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Multiple foliation development during thrusting and synchronous formation of vertical shear zones

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Abstract—Three orthogonal foliations developed during large-scale N–S thrusting in the central portion of the Mount Isa Block, Australia. Two of these foliations, which are well preserved in their original orientations in porphyroblasts of pelitic schists but considerably affected and commonly destroyed in the schist matrix due to the effects of subsequent deformation and metamorphism, formed synchronously and have a common stretching lineation, which is near-horizontal and trends N–S. One foliation formed near-horizontal and the other near-vertical, striking N–S. Both developed during N–S-directed thrusting, with the N–S vertical foliation accommodating sinistral differential displacement between the thrust belt to the west and that to the east. The third foliation which dips steeply to the north and strikes E–W, formed during N–S shortening of the thrust belt and tends to overprint the other foliations formed in the same orogeny.

The N–S vertical foliation is well preserved within a narrow belt of gneissic rocks (called the Wonga–Duchess Belt) that also locally contains the subsequently folded remains of the foliation that formed near-horizontal. This belt separates multiply thrust-repeated beds to the west from large-scale, apparently less repetitive thrusts to the east. The direction of thrusting appears to change across this belt from N to S on the west to S to N on the east. The differential deformation to either side of the belt was taken up by sinistral shear along this belt. Numerous related, but smaller-scale vertical shear zones occur up to 3 km away to either side of this narrow zone. The primary vertical foliation within the Wonga–Duchess Belt appears to have formed during transform-like faulting by progressive inhomogeneous simple shear with no component of orthogonal shortening.

INTRODUCTION

WITHIN the Mount Isa Block in north-eastern Australia lies a 3–4 km wide belt extending at least 140 km N–S (Fig. 1), which contains an intensely developed, near-vertically dipping, N–S-striking foliation as well as the folded remains of a formerly shallowly dipping foliation. This belt, called the Wonga–Duchess Belt, forms a structural high relative to the adjacent metavolcanic and metasedimentary rocks (Tewinga Group, Mary Kathleen Group) in the synclines on either side. The core of the Wonga–Duchess Belt consists largely of gneissic granitoids and subordinate metadolerites.

What has puzzled geologists for some time is the presence of two elongation lineations developed in the main, near-vertically dipping foliation plane (cf. Holcombe & Fraser 1979, "Shinfield Zone" of Passchier 1986). One of these lineations is consistently oriented and plunges down the dip of the foliation, whereas the other varies from horizontal to steeply plunging to either side of the down-dip lineation. The variably oriented lineation was regarded by Holcombe & Fraser (1979) as an old intersection lineation. However, our work, and further work by Holcombe *et al.* (1991) has shown that this lineation, depending on whether or not the rocks contain a pre-existing foliation, is either a combined intersection lineation and stretching lineation, or just a stretching lineation (the latter being the case in many granite gneisses), which have been overprinted by a younger deformation.

The geology changes across the Wonga–Duchess Belt with multiple repeats of stratigraphic units to the west (Fig. 1) resulting from N to S thrusting (Bell 1983, 1991, Loosveld & Schreurs 1987) and fewer, larger-scale thrusts occurring to the east (Bell unpublished report). The Wonga–Duchess Belt could therefore be a major ductile tear fault (cf. Dahlstrom 1970) accommodating differential lateral transport of thrust sheets to either side. As Loosveld (1989) presented evidence for northerly directed thrust movement in the eastern Mount Isa Block, the Wonga–Duchess Belt could also be a transform-fault-like structure with opposite directions of thrusting on either side.

Recognition of the timing and significance of the N–S-striking, near-vertical foliation and the early-formed lineation is complicated by the presence of a younger regional deformation, D_2, the axial planes of which are also oriented N–S (Bell 1983, 1991, Winsor 1986, Reinhardt 1992, in press). In general, deformation and metamorphism during D_2 appears to have erased most of the D_1 microstructures in the rocks outside the Wonga–Duchess Belt, except within porphyroblasts that grew early in D_2, or in zones of low strain during D_2, such as hinges of D_2 folds.

Obliteration of early developed foliations during subsequent deformation is a major problem in orogenic belts because it inhibits the unravelling of the deformation history (e.g. Bell 1986, Bell & Johnson 1989, Johnson 1990a,b). However, overgrowth of early foliations by porphyroblastic minerals commonly appears to preserve these fabrics in the orientations in which they formed provided subsequent deformation is ductile (e.g. Fyson 1980, Bell 1985, Hayward 1990, Johnson

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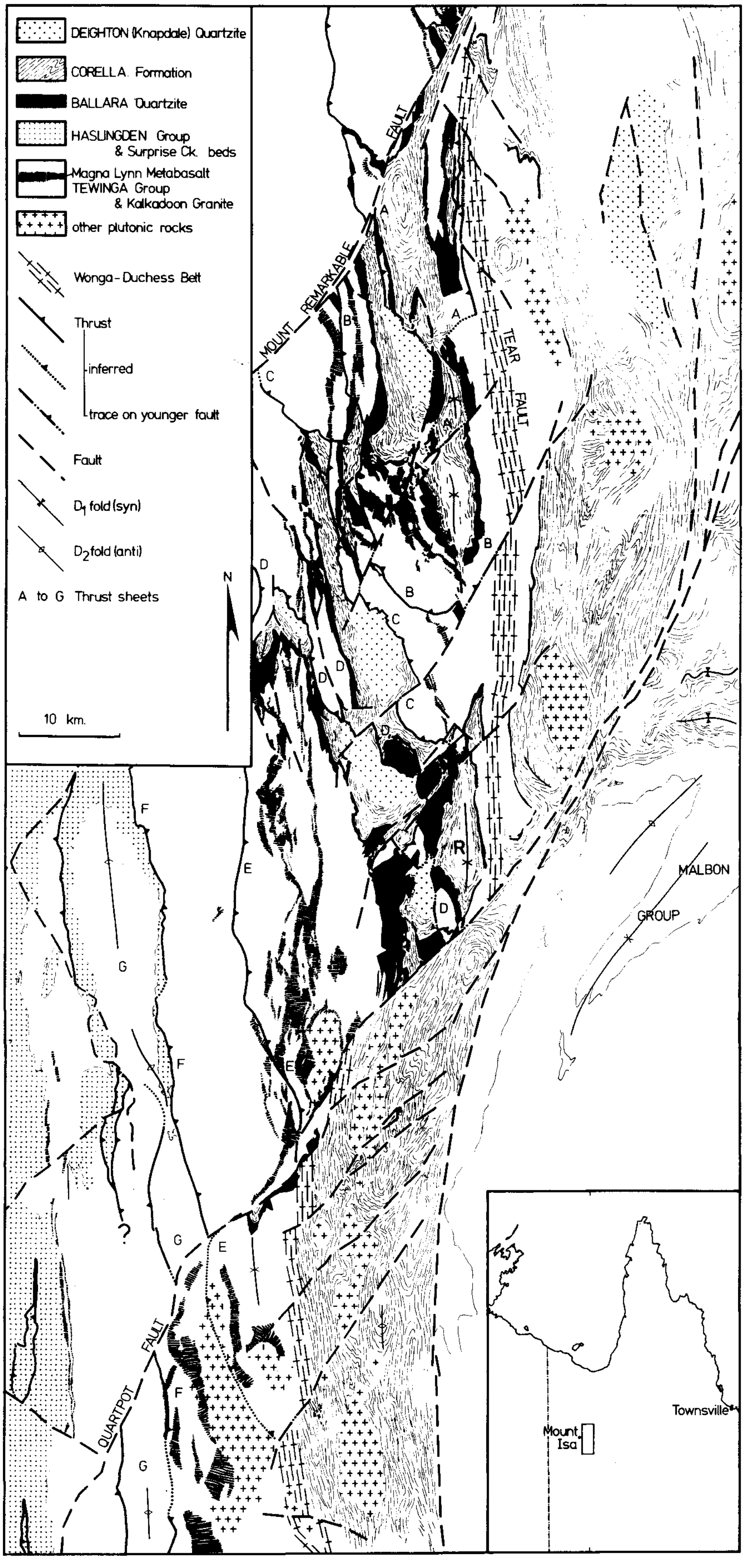


Fig. 1. Interpretative map of the central Mount Isa Block showing the change in geometry of major thrusts across the Wonga–Duchess Belt. Seven major thrust sheets (A–G) are present to the west of the Wonga–Duchess Belt, whereas only one major thrust sheet is apparent to the east. R, Rosebud Syncline (area covered by Fig. 2).

1990a,b). Thus, the study of porphyroblast inclusions is one of the most useful methods of deciphering the structural–metamorphic histories of polydeformed terrains. Abundant porphyroblasts containing pristine D_1 inclusion trails occur in amphibolite-grade pelitic rocks adjacent to the Wonga–Duchess Belt (Reinhardt & Rubenach 1989). We investigated these internal foliations in conjunction with mesoscopic structural relationships to see if they shed light on the origin of the foliation–lineation relationships and the macrostructure.

STRUCTURAL HISTORY

The structural history of the western and central Mount Isa Inlier involves three major contractional deformation phases which affected the Mid-Proterozoic cover sequences. Local patches of previously deformed and metamorphosed basement are also preserved (Page & Blake 1988). The deformations of the cover sequences have been dated west of Mount Isa within the Sybella Granite using Rb–Sr whole-rock techniques combined with U–Pb on zircon for a control on the emplacement age (Page & Bell 1986). The first deformation, D_1 (1610 Ma), produced thrusts and locally a pervasive, shallowly dipping foliation during N–S shortening (Bell 1983, 1991). The structural character of these thrusts varies from knife-sharp contacts to foliated breccias to mylonitic gneisses depending on location within the tectonic pile (e.g. Bell 1991).

The second deformation D_2 (1545 Ma) produced regional folds about steeply dipping, N–S-oriented axial planes, and a generally well developed schistosity S_2 with a near-vertical mineral elongation lineation L_2^2 during E–W shortening (e.g. Winsor 1986, Holcombe *et al.* 1991, Reinhardt 1992, in press). The third, D_3 (1515 Ma) produced local, generally small-scale folds and crenulations about NNW–SSE-oriented axial planes (Winsor 1986, Bell 1991, Reinhardt in press). In the central part of the Mount Isa Block, the main regional metamorphism occurred during D_2, reaching about 600–650°C and 4 kbar (Reinhardt & Rubenach 1989, Reinhardt 1992, in press, N.H.S. Oliver personal communication).

To the west of the Wonga–Duchess Belt, the presence of D_1 thrust sheets is evident from the multiple repetition of stratigraphic units (Fig. 1) (cf. Bell 1983, 1991, Loosveld & Schreurs 1987). Immediately adjacent to the Wonga–Duchess Belt, the macroscale, pre-D_2 structures become very complex. Within the Rosebud Syncline, small-scale thrusts and near-vertical shear zones are common and can still be recognized despite the strong D_2 overprint (Fig. 2). However, only few of the D_1 thrusts visible on the western side of the map are folded about the large-scale D_2 Rosebud Syncline such that they re-appear on the eastern limb. The remainder converge to the east with near-vertical shear zones that dominate the structure on the eastern limb (Figs. 2 and 3). The Wonga–Duchess Belt cuts the eastern edge of

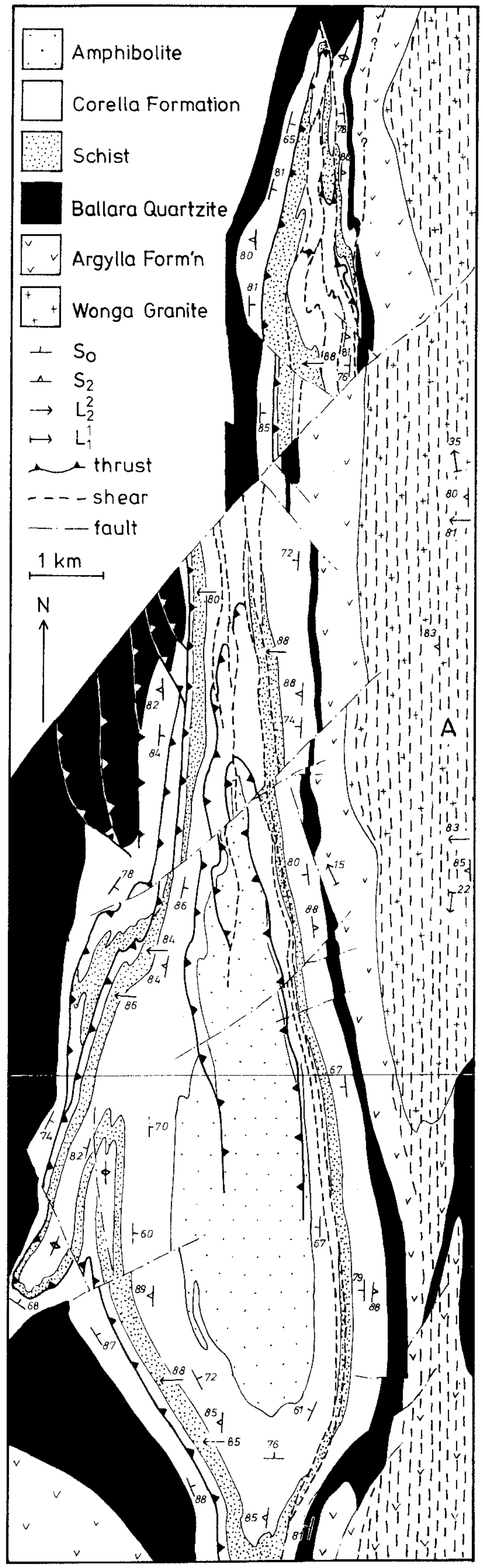


Fig. 2. Map of the structural relationships in the Rosebud Syncline (from Reinhardt 1987) and the immediately adjacent Wonga–Duchess Belt. Note the cessation of thrusts against near-vertical N–S shear zones in the hinge region and on the eastern limb. The location marked A is where the photograph shown in Fig. 6(c) comes from. Corella Formation (calc-silicate rocks, calcareous schists, marble, metapelitic schists) and Ballara Quartzite constitute the Mary Kathleen Group; the underlying Argylla Formation (felsic metavolcanics) forms the uppermost member of the Tewinga Group.

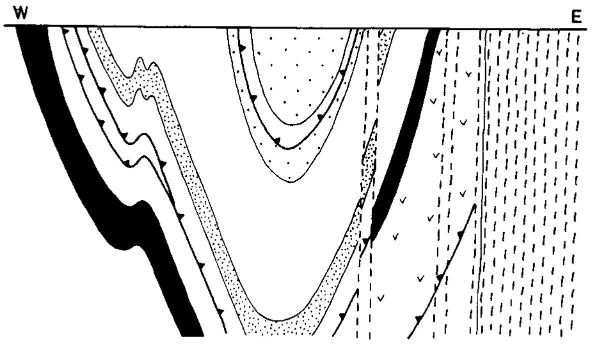


Fig. 3. Cross-section across the Rosebud Syncline along the line indicated in Fig. 2. Note the cessation of thrusts from the western limb of the syncline against steep shear zones along the eastern limb. Vertical scale = horizontal scale.

this area with the same geometry as these smaller-scale shear zones, truncating the larger-scale thrusts (Fig. 1). These geometrical relationships suggest that each of the near-vertical shear zones accommodated differential horizontal displacement to either side during thrusting. Differential lateral movement is also indicated by the presence of ramps in the western limb of the Rosebud Syncline which have no counterparts at the equivalent stratigraphic level on the eastern limb (Fig. 2).

The synchroneity of thrusts and near-vertical shear zones is strongly supported by zircon U–Pb and whole-rock Rb–Sr ages obtained from gneissic granitoids within the Wonga–Duchess Belt, containing a near-vertical N–S-striking foliation (hereafter referred to as S_{1v}). The Wonga metagranite has SHRIMP ion-microprobe U–Pb ages from zircons in the range 1730–1760 Ma (Page 1990) suggesting this was the age of emplacement. However, Rb–Sr whole-rock ages from these sites range from 1621 to 1629 Ma (Page 1978). The S_{1v} at these dating sites contains a well-developed stretching lineation (L_1^1) which varies in orientation through the horizontal along the length of the Wonga–Duchess Belt, about a generally very weak down-dip stretching lineation. The 1621–1629 Ma Rb–Sr whole-rock ages of this near-vertical foliation correlate with the regional D_1, suggesting that the Rb–Sr ratios have not been reset by the younger 1545 Ma D_2 event with the steep stretching lineation (L_2^2). Hence, within those gneisses that were dated, the effects of this younger deformation have not been significant, contradicting the interpretation of Holcombe *et al.* (1991) that all the steeply dipping foliation is a product of isoclinal folding of a previous flat-lying foliation (S_{1h}, see also below) during the regional D_2. An intense deformation associated with isoclinical folding during D_2 would have reset the Rb–Sr whole-rock ages in these granitic gneisses to the D_2 age based on the results of Page & Bell (1986) from the Sybella Granite to the west (e.g. Black *et al.* 1979). We therefore conclude that the near-vertical foliation in the gneisses of the Wonga–Duchess Belt originated as a near-vertical D_1 structure which now shows a relatively weak D_2 overprint on the same S surface ('$S_{1v,2}$').

Between the Rosebud Syncline and the Wonga–Duchess Belt, variable intensity of S_2 development in different rock types and the pervasive metamorphic overprint make it difficult to detect the presence of D_1 shear zones, unless they cut and displace lithological boundaries in a disruptive fashion (Fig. 2). Since S_2 has the same orientation as the S_{1v} foliation in these zones, the orientation of the stretching lineation is critical for distinguishing between these two foliations.

STRETCHING LINEATION VARIATION BETWEEN S_{1h}, S_{1v} AND S_2

To the west of the Wonga–Duchess Belt, D_1 thrusting was directed N–S. This is based on the N–S orientation of D_1 stretching lineations preserved in regions of near-horizontal S_0 and near-horizontal mylonitic foliation (S_{1h}) in both broad and tight hinges of D_2 folds around and to the west and northwest of Mount Isa (Bell 1986, 1991), as well as the geometry of imbricate and lateral ramp development in this portion of the Mount Isa Block (Bell 1983, 1991, Loosveld & Schreurs 1987, Reinhardt in press). Consequently, prior to the rotational effects of D_2, stretching lineations (L_1^1) on shallowly dipping mylonitic foliations (S_{1h}) associated with thrusting, should have a N–S orientation. Similarly, stretching lineations (L_1^1) forming on near-vertical N–S oriented shear zones (S_{1v}) that accommodated any differential lateral displacement during thrusting, should have near-horizontal orientations.

West of the Wonga–Duchess Belt, the subvertical stretching lineation L_2^2 that formed during D_2 dominates and is commonly the only one seen in outcrop (Reinhardt 1992, in press). Only at locations where the effects of D_2 have not been too strong, an older L_1^1 may still be preserved. Figure 4 shows a rock in which the effects of both D_1 and D_2 are preserved because development of S_2 was not sufficiently intense to destroy the stretching lineation produced during D_1. Consequently, this rock contains two stretching lineations on the one foliation surface. S_{1v} was simply intensified due to development of S_2 with the same orientation.

As mentioned previously, within the Wonga–Duchess Belt, two stretching lineations are commonly preserved on the near-vertical, N–S-striking S_{1v} (Figs. 5 and 6a & b) (see also fig. 3b in Passchier 1986, and fig. 8 in Holcombe *et al.* 1991); one is near-vertical and identical to L_2^2, whereas the other varies in plunge from north to south through the horizontal. Holcombe & Fraser (1979) considered this variably plunging lineation to be an intersection lineation. This is the case in some locations, where zones of shallowly dipping S_{1h} had developed, although it commonly has a parallel or subparallel mineral elongation lineation (now also recognized by Holcombe *et al.* 1991). However, in widespread outcrops of gneissic granite that never contained any S_{1h}, this L_1^1 lineation is defined by elongate minerals, mineral aggregates and ellipsoidal xenoliths. In bedded rocks close to the Wonga–Duchess Belt, such as the pelitic schists and Argylla Formation in Fig. 2, this variably

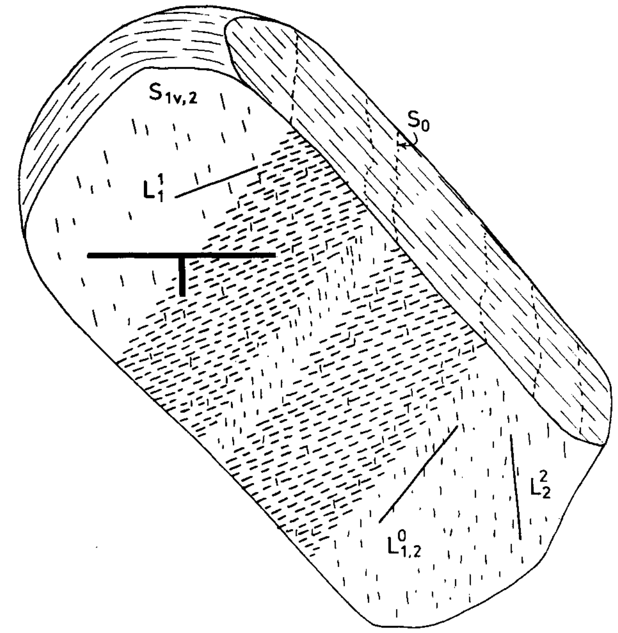


Fig. 4. Sketch of a quartz-rich pelitic schist from the eastern limb of the Rosebud Syncline containing both mineral elongation lineations L_1^1 and L_2^2 on the S_2 surface. As S_2 lies parallel to the pre-existing S_{1v}, the foliation plane is here referred to as '$S_{1v,2}$'. Bedding (S_0) is also present in this specimen, and the intersection lineation $L_{1,2}^0$ on the S_2 surface lies oblique to both mineral elongation lineations. The L_1^1 lineation shows up best in the more micaceous beds. From the orientation mark on the specimen (88W/358) it can be seen that L_1^1 is plunging north at 22°. Shorthand terminology of mineral elongation lineations and intersection lineations after Bell & Duncan (1978); the super- and subscripts of the intersection lineations refer to the intersecting S surfaces.

plunging mineral elongation lineation may also be oblique to the bedding–cleavage intersection when no other foliation but a near-vertical one is present (Fig. 4). Clearly, in these locations, it is just a stretching lineation developed on S_{1v}.

During heterogeneous strain associated with development of S_2 parallel to the pre-existing S_{1v}, the originally horizontally oriented L_1^1 was variably rotated towards L_2^2 in a similar manner to rotation of fold axes within their axial planes (cf. Sanderson 1973). This is confirmed by the similarity between the L_1^1 distribution (Fig. 5) and

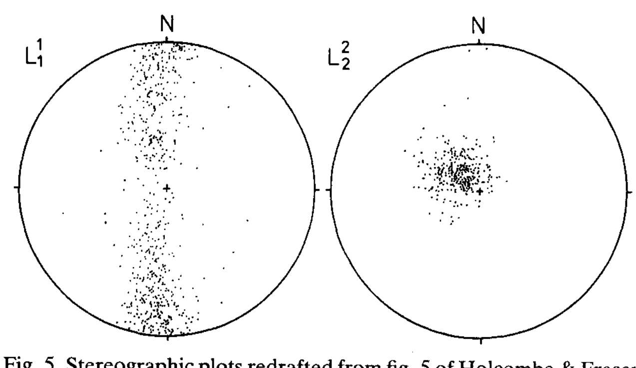


Fig. 5. Stereographic plots redrafted from fig. 5 of Holcombe & Fraser (1979) showing L_1^1 and L_2^2. The L_1^1 data include some intersection lineations, but these have the same distribution as L_1^1 in rocks containing no other foliation but the near-vertical S_{1v} (R. J. Holcombe and P. J. Pearson personal communication 1988).

the orientation of F_2^0 fold axes in the Rosebud Syncline which form a N–S girdle in a stereo net, due to rotation in the S_2 plane towards L_2^2 (Reinhardt 1992, in press). Figure 5 shows that the variation in plunge of L_1^1 is uniformly distributed to both the north and south about L_2^2 within $S_{1v,2}$, and hence L_1^1 must have been approximately horizontal prior to D_2 (see also Holcombe *et al.* 1991).

As one approaches the Wonga–Duchess Belt from the west, visible remains in outcrop of the D_1 stretching lineation (L_1^1) first appear about 1 km from its boundary within the eastern margin of the Rosebud Syncline (Fig. 2). This is also the area where remains of near-vertical D_1 shear zones become obvious through their disruptive effect on stratigraphy. Most commonly, however, the development of a pervasive S_2 in the metasedimentary rocks adjacent to the Wonga–Duchess Belt destroyed D_1 structures in the rock matrix, and remains of S_{1h}, S_{1v} and L_1^1 are largely confined to porphyroblasts (see below).

SHEAR SENSE DURING D_1 ALONG S_{1v}

Although S_{1v} within the Wonga–Duchess Belt is mylonitic, and larger feldspar grains are preserved within a generally finer-grained matrix in mylonitized Wonga Granite, no consistent shear sense could be determined from the S and C plane relationships, as both symmetries are always present. However, a very consistent shear sense for movement on S_{1v} can be obtained mesoscopically from mafic xenoliths elongate parallel to L_1^1 (Fig. 6a), which are common within the mylonitic gneissic granites. This shear sense is always sinistral and stays constant for 1.5 km perpendicular to the strike of the Wonga–Duchess Belt at location A in Fig. 2 where there is almost continuous outcrop of this xenolith-bearing gneissic granite. It is preserved by a slight angular discordance between the elongation of the xenoliths and S_{1v} (Fig. 6c). The xenoliths were probably aligned by flow during granite emplacement in an orientation that originally lay at a high angle to the subsequently formed S_{1v}, and although the strain during D_1 was very high, it was unable to rotate them into complete alignment with S_{1v}, especially when viewed on rock faces oblique to L_1^1.

The lack of any consistency in the smaller-scale shear-sense indicators such as S and C planes is a consequence of the overprinting effects of D_2. The Wonga–Duchess Belt lies effectively in a large antiformal hinge of a D_2 fold as macroscopic D_2 synclines occur to either side. Consequently, the deformation during D_2 was essentially coaxial in this belt. Because S_2 formed exactly parallel in orientation to the pre-existing near-vertical S_{1v}, the overall coaxial character in this region during D_2 on a small scale has destroyed any consistency of asymmetry previously present in the geometry of the foliation around large feldspars. However, the strain during D_2 was insufficient to affect the larger-scale asymmetry of the elongate xenoliths relative to S_{1v}. This also explains the conflicting quartz *c*-axis diagram asymmetries with other shear criteria observed by Holcombe *et al.* (1991).

FOLIATIONS AND LINEATIONS PRESERVED AS INCLUSION TRAILS IN PORPHYROBLASTS

The schists of the Corella Formation west of the Wonga–Duchess Belt contain multiple generations of prophyroblasts. The systematic variation of the inclusion trail geometry has been used to establish the timing of mineral growth relative to progressive deformation. The mineral sequence obtained is consistent with a prograde, syn-D_2 sequence of metamorphic reactions up to middle amphibolite facies conditions (Reinhardt & Rubenach 1989, Reinhardt 1992).

For the pre-D_2 deformation history, the early-D_2 porphyroblasts proved to be critical, as they contain D_1 fabrics with only incipient overprinting by D_2, or no overprint at all. Syn-D_2 growth of the early andalusite and cordierite generations is indicated by the preservation of curvatures of S_1 at the porphyroblast rims towards the main S_2 foliation of the schist matrix (Reinhardt & Rubenach 1989, Reinhardt 1992; cf. Bell *et al.* 1986). Remains of S_1 are also found in porphyroblast embayments and strain shadows, again showing continuity with the S_2 foliation. Millipede microstructures indicate a deformation history during D_2 of progressive, bulk, inhomogeneous shortening which was initially coaxial (e.g. fig. 7 in Reinhardt & Rubenach 1989; cf. Bell 1981).

The S_1 inclusion trail orientation is commonly constant across a thin section, even though there are no remains of this earlier-formed foliation preserved in the rock matrix. Hence it was possible to measure the three-dimensional orientation of the inclusion fabrics in oriented specimens by cutting three spatially-oriented orthogonal sections. The combination of differently oriented sections also allowed us to distinguish between linear and planar fabrics. The accuracy of the data is estimated at $\pm 25°$, taking into account measurement inaccuracy in the field and laboratory, and the variation of foliation orientation on the scale of a sample. Small angles between the S_1 traces of different porphyroblasts have been observed in some samples, and may be due to incipient crenulation of S_1 late in D_1 (see below) or early in D_2.

The inclusions in early-D_2 porphyroblasts are generally much finer-grained than the S_2-foliated schist matrix. The anisotropy of the inclusion fabrics is defined by the alignment of platy minerals (biotite, hematite, ilmenite) and/or preferred orientation of elongate quartz grains. It should be noted that the anisotropy of the D_1 fabrics is almost certainly not as strong as it originally had been. During the cordierite- and andalusite-forming reactions, chlorite, much white mica and also some quartz had been used up (Reinhardt 1992). Of these minerals, only quartz remained in amounts large enough to conserve the old D_1 microstructures. Also, the degree of inclusion fabric anisotropy varies between different samples. Many specimens have inclusion fabrics which are anisotropic in all sections, other inclusion fabrics show no anisotropy at all. This contrast in pre-D_2 rock strain indicates deformation partitioning during D_1.

Amongst the distinctly anisotropic pre-D_2 fabrics, three main groups were identified within porphyroblasts (Figs. 7–10). These are: (1) a near-vertical N–S foliation S_{1v} with a horizontal stretching lineation (Fig. 7); (2) a near-horizontal foliation S_{1h} with a N–S-oriented stretching lineation (Fig. 8); and (3) a weakly developed, E–W-striking, steeply N-dipping foliation $S_{1E\text{–}W}$, for which we were unable to determine a stretching lineation (Figs. 8d & e and 9). The combination of S_{1v} with $S_{1E\text{–}W}$ and of S_{1h} with $S_{1E\text{–}W}$ is very common. Rarely, all three foliations are preserved within the same porphyroblasts (Fig. 9b). In the examples shown here, no trace of S_2 or L_2^2 is visible in the porphyroblast cores, but the matrix around the porphyroblasts is a pervasive S_2–L_2^2 fabric. The S_2 and L_2^2 orientations shown in Figs. 7–9 are readings taken on the outcrop or from the oriented specimens.

As can be seen from the block diagrams in Figs. 7–9, the determination of *S* and *L* in three orthogonal sections is unequivocal. If an *S*–*L* fabric is present, the anisotropy must be most pronounced in a section normal to *S* and parallel to *L*, compared with all other sections (cf. Figs. 7a & b vs 7c & d; Fig. 8c vs 8a & b). Furthermore, platy minerals will be aligned primarily in the foliation plane (Figs. 7b & d).

Apart from their orientation, S_{1v} and S_{1h} are texturally very similar, and the stretching lineation on both foliations has the same orientation. $S_{1E\text{–}W}$ is commonly defined by preferred alignment of scattered biotite inclusions (Fig. 8d) which overgrew and cross-cut both S_{1h} and S_{1v}. Rarely, $S_{1E\text{–}W}$ is present as a crenulation cleavage (Fig. 9). The common origin of the biotite alignment and the crenulation cleavage is evident from the occurrence of such biotites within, and parallel to, the originally mica-rich lithons of the differentiated crenulation cleavage.

The geometric relationships between the various foliations are shown in Fig. 10. S_{1v} is sub-parallel to S_2, but is readily distinguished from this later foliation by its sub-horizontal stretching lineation that lies at nearly 90° to L_2^2, as well as the fact that it is overprinted by $S_{1E\text{–}W}$, which is in turn overprinted by S_2; both S_{1v} and $S_{1E\text{–}W}$ are commonly destroyed in the matrix.

SIGNIFICANCE OF FOLIATION–LINEATION RELATIONSHIPS

We propose S_{1h}, S_{1v} and $S_{1E\text{–}W}$ are three distinct foliations whose orientations in space closely reflect the original geometry of the D_1 fabrics. The overprinting relationships, the relatively uniform orientation of S_1 and L_1^1 in the porphyroblasts of any one sample, and the consistent S_{1h}–S_{1v}–$S_{1E\text{–}W}$–L_1^1 geometries in the study area are evidence against porphyroblast rotation during

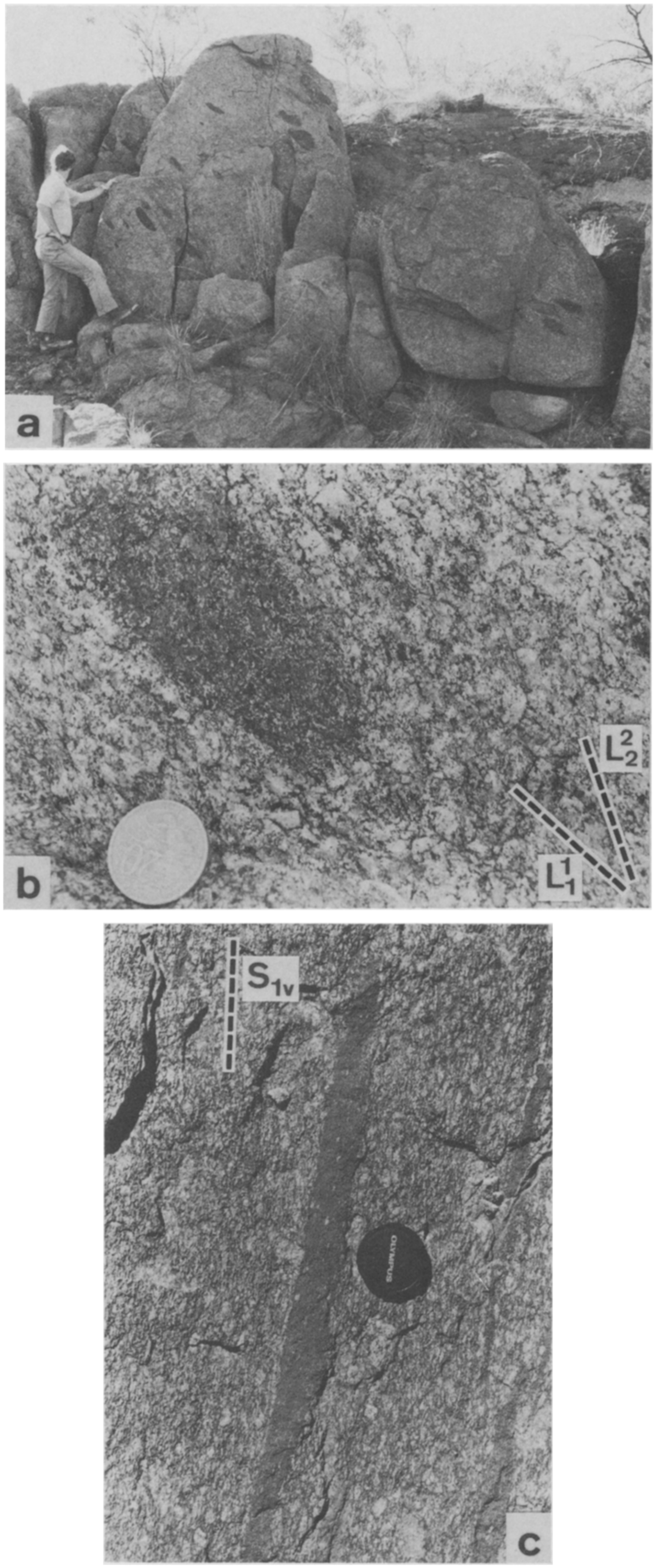
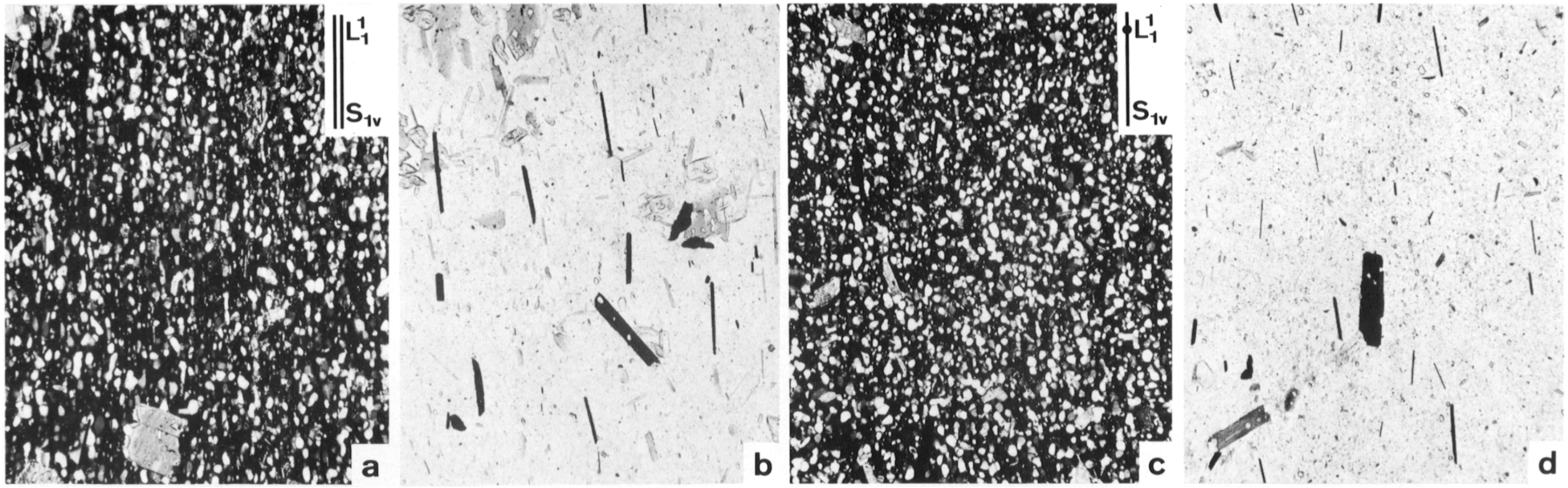
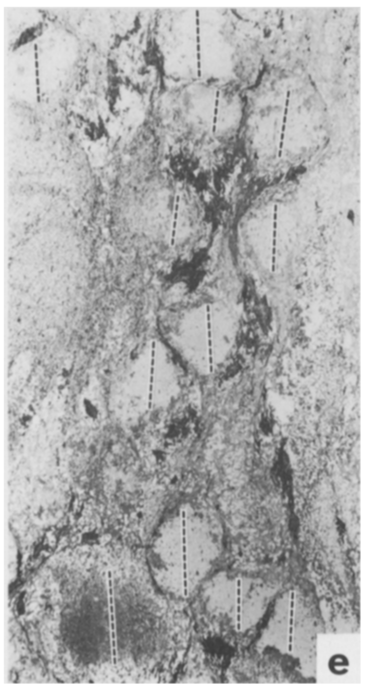


Fig. 6. (a) Xenoliths elongate parallel to L_1^1 in the S_{1v} plane in mylonitic gneissic metagranite from the Wonga–Duchess Belt a few hundred metres southeast of location A in Fig. 2. (b) Close-up of an $S_{1v,2}$ foliation surface. L_1^1 is here the most easily observed mineral elongation lineation and is defined by the xenolith and aligned elliptical feldspars. L_2^2 is much finer and more difficult to observe. It is best defined by small aligned biotite grains. (c) Xenoliths on a horizontal outcrop surface (location A in Fig. 2). These elongate xenoliths are plunging at around 40° to the south. The S_{1v} foliation in the gneissic metagranite lies at a low angle to the long axes of the three xenoliths. The effects of D_2 are weak in this outcrop. The angular relationship between S_{1v} and the long axes of the xenoliths stays constant for around a total of 1.5 km perpendicular to the strike of S_{1v} about A and indicates a sinistral shear sense parallel to S_{1v}. Note how the xenolith on the upper right-hand side has undergone differential shear of its lower tail (cf. Bell & Johnson 1992).





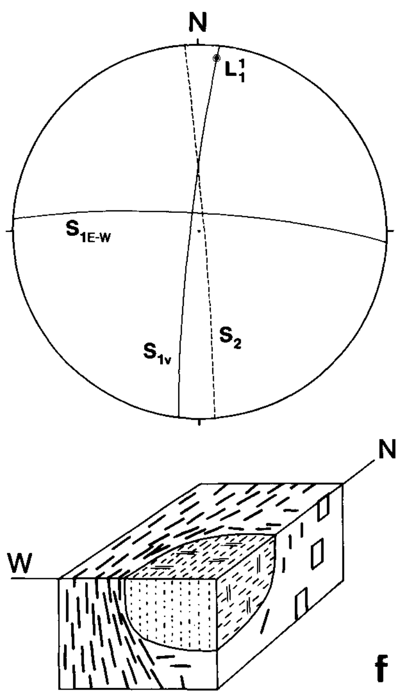


Fig. 7. Example of three-dimensional analysis of porphyroblast inclusions preserving S_{1v} and L_1^1 in a cordierite–andalusite schist (Ro 116). Photographs (a)–(d) show inclusions in cordierite (andalusite is less abundant but has identical inclusion patterns in this sample). The anisotropy of the quartz and feldspar inclusions is commonly best recognized if the host grain is in extinction. The fine grain of the inclusion trails made it necessary to use high magnification. Scale: long side of photographs (a)–(d) 1.6 mm. (a) Horizontal section with S_{1v} trace and L_1^1. Crossed polarizers. Long side of photograph oriented N–S. (b) Horizontal section showing the alignment of hematite platelets (black) and biotite grains in S_{1v}, which is about perpendicular to the plane of view. Plane-polarized light. Orientation of photograph as in (a). (c) E–W-oriented, vertical section with S_{1v} trace, normal to L_1^1. Crossed polarizers. Short side of photograph oriented E–W. Note that the fabric anisotropy is much weaker than in the horizontal section (a). (d) E–W-oriented, vertical section showing the alignment of hematite platelets and biotite grains in S_{1v}. Plane-polarized light. Orientation of photograph as in (c). In the N–S-oriented, vertical section subparallel to S_{1v} and L_1^1, no distinct inclusion pattern can be recognized in plane-polarized light as the section is sub-parallel to the preferred orientation of the platy minerals shown in (b) and (d). (e) Inclusion trail orientations (here: S_{1v} with L_1^1) across a horizontally oriented thin section. The light-coloured porphyroblasts are cordierite, the dark one is andalusite. Length of section 4 cm. (f) Summary of structural data for Ro 116. The stereo plot shows the average orientations of D_1 structures obtained from inclusion trails, and the S_2 orientation of the schist matrix. The schematic block diagram shows three orthogonal sections, with inclusion trail orientations and the external S_2–L_2^2 fabric.

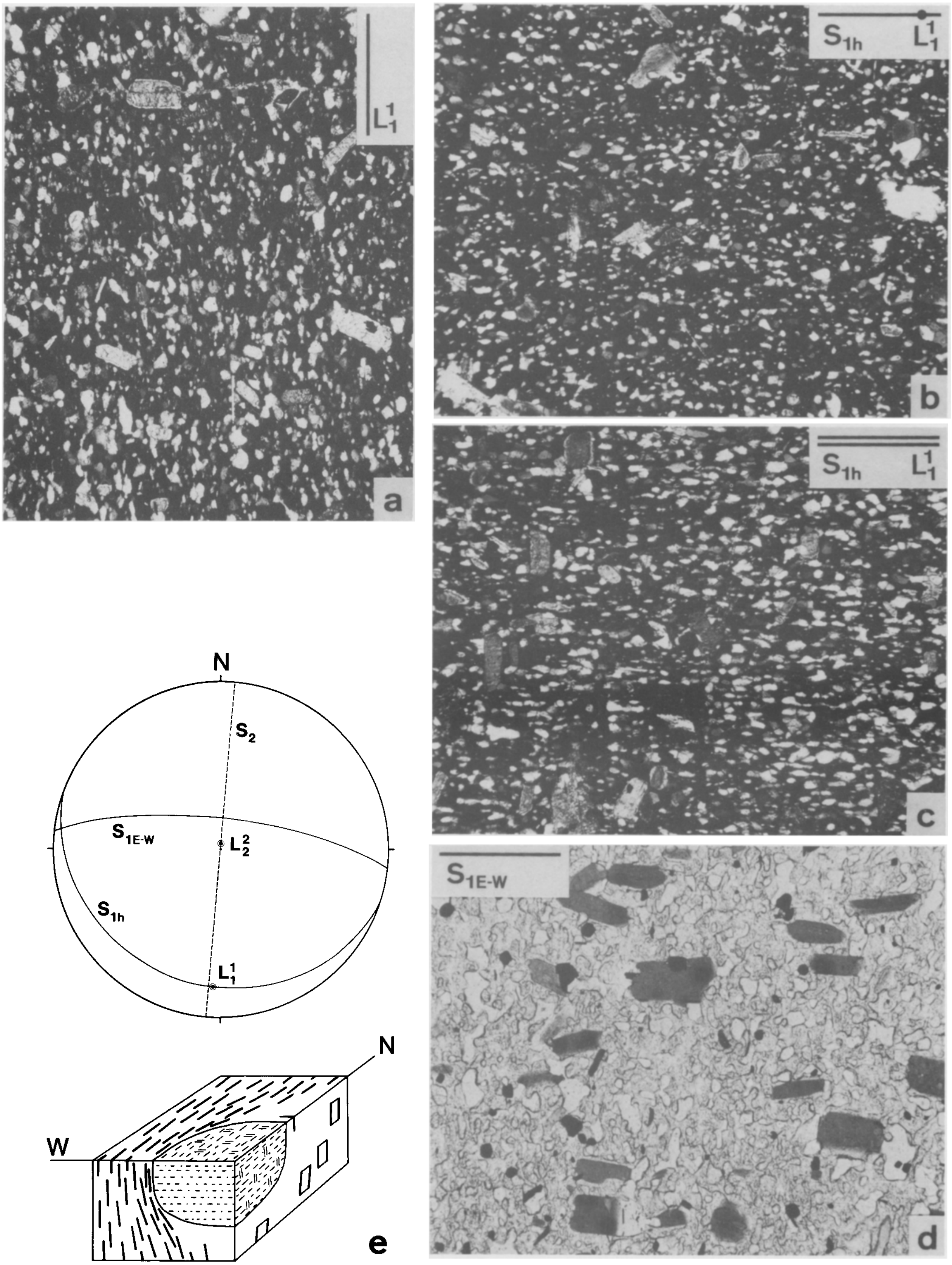


Fig. 8. Example of three-dimensional analysis of porphyroblast inclusions preserving S_{1h}, L_1^1 and $S_{1E\text{-}W}$ in an andalusite schist (Ro 153). Photographs (a)–(d) show inclusions in andalusite. Scale: long side of photographs (a)–(c) 1.6 mm and (d) 1.3 mm. (a) Horizontal section, subparallel to S_{1h} and L_1^1. Crossed polarizers. Long side of photograph oriented N–S. Note that the relatively large biotite grains are not part of the S_{1h}–L_1^1 fabric, but overgrew it, as shown in (d). (b) E–W-oriented, vertical section with S_{1h} trace, normal to L_1^1. Crossed polarizers. Long side of photograph oriented E–W. (c) N–S-oriented, vertical section with S_{1h} trace and L_1^1. Crossed polarizers. Long side of photograph oriented N–S. (d) Horizontal section showing the alignment of biotite inclusions in $S_{1E\text{-}W}$ (which is nearly perpendicular to the photo plane). Biotites show maximum absorption, as polarizer is oriented E–W. Plane-polarized light. Long edge of photograph oriented E–W. Such late-formed biotites have typically low length/width ratios, unlike the much finer-grained biotites aligned in S_{1v} or S_{1h} (cf. Figs. 7b & d). (e) Summary of structural data for Ro 153. The stereo plot shows the average orientations of D_1 and D_2 structures. The schematic block diagram shows all three orthogonal sections, with orientations of the inclusion trails and the external S_2–L_2^2 fabric. The closeness of L_1^1 to the intersection of S_{1h} and S_2 is purely coincidental. L_1^1 is defined by a mineral shape fabric and cannot be confused with an intersection lineation.

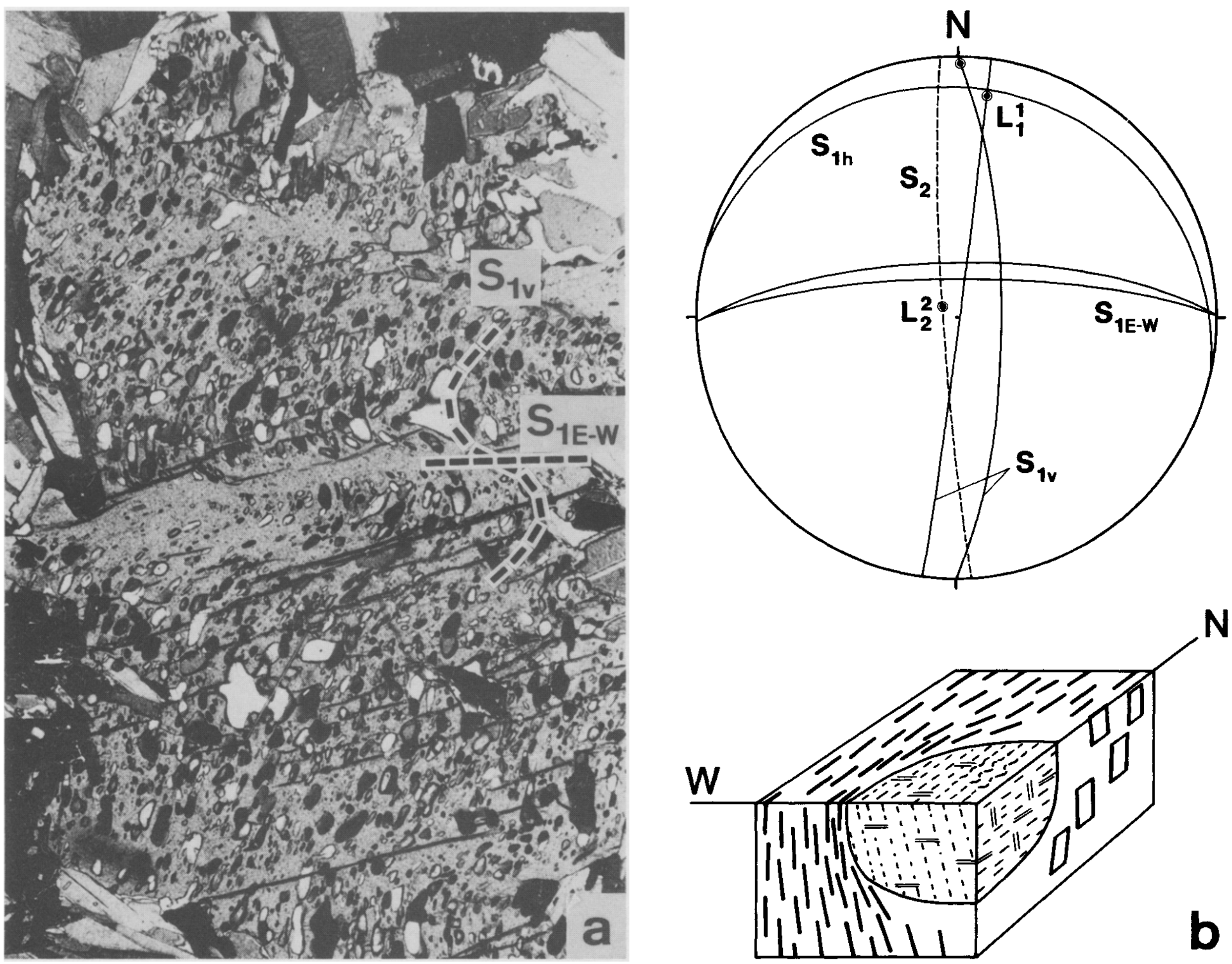


Fig. 9. (a) Differentiated crenulation cleavage preserved in andalusite. Crenulations of S_{1v} due to $S_{1E\text{-}W}$. As much of the mica had been dissolved during the andalusite-forming reaction, the originally mica-rich lithons are now quartz-inclusion-poor portions in the andalusite. Horizontal section, north points up the page. Crossed polarizers. Scale: width of base is 1.3 mm. (b) Summary of structural data for Ro 966 and Ro 1068. Both samples come from the same outcrop and have been measured independently. The main S_{1v} in the andalusite and cordierite porphyroblasts is defined by a planar fabric of rod-shaped quartz grains which also define an L_1^1, similar to Ro 116 in Fig. 7. Scattered inclusions of small, thin biotite flakes define a planar fabric with an S_{1h} orientation. S_{1v} is locally crenulated as seen in (a).

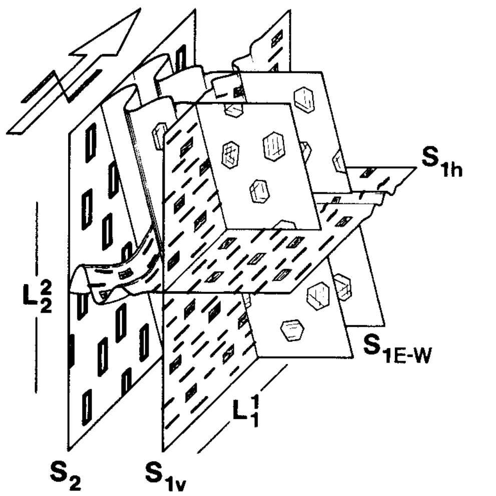


Fig. 10. Schematic diagram of D_1 and D_2 foliations and lineations and their mutual overprinting relationships. The right-hand part of the diagram shows the D_1 structures as preserved in the early-D_2 porphyroblasts. Note that development of $S_{1E\text{-}W}$ locally involves crenulation of both S_{1v} and S_{1h} (e.g. Fig. 9). Evidence for D_2 overprinting D_1 structures is preserved on the margins of some porphyroblasts (Reinhardt & Rubenach 1989, Reinhardt 1992) and through rotation of L_1^1 about a constant L_2^2.

D_2 deformation. In particular, the presence of S_{1h}, S_{1v} and $S_{1E\text{-}W}$ in single porphyroblasts in S_2-foliated rocks (Fig. 9) shows that the near-perpendicular relationship between S_{1h} and S_{1v} cannot be a product of a 90° rotation of the porphyroblasts. The constant orientation of S_2 in this area (Reinhardt 1992, in press) also excludes post-D_2 block rotation on late faults. The preservation of original foliation orientations within porphyroblasts in subsequently folded rocks is known from other areas and appears to be a common phenomenon (see also Bell & Johnson 1990, for a discussion of further examples).

Our interpretation is strongly supported by the local preservation of each of the D_1 foliations in the field within zones of low strain during D_2. The mesoscopic evidence for overprinting of S_2 on S_{1v}, since they are parallel, occurs within gneissic granitoids that were only weakly deformed during D_2. This evidence consists of the intense sub-horizontal stretching lineation overprinted by a very weak vertical stretching lineation, the consistent shear sense from xenoliths associated with D_1, conflicting shear senses from smaller S-and-C-plane-like structures due to the overprinting effects of D_2, and finally, the D_1 age of this foliation.

The near-horizontal, N–S-oriented L_1^1 associated with S_{1v} in these porphyroblasts confirms our earlier conclusion that the L_1^1 stretching lineation in the Wonga–Duchess Belt was horizontal prior to D_2, and was later variably rotated within the matrix towards L_2^2 (Fig. 5). The near-horizontal, N–S-oriented L_1^1 on both S_{1h} and S_{1v} defines the bulk direction of movement during D_1. We conclude that these two foliations formed synchronously during the D_1 orogeny (Figs. 11 and 12).

S_{1h} is interpreted as a shallow-dipping or horizontal foliation associated with gravitational spreading and the generation of thrusts (e.g. Platt *et al.* 1983, Law *et al.* 1984, 1986, Bell & Johnson 1989, 1992), whereas S_{1v}

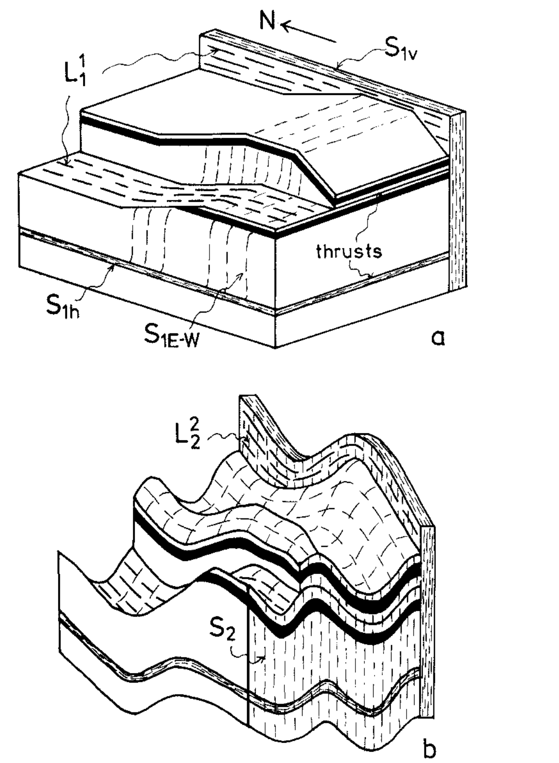


Fig. 11. (a) Three-dimensional sketch of the relationships between S_{1h}, S_{1v}, $S_{1E\text{-}W}$ and L_1^1 across the Rosebud Syncline to the western margin of the Wonga–Duchess Belt, prior to D_2. (b) Sketch showing the overprinting effects of D_2 on the D_1 structures in (a). Note the variation in L_1^1 about L_2^2.

formed in near-vertical D_1 shear zones recording transcurrent displacement within the thrust belt. In particular, S_{1v} formed locally close to the edge and, more intensely, within the Wonga–Duchess Belt. The combined S_{1h}–S_{1v}–L_1^1 geometry observed microstructurally supports our interpretation of the regional structure as a system of interpenetrating thrusts and sub-vertical shear zones prior to D_2 (Fig. 12). This also provides an explanation for the juxtaposition of zones of near-vertical and horizontal foliation in the same outcrop on the eastern edge of the Rosebud Syncline, both with

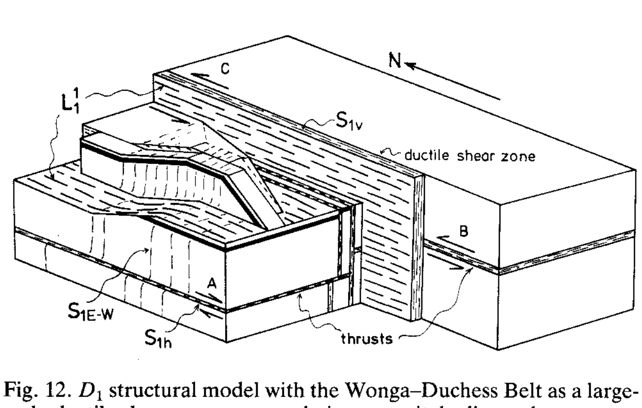


Fig. 12. D_1 structural model with the Wonga–Duchess Belt as a large-scale ductile shear zone accomodating oppositely directed movement during thrusting of the rocks on either side (location A—top to south; location B—top to north; location C—sinistral shear across the Wonga–Duchess Belt). Subsidary shear zones are shown to the west. Note how the uppermost thrust imbricate has undergone differential displacement across one of these during D_1. Note that L_1^1 has the same orientation along the thrusts as in the vertical shear zones.

shallow mineral elongation lineations, without any transitional zone between them.

In all samples examined, the relatively weak S_{1E-W} is the latest pre-D_2 foliation. Its orientation indicates N–S-directed compression. We therefore regard S_{1E-W} as having been generated by the same N–S shortening orogeny that produced the D_1 thrusts. S_{1E-W} most likely reflects the latest stage of compression in D_1, when the major S_{1h} and S_{1v} shear zones had become inactive. Steep foliations with a similar origin are also present in other thrust terrains (Mitra *et al.* 1984, Platt & Behrmann 1986, Casas & Monoz 1987). S_{1E-W}-type of foliations could form simultaneously with thrusting adjacent to frontal ramps but would tend to dip more shallowly towards the heel than observed here (Mitra & Elliott 1980).

Our study demonstrates that the most pristine preservation of the D_1 fabrics is found within the early syn-D_2 porphyroblasts in pelitic schists. In the schist matrix, these early fabrics have generally been obliterated. The state of preservation of S_{1v} and L_1^1 in the Wonga–Duchess Belt lies between these extremes. That is, L_1^1 is still identifiable, but has been clearly affected by D_2, and S_{1v} has been intensified during the formation of S_2, while S_{1h} has been variably rotated by the effects of folding during D_2 (see also Holcombe *et al.* 1991). The preservation of D_1 structures in the Wonga–Duchess Belt is probably due to the unreactive nature of the major rock types within it, such as the gneissic granitoids, during D_2. A lack of reaction-enhanced ductility (White *et al.* 1980) in these rocks would have prevented extensive deformation and recrystallization.

The geometry of the relic D_1 foliations and the regional structural relationships suggest that, within the D_1 thrust belt, the Wonga–Duchess Belt was a major zone of transcurrent shearing, with subsidary shear zones along its margins. The zones of near-vertical, N–S-striking foliation with the remains of an originally shallowly plunging stretching lineation lie approximately parallel to the transport direction during D_1 thrusting and accommodated differential lateral movement of the thrust sheets.

DISCUSSION

The obliteration of earlier foliations and re-use of others within the matrix of schists and intensely deformed gneisses is a problem that faces all who work in multiply deformed terrains. However, indicators of multiple deformation and metamorphism, such as truncational foliations and other complex inclusion trails preserved in porphyroblasts, are much more common than previously realized; but even where they are present, they only preserve a small fraction of the deformational–metamorphic history that the rock has been through (e.g. Bell & Hayward 1991). Other indicators of a multi-stage deformation history, such as the conflicting shear-sense criteria common to shear zones, have also been previously disregarded (e.g. Bell & Johnson 1992).

Furthermore, the complex geometries of thrust belts may well produce a variety of foliation orientations during a single deformation episode. For example, the foliation may vary within thrust sheets, particularly in frontal or lateral ramp structures (e.g. Mitra & Elliott 1980, Sanderson 1982). As in the region discussed here in detail, interference patterns of thrusts and tear faults may be present, implying that a corresponding variety of microstructures developed in sufficiently ductile rocks. Evidently, the recognition and interpretation of such intricate structural patterns is rendered difficult in subsequently folded and metamorphosed terrains. As our study shows, even such complex structures can be resolved, whereby the record of early fabrics in porphyroblasts proved to be particularly important.

Without the preservation of inclusion trails in porphyroblasts or early foliations in the strain shadows of competent heterogeneities, such as veins, porphyroclasts and pebbles (Bell & Johnson 1992), the early deformational–metamorphic history is commonly lost or may not be recognized. For example, Holcombe *et al.* (1991) interpreted these same rocks of the Wonga–Duchess Belt as having formed within an extensional décollement. Their model involves folding of a flat-lying foliation that formed during N–S extension into a steep orientation during E–W shortening. Because they did not use the geometry of earlier foliations preserved in porphyroblasts, they did not recognize the presence of two of the earlier foliations described herein and the considerable potential tectonic significance of S_{1v}. Consequently, they made no attempt to explain the lack of resetting of Rb–Sr isochrons in granitic gneiss during D_2, even though they argue that these rocks were deformed with sufficient intensity to be isoclinally folded parallel to the vertical S_2. They did not recognize the S_{1v} actually formed in this orientation, although they realized that two stretching lineations were present on the one foliation plane. Hence, their model cannot explain the thrust relationships that we have observed to the west of the Wonga Belt.

Our model is corroborated by critical field relationships within the Wonga–Duchess Belt. Along this belt, the Ballara Quartzite is continuous except for two critical breaks across anticlinal hinges. The first occurs in the northern part of the map in Fig. 13 in the area marked A–A–A, the second occurs in the south marked B. In this second location, the Ballara Quartzite has been juxtaposed across a shear zone (see also Fig. 2). The lack of continuity of this marker horizon across the Wonga Belt marks the site of a major shear zone.

Unlike the Rosebud Syncline, the Little Beauty Syncline immediately to the north shows repeated high-angle normal faulting on its limbs (cf. fig. 22 in Holcombe *et al.* 1991). The apparent conflict between extension in the Little Beauty Syncline and thrusting in the Rosebud Syncline could be resolved by connecting the basal detachment of the zone of imbricate extension with a zone of thrusting as shown in Fig. 14. Such a geometry can form due to gravity sliding when rocks have been uplifted to a fairly high level in the orogenic

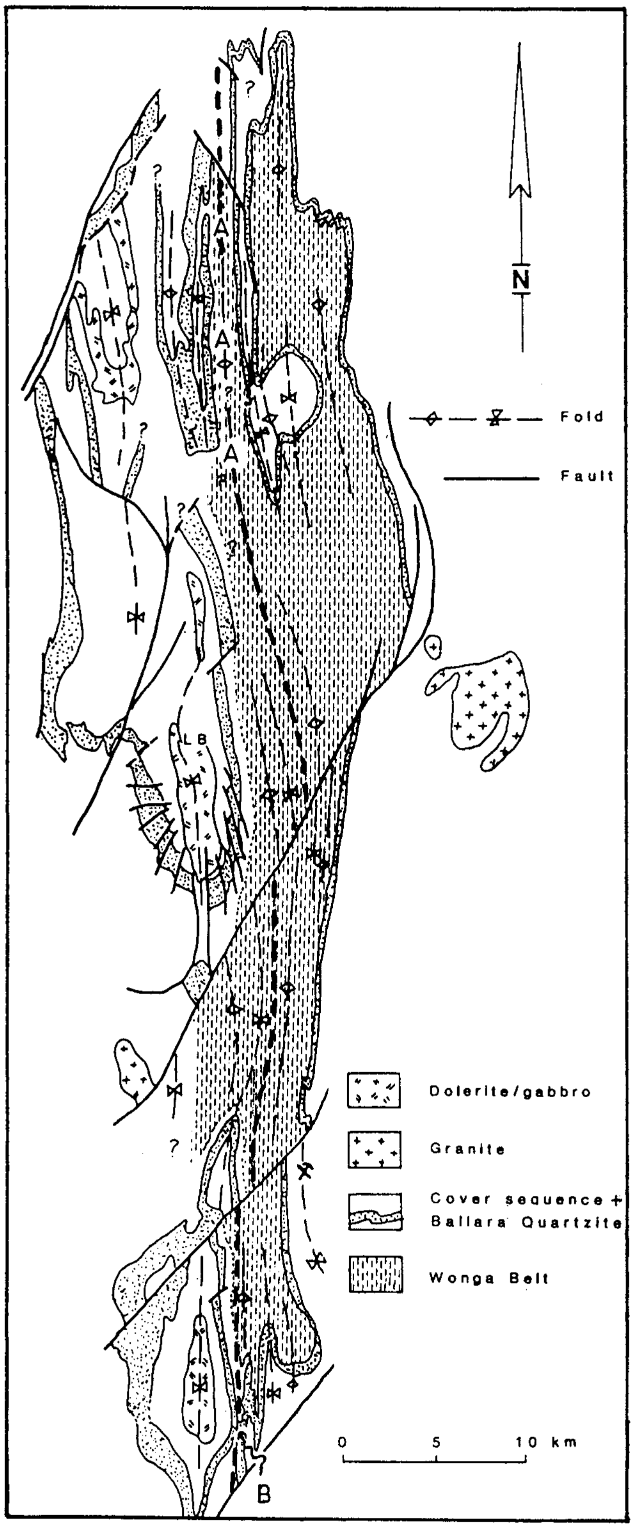


Fig. 13. Distribution of Ballara Quartzite across the Wonga–Duchess Belt (modified from fig. 1 in Holcombe *et al.* 1991). Note the lack of continuity of Ballara Quartzite at A–A–A and that Holcombe *et al.* (1991) questioned the structural relationships at this location. Note also the apparent continuity at B but that Ballara Quartzite is disrupted at this location on the more detailed map shown in Fig. 2. The heavy dashed line marks the throughgoing location of stratigraphic disruption.

pile (e.g. Bell and Johnson 1989, 1992). However, the age of these faults is still uncertain, except that they predate D_2. They may have formed even before D_1 thrusting, possibly during the evolution of the sedimentary

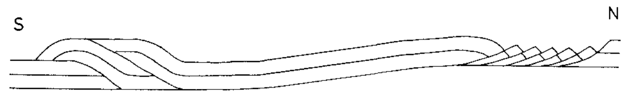


Fig. 14. Schematic cross-section showing how extensional geometries in the Little Beauty Syncline (cf. Holcombe *et al.* 1991) can transfer into thrust geometries in the Rosebud Syncline.

basins in which the 1800–1670 Ma old cover sequences (Upper Tewinga, Mary Kathleen, Haslingden and Mount Isa Groups; Blake 1987) were deposited. The stratigraphic record indicates typical rift basin sequences, and hence crustal stretching during this period (e.g. Reinhardt in press).

REGIONAL TECTONIC MODEL

It is appropriate to speculate on a tectonic model that could explain the structural relationships across the Wonga–Duchess Belt as well as the larger-scale geometric relationships in the Mount Isa Block. Such a model would need to be able to explain the following.

(1) N- to S-directed thrusting during D_1 to the west of the Wonga–Duchess Belt (Bell 1983, 1991, Loosveld & Schreurs 1987, this study).

(2) The apparently oppositely directed thrusting to the east of the Wonga–Duchess Belt (Loosveld 1989).

(3) The occurrence of older, high-grade metamorphic rocks to the northwest and southeast, in the Murphy Inlier and Gin Creek Block, respectively (Beardsmore *et al.* 1988, Switzer 1988).

(4) The location of older, potentially high-grade rocks along the Wonga–Duchess Belt (R. W. Page personal communication 1988),

According to the study of Loosveld (1989), the thrusting direction east of the Wonga–Duchess Belt is the opposite of what we observed to the west. Although Loosveld (1989) considered the movement during thrusting to have been more NW- to NNW- than N-directed, the stretching lineations from which he deduced this may have been rotated during the subsequent D_2 orogeny. The Wonga–Duchess Belt may therefore have been a transform-like structure during the D_1 orogeny with opposite directions of thrusting to either side.

A tectonic model that takes into consideration the points listed above is shown in Fig. 15. In this very schematic model, the high-grade core of the D_1 orogen is located in the basement rocks of the Murphy Inlier and the Gin Creek Block, and is offset at a transform-like fault along the Wonga–Duchess Belt. Thrusting occurs during gravitational spreading to both the north and the south of the orogen core resulting in oppositely directed thrusts and sinistral shearing across the Wonga–Duchess Belt. The belt of older, high-grade metamorphic rocks to the northwest as exposed today is quite narrow. This is possibly a result of much younger shortening and associated thrusting during the Carboniferous which had considerable impact on the rocks in central Australia to

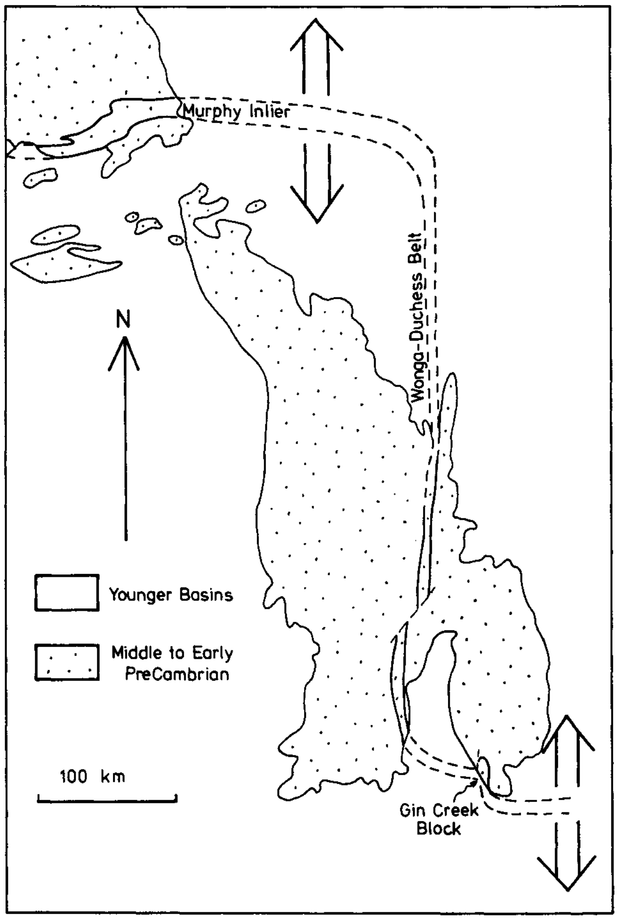


Fig. 15. Schematic plan view sketch of the orogen core in D_1 time showing the transform-like character of the Wonga–Duchess Belt and how the direction of thrusting would change across it generating a vertical sinistral shear zone.

the west (Teyssier 1985) as well as to the east (K. Lawrie personal communication, B. Davies in preparation).

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