thin section. Consequently, microscale study was the only way to correctly structurally analyse the macroscale geometry, especially in terms of strike-trend line patterns.

Alternative structural solutions are possible if strike-trend lines are generated in isolation of detailed microstructural work. Given the presence of macroscale structural lineaments (faults in Figs. 1 and 2) on aerial photographs and common small-scale faults, a possible strike-trend line pattern could have been constructed by invoking the presence of faults separating zones of folded and nonfolded fabrics. Johnson and Duncan (1992) demonstrated how fault structures can be identified in complexly deformed terrains via the use of detailed geometric analysis. However, unless lithological mismatch is obvious (e.g., figs. 15 and 16 of Johnson and Duncan, 1992), such an analysis is largely unconstrained if detailed structural work is not done to test the possibility of foliation re-use/reactivation in zones of foliation mismatch. If detailed microstructural work had not been done in the present study, the presence of a NW–SE-striking S_4 axial plane and a rough estimate of its orientation could still have been inferred from the geometries of folded earlier structures. However, fault solutions would have been necessary between these zones. In the present study area, foliations are continuous between the zones of folded and non-folded fabrics despite dramatic changes in orientation over short distances. The best tool for fault identification would seem to be the recognition of an associated mismatch in lithological layering (e.g., figs. 15 and 16 of Johnson and Duncan, 1992).

The successive growth of porphyroblasts of different compositions preserved the progressive development of D_4 fabrics and enables the microstructural relationships between the inclusion trails and the matrix schistosity to be used to identify the critical role of foliation “reworking” (e.g., Fig. 12). It is noteworthy that, although D_4 was an event intense enough to form macroscopic folds of all pre-existing surfaces, it very rarely
produced its own axial-plane foliation. Instead, the axial-planar fabric is generally a pre-existing foliation that has been straightened out (and sometimes attenuated) such that deformation is accommodated by the pre-D$_4$ surfaces. Although D$_4$ structures are present as micro-crenulations, no other axial-plane microstructures were produced. In addition, many of the crenulations formed early in the D$_4$ event have been destroyed during foliation reworking in the later stages of this deformation. As a result, earlier developed structures (that is, S$_1$ and occasionally S$_2$) were actually emphasized during the D$_4$ deformation. Consequently, without detailed and extensive microstructural work it is very easy to miscorrelate fabrics and misinterpret macroscale geometries in multiply deformed areas, thereby leading to problems in establishing correct deformation histories and geometric relationships.

7. Conclusions

Four deformations of different intensity have affected the rocks of the study area. D$_4$ produced major modification of pre-existing structures and fabrics through reactivation and re-use of pre-S$_4$ foliations and bedding. Progressive growth of porphyroblasts in D$_4$, especially garnet and staurolite, records progressive development of microstructures produced during development of a macroscopic fold. The re-use of pre-S$_4$ foliations is a result of their pre-existing orientations and macroscale partitioning of D$_4$ deformation that produced zones of locally intense foliation reorientation and reworking. The use of faults to justify strike-trend line solutions for areas of foliation mismatch may not be valid if foliation re-use is not taken into account.

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