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Folding in high-grade rocks due to back-rotation between shear zones

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Abstract

Folds with a sense of asymmetry opposite to the bulk shear sense may form in high-grade rocks due to back-rotation between ductile shear zones. Layers back-rotated into the shortening field can undergo additional buckle folding. With progressive deformation, shear zones and domains of back-rotated foliation between shears rotate towards the $X-Y$ (flattening) plane of the finite strain ellipsoid. In high-grade gneiss, the migration of melt into shear zones may facilitate displacement along them and accentuate back-rotation of material between shear zones. Folding during back-rotation occurs when the spacing between shear zones does not increase sufficiently to accommodate the length of back-rotated layers or between non-parallel shear zones. Folds formed by back-rotation between shear zones commonly have pegmatites sub-parallel to their axial planes, thickened overturned limbs and occur in localised packages. Associated shear zones have the same sense of shear on both attenuated limbs of folds formed by back-rotation. Examples are given for folds between transcurrent and normal ductile shear zones in the Albany Mobile Belt and Leeuwin Complex (Western Australia) and the Dharwar Craton (India). © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Shear zones; Granulites; Amphibolites; Albany Mobile Belt; Leeuwin Complex; Dharwar Craton

1. Introduction

1.1. Aims

This paper describes how folds with the opposite sense of asymmetry to the sense of displacement on bounding shear zones may develop when there is a large degree of back-rotation between pairs of ductile shear zones. It is shown that the opposite sense of shear displacement could easily be misinterpreted from asymmetric folds, which in turn may lead to errors in regional tectonic interpretation.

1.2. Previous studies of folds within and between shear zones

Where layers originally sub-parallel to the boundary of a ductile shear zone have been folded, the asymmetry of folds with axes orthogonal or at a high-angle to the mineral elongation lineation is frequently used as an indicator of the bulk shear sense. The mineral elongation lineation here is taken as the direction of shear displacement. Exceptions where the mineral elongation lineation may not equate to the direction of shearing (as discussed by Simpson and De Paor, 1993), and comments by Jiang (1999, p. 257) on section use for the observation of kinematic indicators, will not be considered in this paper. In their review of ductile deformation processes, Williams et al. (1994) consider the asymmetry of ‘drag’ folds as probably one of the most reliable kinematic indicators if used with caution. Shear-related folds, overturned consistent with the bulk sense of shear, may develop due to local perturbations during differential shearing parallel to the layering (Rhodes and Gayer, 1977). The overturning of folds consistent with the sense of shearing within ductile shear zones has been studied by Fossen and Holst (1995) and modelled experimentally e.g. low-strain stages of models by Cobbold and Quinquis (1980), Fossen and Rykkelid (1992) and Bons and Jessell (1998). Platt (1983) also showed from theoretical considerations that a shear zone-parallel foliation folds during progressive shearing and becomes overturned towards the movement direction. Even at higher strain when fold axes are likely to be rotated towards the movement direction forming sheath folds, the sense of asymmetry of minor folds around the sheath has still been used as a kinematic indicator (e.g. Fossen and Rykkelid, 1990, fig. 14). Ramsay et al. (1983, fig. 4), however, show that whilst the asymmetry of early-formed folds within a ductile shear zone is consistent with the bulk sense of shear, the sense of asymmetry may reverse at high shear strain. This reversal of fold asymmetry is due to rotation of the enveloping surface of parasitic folds into the extensional field with progressive deformation (Ramsay et al., 1983).

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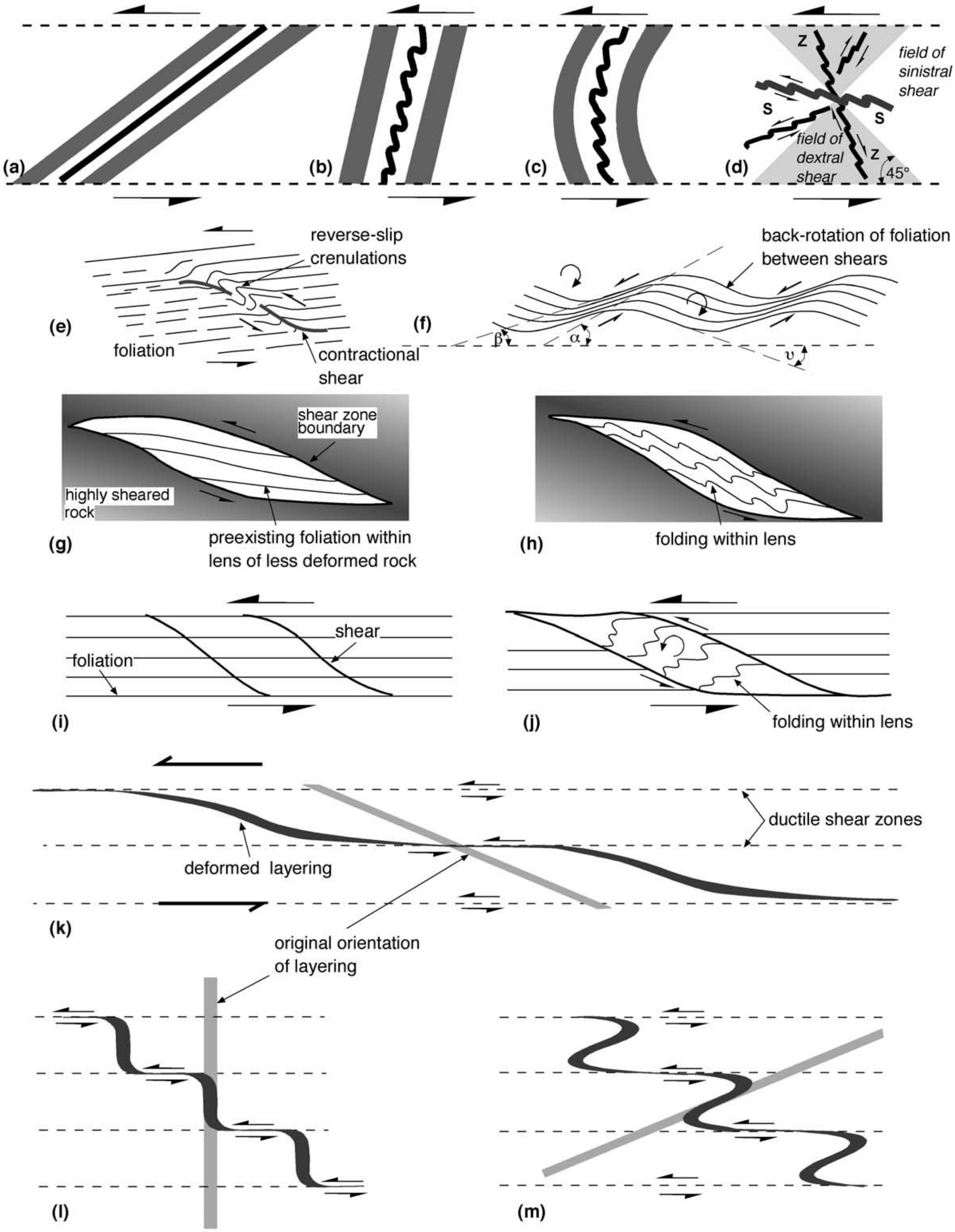


Fig. 1. Previous concepts for deformation between shear zones. (a–d) Progressive shearing of inclined layers (after Ghosh, 1966). Short-wavelength folds are formed in the thinner, competent (black) layer. The asymmetry of folds depends on the orientation of the layer with respect to shear zone boundaries. Folds with both sinistral and dextral vergence can form, as shown in (d). (e) Reverse-slip crenulations (contractional or reverse shear band; Dennis and Secor, 1990). (f) Extensional crenulation cleavage. Average angles determined by Platt and Vissers (1980) are $\alpha = 29.4°$, $\beta = 16.8°$, $\upsilon = 16.9°$. Modified after Platt and Vissers (1980). (g,h) Formation of folds in a lens of less deformed rock in a ductile shear zone (modified after Ghosh and Sengupta, 1987). Layers within the lens inclined to shear zone boundaries (g) are folded with progressive deformation (h). (i,j) Folding of layers between two contractional shears within a shear zone (modified after Fossen and Rykkelid, 1990). Layers between two cross-cutting shear zones (i) and shear zones are forward rotated with further shearing, producing folds overturned towards the shear direction (j). (k–m) Formation of folds between shear zones in a layer at different initial angles to shear zones. Parts (k) and (m) modified after Schmidt (1932, figs. 22 and 23) and (l) based on figs. 51 and 53 of Sander (1948). Note that there is no forward- or back-rotation of the layer; folds form solely due to drag into shear zones. Folds with opposite asymmetry to the sense of displacement on shears are formed in (m).

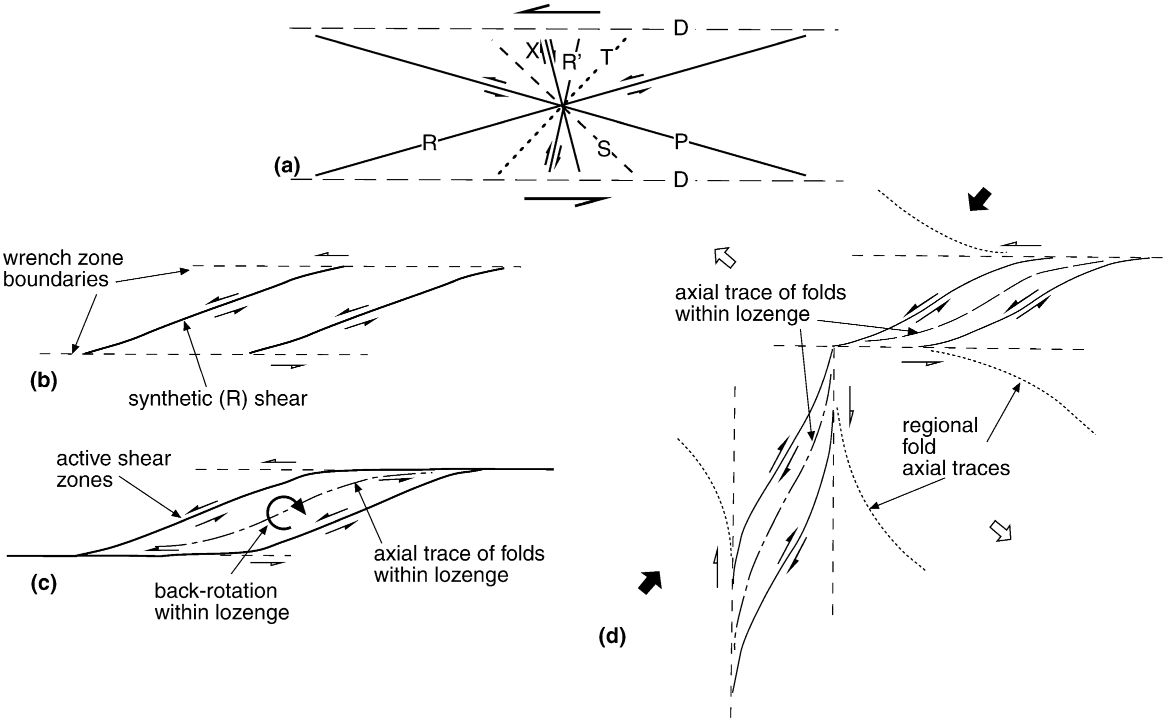


Fig. 2. Model of Boudon et al. (1976) for back-rotation of layering within blocks bounded by Riedel shears in wrench zones (Riedel, 1929; Tchalenko, 1968, 1970). (a) Schematic diagram showing structures that may develop within a sinistral wrench zone. D = principal displacement shear, R and R' = primary and secondary (synthetic and antithetic) Riedel shears, X = conjugate shear, T = extension fracture/normal fault, S = cleavage, regional fold axial plane or thrust/reverse shears, and P = restraint shear. (b,c) Formation of lozenge-shaped block bounded by R shears linked to *en relais* stepping D shears. Back-rotation may take place within this lozenge during continued displacement on bounding shears forming open folds with axial surfaces sub-parallel to bounding shears. (d) Lozenge-shaped blocks created within conjugate wrench zones. Outside the lozenges, fold axial traces form at right angles to the regional maximum shortening direction (solid arrows; open arrows = regional extension). Regional axial traces bend progressively towards parallelism to wrench zone boundaries. Note obliquity between regional folds and folds developed within each lozenge due to back-rotation.

Folds whose asymmetry is consistent with the bulk shear sense may also form in association with displacement on discrete shear zones, such as:

- along reverse-slip crenulation cleavage (Fig. 1e) of Dennis and Secor (1990);
- single extensional shear bands (Fig. 1e), as illustrated from natural examples by Fossen and Holst (1995, fig. 4) and Fossen and Rykkelid (1990, figs. 2 and 11b and c) and as produced in analogue models by Fossen and Rykkelid (1992);
- in localised contractional zones between stepping, synthetic shear bands (Rykkelid and Fossen, 1992);
- within a shear-bounded tectonic lens (Ghosh and Sengupta, 1987), Figs. 1g and h; and
- between P or 'reverse-fault type' shear bands of Marcoux et al. (1987), as described by Fossen and Rykkelid (1990), Fig. 1i and j.

When a layer is inclined at a large angle towards the sense of shear, folds can have the same or opposite sense of asymmetry to the bulk sense of displacement (Fig. 1a–d). Ghosh (1966) has shown from experiments that when layers of differing viscosity in an incompetent matrix undergo synthetic rotation within a ductile shear zone, asymmetric folds may be produced in a thin competent layer whereas layers of intermediate competency may deform by layer-parallel shortening (Fig. 1a–c). Folds formed at different stages as the layer rotates with respect to shear zone boundaries may have different asymmetry (Fig. 1d). If some layers start to buckle late during their rotation early-formed, short-wavelength folds in the more competent layer may exhibit an incongruent relationship to open, large-wavelength folds in the more competent layers.

The term Gleitbretter folds (from the German *gleiten* = to slide, and *brett* = board, referring to the thin slices of rock between shear planes) was used by Schmidt (1932), Sander (1948) and Hills (1963) to describe folds where folding occurs between narrow parallel shear zones or slip surfaces. See also Tromp (1937, pp. 36–39) for a concise English explanation. In some Gleitbretter folds, the sense of shear is symmetrical about the fold axial plane, whereas in others it has a constant sense in the two limbs of the fold (Hills, 1963, p. 238). The form of folds depends on the angle between the shear planes and the initial orientation of the folded surface (Hills, 1963). A particular case of Gleitbretter-style shear folding (similar to that portrayed by Sander, 1948 fig. 52c) has been simulated geometrically by Delteil (1985). Delteil's results

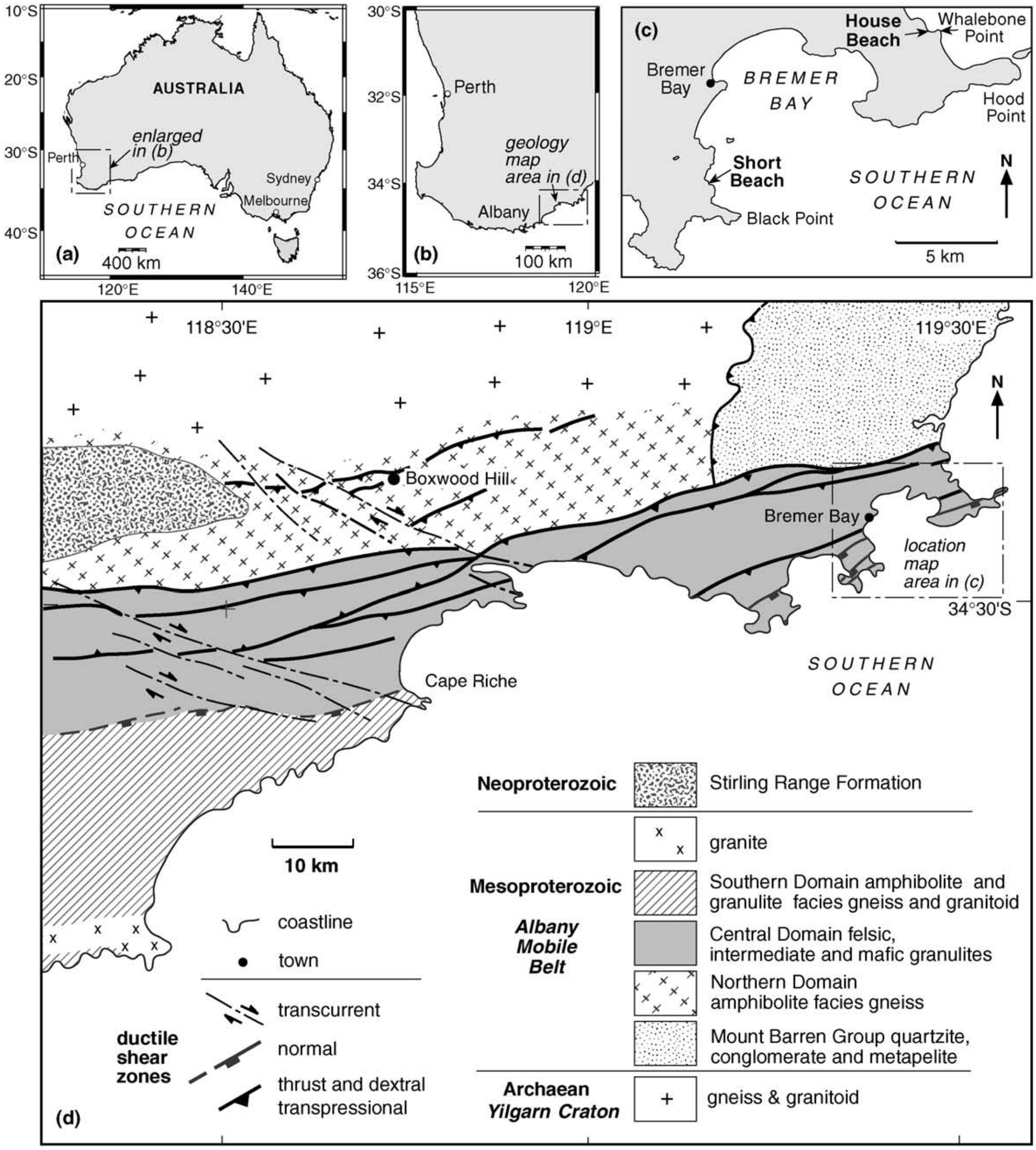


Fig. 3. (a–c) Location of Short Beach and House Beach study sites in the Bremer Bay area of southern Western Australia. (d) Simplified regional geology map of the eastern Albany Mobile Belt showing interpreted regional thrusts and extensional shear zones. Bremer Bay is situated within the Central Domain of the Albany Mobile Belt.

indicate similar folds may form due to uniform-sense shear of variable amplitude along closely spaced planes oblique to the initial layering. In all these examples, the distance between shear planes remains constant throughout the deformation history and there is no rotation of the shear planes with respect to the applied stress field. Schmidt (1932), Tromp (1937) and Sander (1948) also illustrate the formation of folds in a layer cut by discrete shear zones. In their models, the layer away from cross-cutting shear zones retains its original thickness and orientation and folds formed between shear zones are produced by drag into the shear zones. In their models:

- extended lenses will develop if the layer initially is inclined away from the sense of shear (Fig. 1k);
- simple drag folds form when the layer is initially normal to the shear zones (Fig. 1l); and
- folds overturned in a sense opposite to the sense of shear will develop where the layer initially dipped towards the sense of shear (Fig. 1m).

Sander (1948) expands this model to show that once formed, folds may progressively rotate in the same sense as the sense of shear along bounding shear zones.

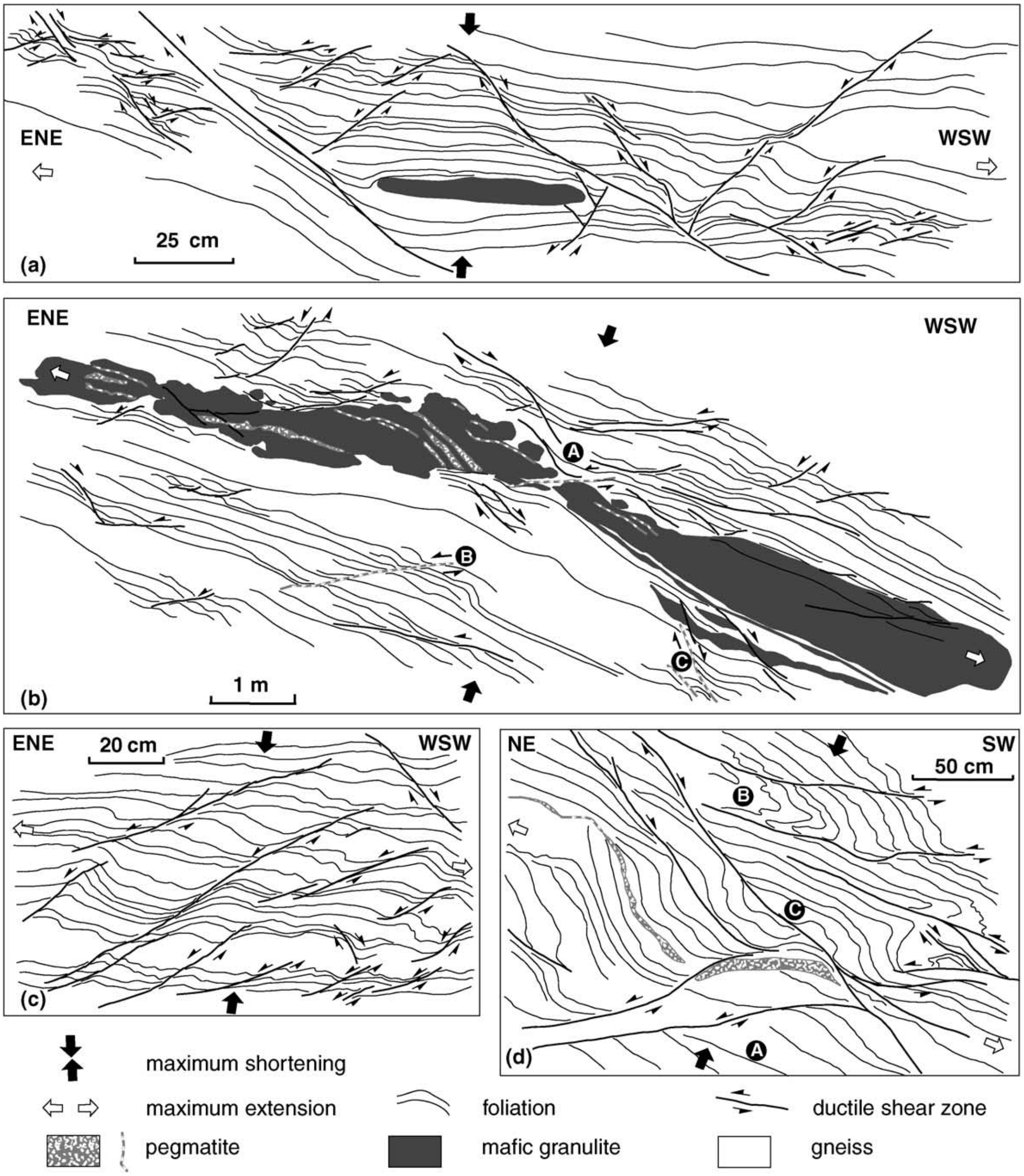


Fig. 4. Oblique sections through conjugate ductile shear zones in granulite facies gneiss at Short Beach, Bremer Bay (see Fig. 3c for location). Sketches (traced in the field from enlarged photographs) are normal to the general trend of gneissic foliation. Axes of maximum shortening (solid arrows) and maximum extension (open arrows) interpreted from the obtuse and acute bisectors of ductile shear zones are in agreement with principal strain axes determined from anisotropy of magnetic susceptibility. See Fig. 5 for stereographic analysis. (a) Conjugate shears. (b) At A, conjugate shears intersect in boudin neckline of mafic granulite layer. Sinistral and dextral shear zones are intruded by pegmatites formed by in situ partial melting (e.g. B, C). (c) Drag of foliation into closely spaced sinistral shears (dominant) and minor dextral conjugate shears. (d) Higher strain area. Note greater angle between conjugate shears compared with (a) or (c) in same lithology suggests rotation of shear zones towards the X–Y plane of the finite strain ellipsoid. A = regional foliation orientation. Overturned folds between shears at B have undergone further shortening during rotation of shears. Open folds are formed at the intersection of conjugate shears (C).

1.3. Back rotation between faults and ductile shear zones

Although forward-rotation (or co-rotation; Grasemann and Stüwe, 2001) between pairs of shear zones has been described by authors such as Caire (1979), Ghosh and Sengupta (1987) and Fossen and Rykkelid (1990), back-rotation (or counter-rotation; Grasemann and Stüwe, 2001) of layering between pairs of faults or ductile shear zones is common in the following situations:

1. Within lozenge-shaped blocks created by linking of primary Riedel (R) shears and principal displacement

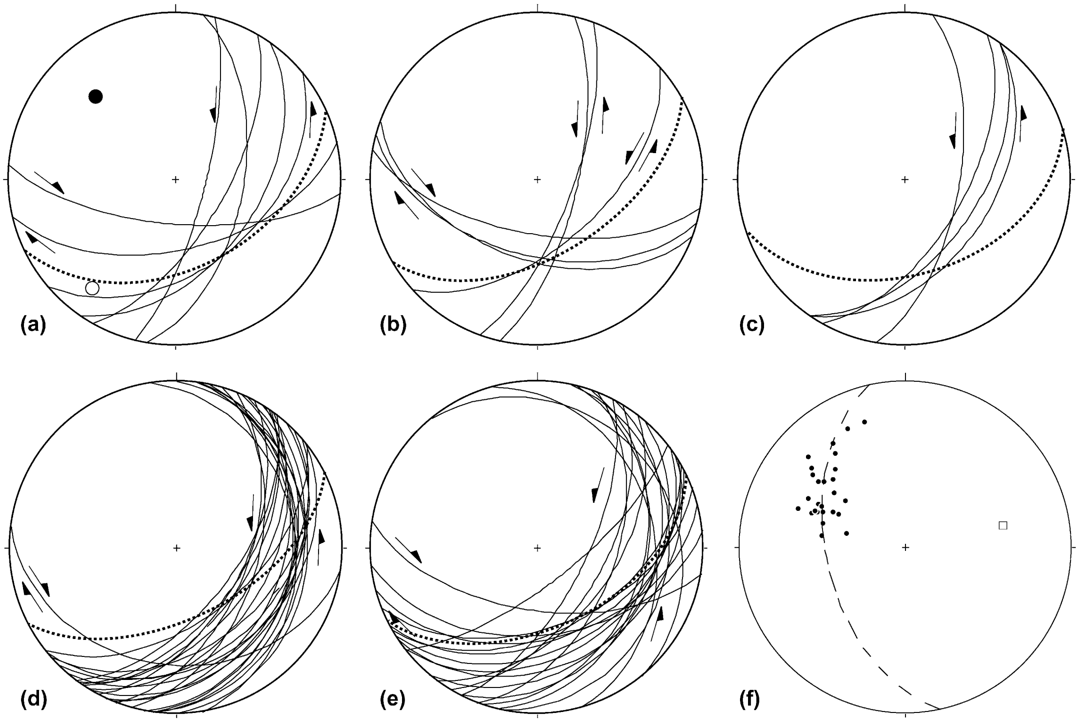


Fig. 5. (a–e) Lower hemisphere, equal area stereographic projections of shears (solid great circles) and gneissic foliation away from shear zones (dashed great circles) at Short Beach, Bremer Bay. The variability in shear zone orientations is interpreted as reflecting differing amounts of rotation towards the regional foliation during progressive deformation. (a) Conjugate shears (seven data), illustrated in Fig. 4b. Mean principal strain axes (fabric lineation/elongation direction = open circle, minimum axis/shortening direction = closed circle) interpreted from the anisotropy of magnetic susceptibility (AMS) by Pisarevsky and Harris (2001) bisect conjugate shears acutely and obtusely, respectively. The gneissic foliation where it has not been reoriented or folded is normal to the minimum AMS axis. (b) Conjugate shears illustrated in Fig. 4a and adjacent area (six data). (c) Shears illustrated in Fig. 7d (four data). (d) Shears illustrated in Fig. 7c and adjacent area (24 data). (e) Shears in the vicinity of those illustrated in Fig. 7e (22 data). (f) Lower hemisphere equal area projection of poles to axial surfaces of folds between shears (points) and pole (open box) to best-fit great circle (dashed).

(D) shears in a brittle–ductile wrench zone (Boudon et al., 1976; Fig. 2).

2. Between parallel planar normal faults (e.g. Davis, 1983, fig. 3) and listric normal faults in sedimentary basins (e.g. Duval et al., 1992, fig. 4; Gross et al., 1997, fig. 4; Withjack and Callaway, 2000, fig. 20). Similar structures have been documented in high-grade rocks at crustal (e.g. Andersen, 1998, figs. 3–5) and outcrop (e.g. Fossen and Rykkelid, 1992) scales.
3. Within crustal-scale detachment fault systems (e.g. Lister and Davis, 1989, figs. 8, 12–14, 17 and 20; Gautier and Brun, 1994, figs. 7–9).
4. In analogue models of normal faulting (e.g. Vendeville and Cobbold, 1987, fig. 4; Fossen and Gabrielsen, 1996, fig. 13b; Gartrell, 1997, figs. 4 and 5).
5. Between blocks of a competent lithology isolated by faulting in a ductile matrix in sedimentary rocks (Gross et al., 1997, figs. 15, 17 and 18) and unconsolidated slides (Nemec et al., 1988, figs. 3–5).
6. Between synthetic shear bands and in development of extensional crenulation/shear band cleavage (Fig. 1f), as portrayed by Platt and Vissers (1980) and Grasemann et al. (2001, fig. 8) and produced experimentally by Williams and Price (1990, figs. 7 and 12).
7. Between strike-slip and oblique-slip faults in an arc massif (Geist et al., 1988).

In the above examples, back-rotated layering remains essentially planar. Open folds may be developed from the deflection of back-rotation layers into bounding brittle–ductile or ductile shear zones. With the possible exception of examples (1) and (6), back-rotation involves a rigid body rotation of both the shear plane and the layering that is folded in a domino or book-shelf manner (Ghosh, 1993, p. 453). Back-rotated layers generally do not exceed orthogonality to bounding shear zones. Johnson (1999), who described back-rotation during crenulation cleavage development, also noted this. Johnson's (1999) crenulation cleavage examples may represent another case of back-rotation between localised shear zones. Although not stated in this paper, the P-domains of the crenulation cleavage described by Johnson (1999) must be shear zones, as the two adjacent short limbs rotate relative to one another (Johnson, pers. comm.). Platt and Vissers (1980) measured the average orientation of back-rotated foliations in extensional crenulation cleavage and found an average amount of back-rotation of ca. 17°.

Folding resulting from greater amounts of back-rotation

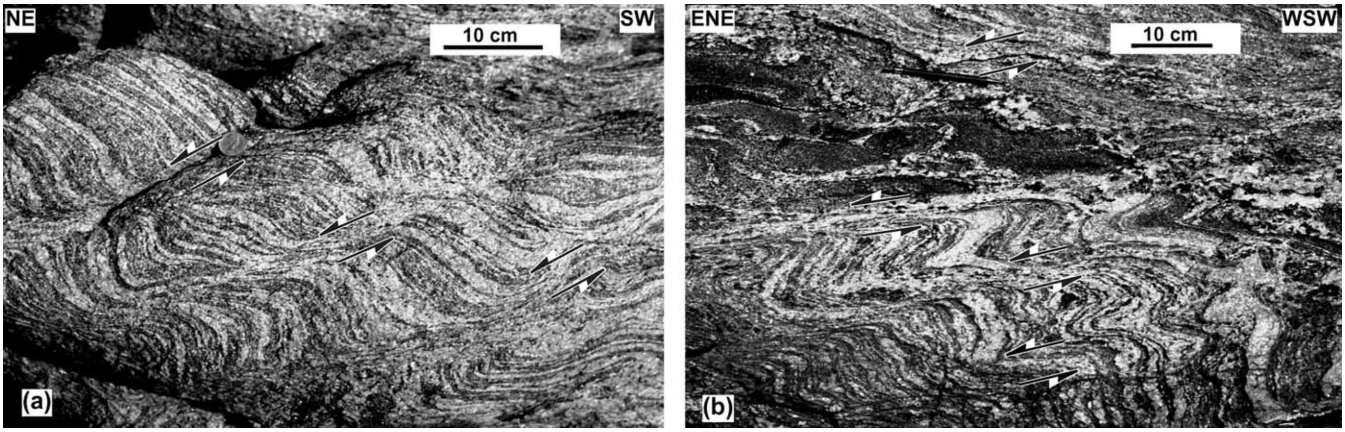


Fig. 6. Folds formed between closely spaced ductile shear zones in migmatitic gneiss, Short Beach, Bremer Bay. (a) Back-rotation of foliation between shear zones producing structures akin to extensional crenulation cleavage (Fig. 1f). (b) Folds with dextral asymmetry developed by back-rotation between shear zones with a dominantly sinistral transcurrent component of displacement. Note buckling of back-rotated foliation in lower right of photo and pegmatites (formed from in situ partial melting) along some shear zones.

between shear zones has generally been overlooked, or attributed to other mechanisms. As shown in the following section, complex asymmetrical folds can form in high-grade gneiss by back-rotation between transcurrent shear zones (first two examples) and normal shear zones (third example).

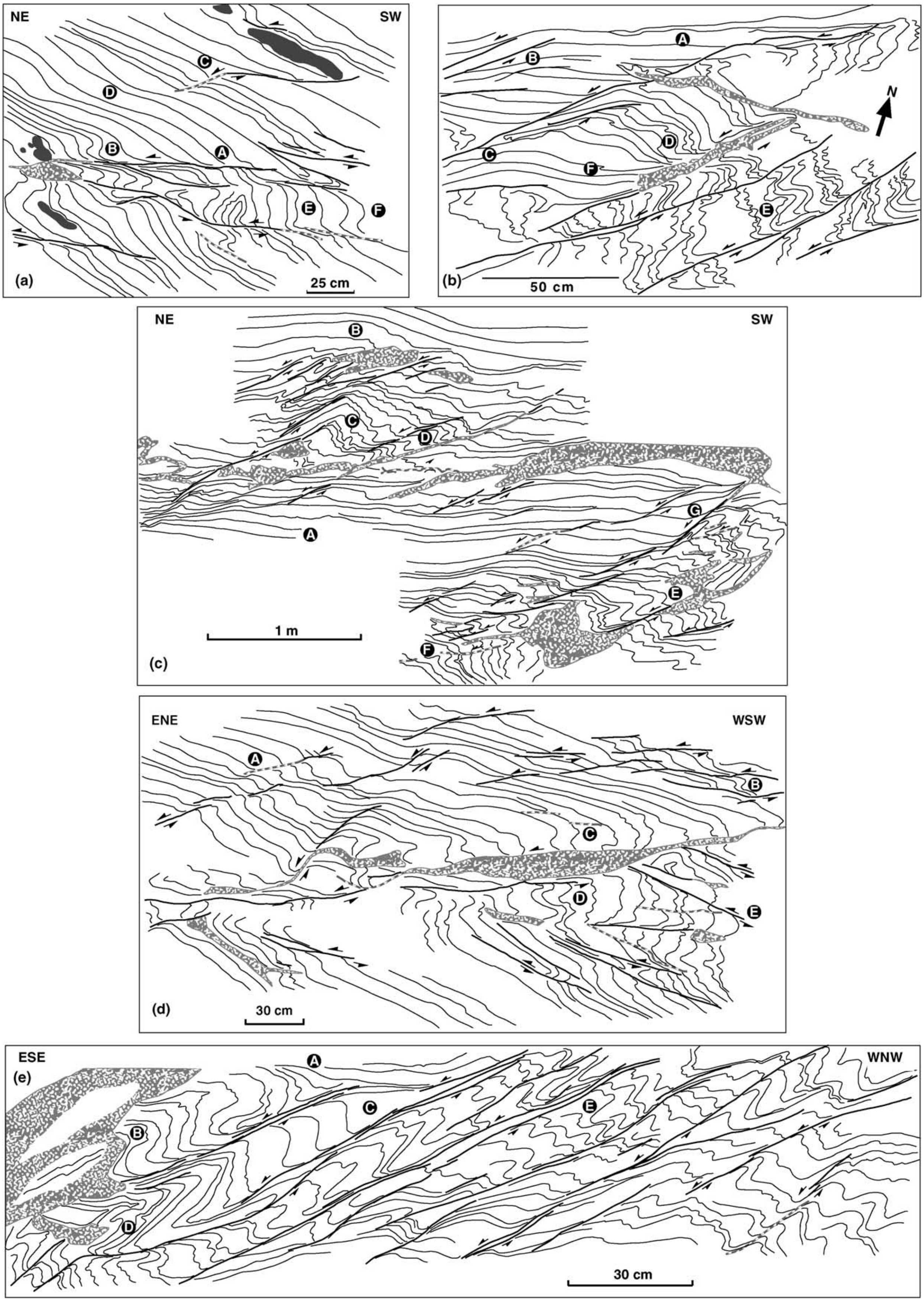
2. Folding due to back-rotation between ductile shear zones

2.1. Bremer Bay, Western Australia

The progressive development of folds between shear zones is seen in granulite-facies, migmatitic gneiss in the Bremer Bay area (Fig. 3) of the eastern Albany Mobile Belt, Western Australia. The Bremer Bay area has undergone a complex deformation history (Harris, 1993, 1995; Pisarevsky and Harris, 2001) during oblique convergence between the Yilgarn Craton of Western Australia (Fig. 3d) and the Mawson Craton of East Antarctica at ca. 1.2 Ga (Black et al., 1992). A gneissic foliation parallel to compositional layering has been folded to form isoclinal recumbent and overturned folds during NW-directed thrusting onto the Yilgarn Craton. These were refolded by open, upright folds above listric extensional shear zones and associated with metre- to decametre-scale boudins during subsequent NW–SE extension. This extensional stage is interpreted as resulting from orogenic collapse, lithospheric delamination, or rebound of a thickened crustal root. New upright folds were formed and pre-existing upright folds tightened and overprinted by a steeply SE-dipping cleavage during a return to NW–SE shortening. The foliation in outcrops of gneiss on headlands by Short Beach and House Beach (Fig. 3c) is moderately to steeply dipping as a result of upright folds. Migmatitic gneiss in both localities is cut by ductile shear zones developed during late-stage, sub-horizontal NW–SE shortening and NE–SW extension (i.e. extension parallel to the local orientation of the orogen).

Line drawings of folds and shear zones in these localities have been traced in the field onto overlapping enlarged photographs. Narrow ductile shear zones striking ca. N–S (sinistral) and E–W (dextral), as shown in Fig. 4, form symmetrically about the gneissic foliation. Their conjugate geometry (Figs. 4 and 5) and orientation of boudin necklines in mafic layers (e.g. location A in Fig. 4b) suggests shears formed during NW–SE contraction and sub-horizontal NE–SW extension. This is in agreement with the orientation of principal strain axes determined from the anisotropy of magnetic susceptibility in the Bremer Bay area by Pisarevsky and Harris (2001). Ratios of long (X) to short (Z) axes of the finite strain ellipsoid of between 2 and 6.3 (assuming $k = 1$) have been estimated by C. Talbot (pers. comm.). These estimates are based on graphical calculations of the orientation of surfaces of no elongation using the method described by Talbot (1970) and Talbot and Sokoutis (1995). Both sinistral and dextral shear zones in migmatitic gneiss have been intruded by pegmatite derived from in situ partial melting (e.g. B and C in Fig. 4b). The gneissic foliation in low strain zones has been deflected into shear zones producing open 'drag' folds (Fig. 4a–c). Folds are also developed at the intersection of conjugate shears (C in Fig. 4d) and between closely spaced shear zones (e.g. B in Fig. 4d).

The Short Beach and House Beach areas (Fig. 3c) preserve stages in the progressive development of folds between closely spaced shear zones (Figs. 6–8). Early stages of folding (Fig. 6a), where foliations between shear zones have back-rotated so that they make angles less than 90° with the bounding shears, resemble extensional crenulation cleavage (Fig. 1f). Rotated segments remain planar except towards their extremities, which are deflected into cross-cutting shear zones. In many cases, greater back-rotation combined with ductile drag into shears results in the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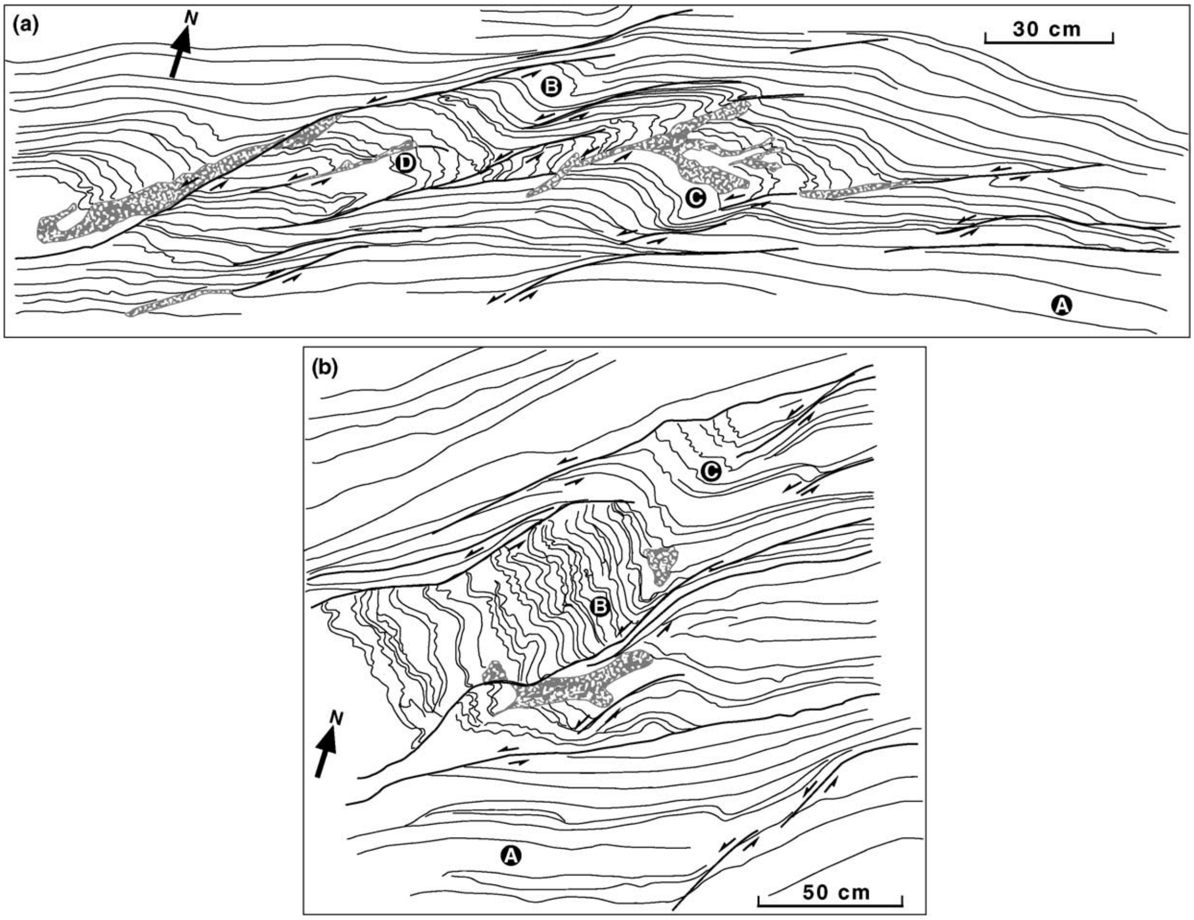


Fig. 8. Localisation of folds within packages bounded by shear zones, House Beach locality. Legend as for Fig. 4. (a) The uniformly oriented foliation (A) away from shears is dragged into sinistral shear zones (B–C) producing folds with dextral vergence. Note intrusion of pegmatites along some shear zones and along some back-rotated layers (e.g. below C). Short-wavelength buckle folds are developed on limbs back-rotated into the shortening field (e.g. D). (b) Layering away from pairs of shears (e.g. A) shows only minor undulations due to incipient shear zones. Layers between two shear zones (as at B) have back-rotated into the shortening field and are deformed by buckle folds. At C, an open fold is developed due to a combination of reverse drag, back-rotation and stepping of shear zones.

formation of asymmetric folds between shear zones (e.g. Fig. 6b). The sense of fold asymmetry is opposite to the sense of displacement on bounding shears. For example, folds with a dextral vergence in Fig. 6b develop between shear zones with a sinistral transcurrent component of displacement. Variable amounts of back-rotation occur in association with a single shear zone (A–B in Fig. 7a) and between two shear zones (E–F in Fig. 7a and C–D in Fig. 7b). Folds also develop above sets of closely spaced shears (e.g. B in Fig. 7c), in a similar manner to extensional forced folds described by Withjack et al. (1990), and in localised contractional sites between *en relais* stepping shear zones (e.g. C in Fig. 7c).

Outside of areas affected by late shear zones, the gneissic

Fig. 7. Line drawings (field tracings on enlarged photographs) of folds at Short Beach (a, c–e) and House Beach (b) due to back-rotation and buckling of foliations between ductile shear zones. Legend as for Fig. 4; see Fig. 3c for locations. (a) Gneissic foliations are dragged into sinistral shear zones. The progression from sinistral deflection of foliation to formation of asymmetrical folds occurs from A to B along a sinistral shear zone. Some shear zones are intruded by pegmatites, especially when they make a steeper angle to the regional foliation, as at C. Open warps (such as at D) represent broad or incipient shear zones. Note increase in back-rotation and folding from E to F. (b) Foliation oriented parallel to the regional trend away from shears (e.g. at A) is deflected into cross-cutting sinistral shears (e.g. B, C) and folded by dextral verging folds (e.g. D). Layers back-rotated so as to have a component of shortening along them have undergone buckle folding, as at E. (c) A = regional orientation of foliation away from shears. Open folds at B and C are formed above the termination of shears. Overturned folds are developed between E and F. Pegmatite has intruded along shears and across folded layers. Note change in angle between shear zones and the regional foliation between F (where shear zones may have rotated from their initial orientation) and G (a shear zone interpreted as forming later in this event). (d) At A, both reverse and normal drag occurs along a shear zone. Overturned folds are formed between and against shears (e.g. at B and C, respectively). Note intrusion of pegmatite along shears, such as between C and D. Back-rotated layers are buckle folded (e.g. at D). At E, early-formed shear zones have rotated into parallelism with the regional foliation. (e) Folds resembling decimetre-scale crenulation cleavage resulting from a combination of drag into shear zones (below A), back-rotation between shear zone (e.g. C) and further folding due to layer-parallel shortening (e.g. E). Note tightening of folds and increase in back-rotation of foliations between shear zones from to A to B and from C to D.

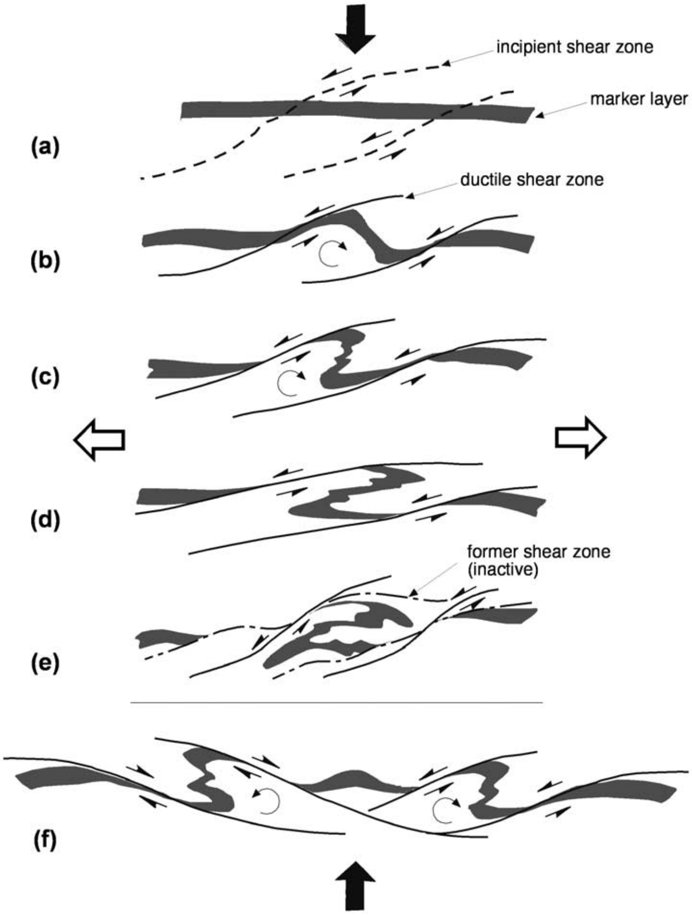


Fig. 9. Schematic diagram showing the progressive development of folds between ductile shear zones based on outcrops at Bremer Bay. (a) Curved shear zones cut gneissic layering. (b) Back-rotation of layer between shear zones. (c) Further back-rotation combined with buckling of limbs rotated so that there is a component of shortening along them. Pegmatites (derived from in situ partial melting in migmatitic gneiss) may intrude along shears. (d) Rotation of shear zones and folds towards the $X-Y$ (flattening) plane of the finite strain ellipsoid. Displacement on shear zones ceases; pegmatites along shears may become foliated. (e) Refolding of previously formed folds between two new cross-cutting shear zones. (f) Folds with opposite asymmetry develop between pairs of conjugate shears. Open, symmetrical folds develop adjacent to the intersection of conjugate shears.

foliation and compositional layering are normal to the maximum shortening direction (Z) determined from magnetic anisotropy and the obtuse bisectrix of conjugate shears. During back-rotation, competent layers may enter the shortening field of the incremental strain ellipse and can therefore undergo buckling. The angle between the surface of no infinitesimal strain and the shortening axis depends on the geometry (k-value) of the bulk strain, even the infinitesimal bulk strain (Talbot, pers. comm.). Flinn (1961, table 11) shows that this angle can range from $35°16'$ (for uniaxial bulk infinitesimal flattening strains) to $54°44'$ (for uniaxial bulk infinitesimal constriction).

Early stages of folding are due to deflection into shear zones (C in Fig.7b) and buckling of competent back-rotated layers (D in Fig. 7b). With greater shortening, short-wavelength buckle folds form in steepened limbs between shear zones (e.g. E in Fig. 7b and D in Fig. 7d). Folds formed by back-rotation and buckling of reoriented layers may be restricted to localised zones between pairs of shear zones (e.g. Fig. 8). Layers outside these zones may be undeformed or show only minor undulations. The complete transition from almost undeformed foliation (normal to the interpreted Z axis of the finite strain ellipsoid) to increasingly overturned folds and minor buckle folding of layers (where they have been back-rotated into the shortening field) is seen between locations A and B in Fig. 7e. Younger, cross-cutting shear zones make a lesser angle with the interpreted Z axis than older shear zones. Folds formed between easterly-dipping shear zones, shears bounding fold packages, and pegmatites intruded along shears have rotated in a clockwise sense towards parallelism with the regional orientation of the undeformed foliation (e.g. E in Fig. 7d).

The process of folding envisaged is summarised in Fig. 9. Open, low amplitude folds initiate due to a back-rotation of layers between two shear zones (Fig. 9a and b). Layers are thinned as they are displaced along each of the bounding shear zones. With further shear displacement, the folds amplify and layers continue to back-rotate. Layers between two shear zones are eventually back-rotated so that they will have a component of shortening acting along them (Fig. 9c)

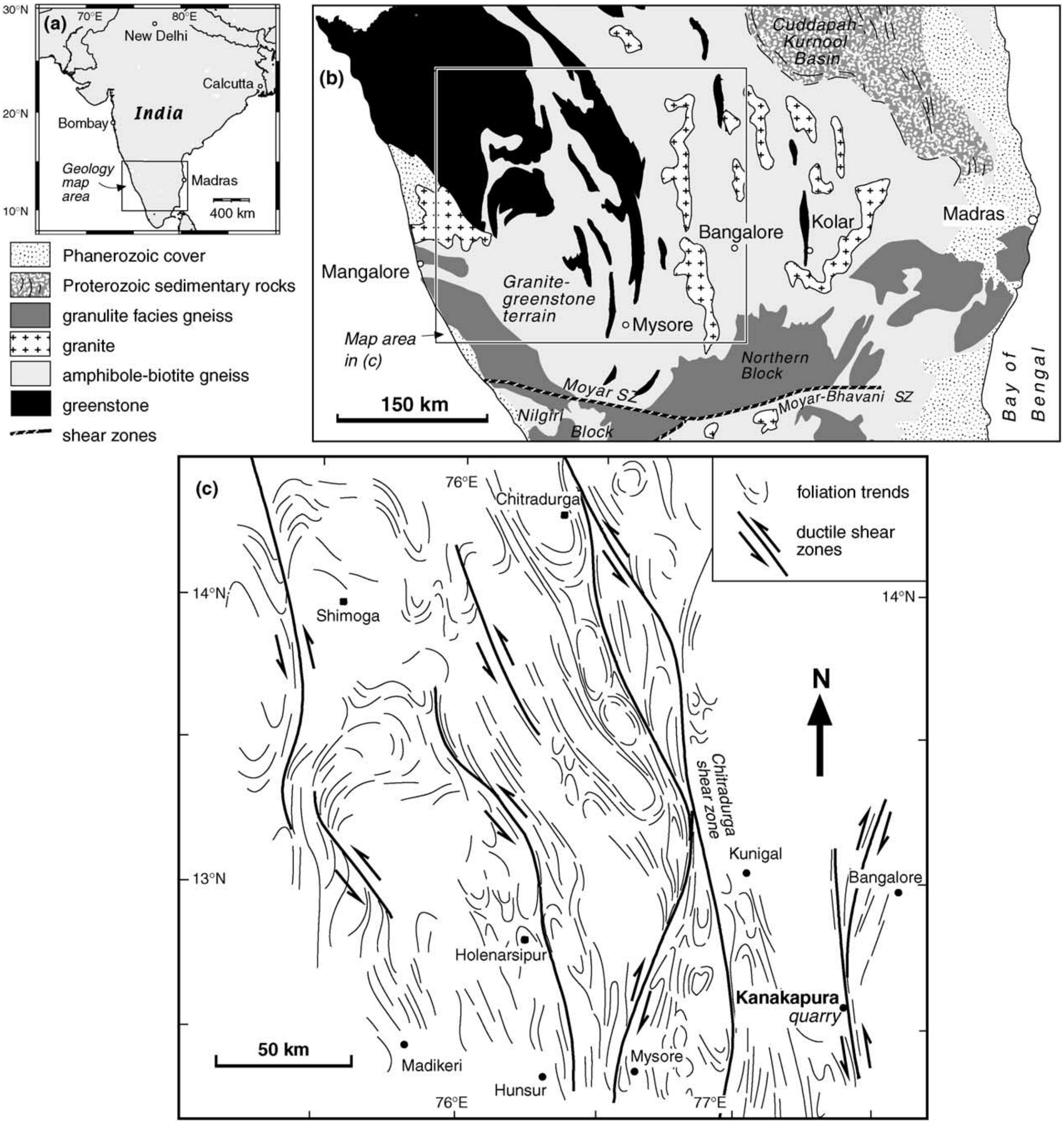


Fig. 10. Location and regional geological setting of the Kanakapura quarry locality. (a) Location of geology map. (b) Simplified regional geology map of southern India based on Eckert and Newton (1993) and Bouhallier et al. (1995). (c) Structural map modified after Bouhallier et al. (1995). The map location is indicated in (b). Kanakapura quarry (source of the cut slices of gneiss illustrated in Fig. 11) is located in the south-eastern part of the map along a regional sinistral transpressional shear zone parallel to the Chitradurga shear zone.

and buckle folds may then develop. The bounding shear zones can also rotate towards parallelism to the X–Y plane of the finite strain ellipsoid (as portrayed by Sander (1948, fig. 54)). Similar rotation of regional strike-slip faults has been documented by Ron et al. (1984) and Garfunkel and Ron (1985). Fold axial surfaces may eventually rotate into parallelism with the regional foliation producing intrafolial folds (Fig. 9d). These intrafolial folds can then be refolded by folds formed between younger, cross-cutting shear zones (Fig. 9e) with continued deformation. Conjugate sets of closely spaced ductile shear zones are likely to develop during bulk coaxial deformation (e.g. Fig. 4d). Folds between each set of shears may develop contemporaneously, but with opposite asymmetry to folds in the conjugate set (Fig. 9f). Broad, open folds can also form near the intersection of conjugate shear zones (Figs. 4d and 9f).

2.2. Kanakapura, Southern India

Gneiss from a quarry at Kanakapura in the Dharwar

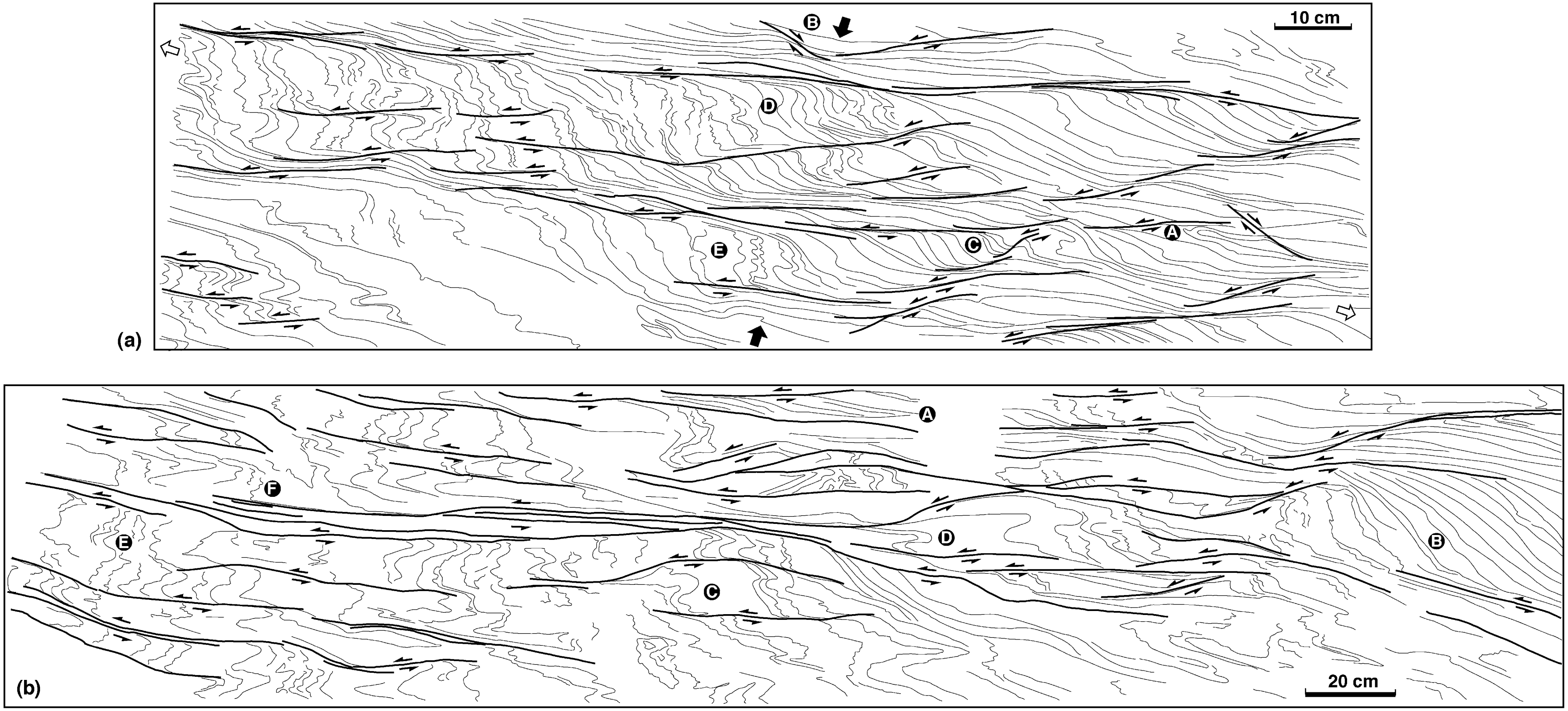


Fig. 11. Line drawings from enlarged photographs of unoriented, abutting polished slices (cut sub-parallel to the shear direction) in gneiss from Kanakapura (see Fig. 10 for location and regional structural setting). (a) The S_1 gneissic foliation and isoclinal F_2 folds (as at A) away from zones of intense folding are displaced by ductile shear zones. The regional maximum shortening (solid arrows) and extension (open arrows) directions are estimated from the obtuse and acute bisectors of conjugate shears (as at B). Back-rotation between shears and deflection of foliations into shear zones creates folds similar to extensional crenulation cleavage (as at C). Overturned folds with dextral vergence form by greater amounts of back-rotation (e.g. D). Foliations rotated into the shortening field are deformed by shorter wavelength, more symmetrical folds (as at E). (b) The pre-shearing orientation of foliation is preserved in low strain area at A. Back-rotation of foliation, with only minor deflection into shear zones, can be seen at B. Folds with dextral vergence are developed between shears at C and D. Short-wavelength buckle folding occurs where foliations have back-rotated into the shortening field (e.g. at E and F; note folding of F_2 isoclinal folds at E).

Craton, Karnataka State, southern India (Fig. 10) shows the progressive development of folds between ductile transpressional shear zones. Regional foliation trends in the western and central Dharwar Craton are deflected and displaced in a sinistral sense along NNW-striking shear zones and in a dextral sense along minor NNE-striking shear zones (Fig. 10c), indicating bulk E–W shortening (Ramakrishnan, 1993; Bouhallier et al., 1993, 1995). The most prominent structure, the Chitradurga Shear Zone (or Chitradurga Belt of Narain and Subrahmanyam, 1986), is a ca. 450-km-long, sinistral transpressional shear zone (Ramakrishnan, 1993). This structure has a prominent gravity expression and has been interpreted by Narain and Subrahmanyam (1986) as representing a closed rift and the position of a likely suture between the western and eastern blocks of the Dharwar Craton. Approximately N-striking Archaean structures (including the Chitradurga Shear Zone) have undergone dextral Quaternary fault reactivation (Valdiya, 1998). The samples studied, however, show only minor evidence for brittle overprinting.

The Kanakapura area, part of the Karnataka high-grade gneiss terrain east of the Closepet Granite, comprises tonalitic to granitic gneiss, amphibolites and two-pyroxene granulites whose petrology is described in detail by Mahabaleswar et al. (1986). Kanakapura is situated along a NNW-striking sinistral transpressional ductile shear zone that is parallel to, and east of, the Chitradurga Shear Zone (Fig. 10c). Shear zones deform folded gneiss intruded by basic dykes and hence represent regional D_3 structures of Sugavanam and Vidyadharan (1988). Shear zones are thought to be coeval with emplacement of the 2.5 Ga Closepet granite (Jayananda and Mahabaleswar, 1990; Bouhallier et al., 1993, 1995).

Fig. 11 shows line drawings of folded gneissic foliation (S_1) and shear zones traced from enlarged photographs of polished slices of Kanakapura gneiss. Examination of large, uncut blocks showed that faces were cut sub-parallel to the shear direction. Isoclinal (F_2) folds of S_1 (as at location A in Fig. 11a) are deformed by cross-cutting shears and associated folds. The transition from layers unfolded in D_3 (except for drag into cross-cutting sinistral and minor dextral shear zones; location B in Fig. 11a) to tightly folded layers within back-rotated packages between shear zones can be clearly seen. A similar progression to that seen at Bremer Bay is observed. Planar, back-rotated layers dragged into shear zones (e.g. C in Fig. 11a; B in Fig. 11b) are folded with dextral vergence with increased back-rotation (e.g. D and surrounding zone in Fig. 11a; C and D in Fig. 11b). Competent layers back-rotated into the shortening field are buckled (e.g. E and F in Fig. 11a and b).

2.3. Leeuwin Complex, Western Australia

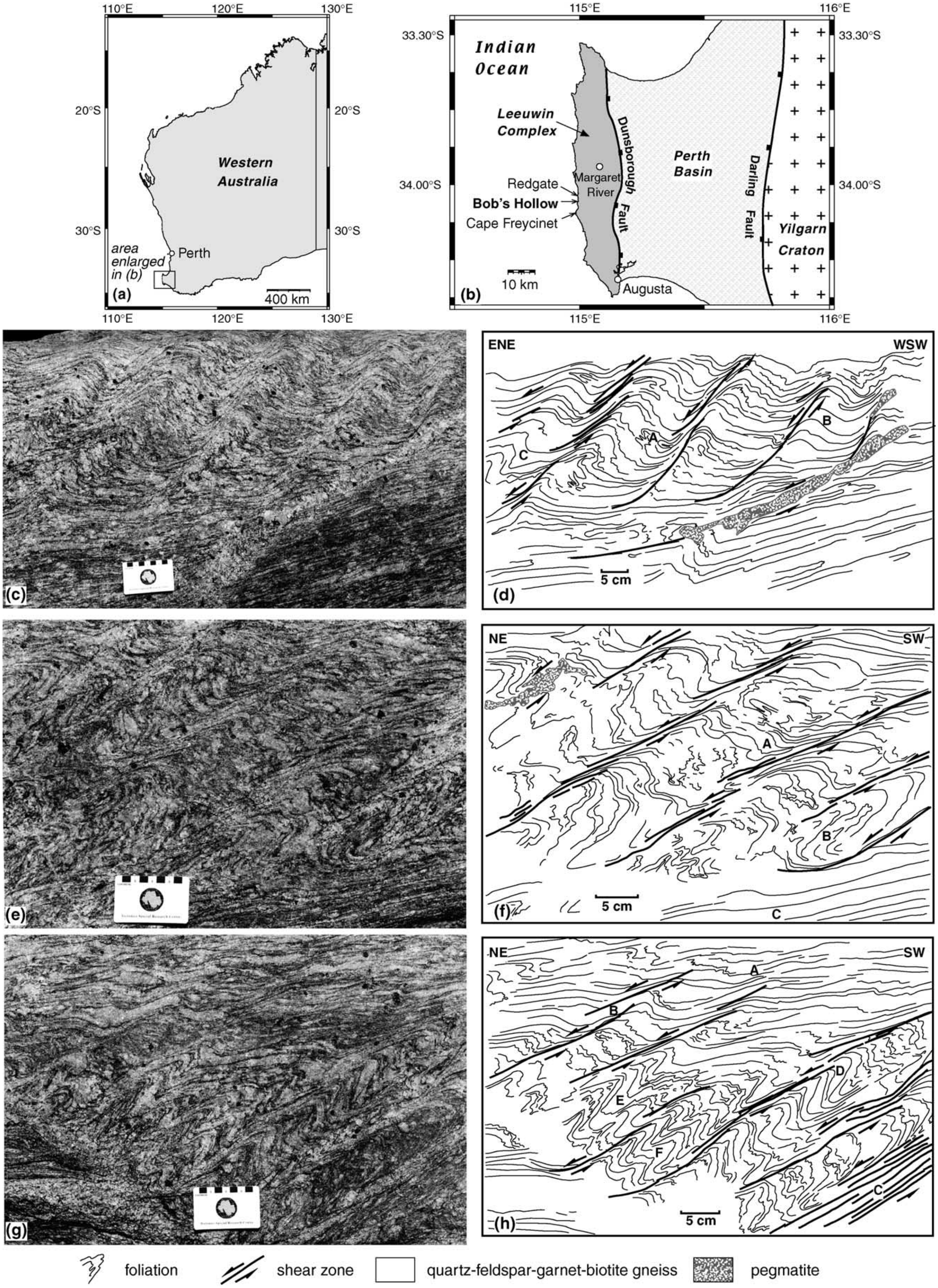
The Leeuwin Complex in southwestern Western Australia (Fig. 12a) comprises ‘A-type’ granites of peralkaline affinity, anorthosite and leucogabbro formed within a continental rift environment and deformed and metamorphosed to amphibolite to granulite facies during the Neoproterozoic (Wilde and Murphy, 1990; Harris, 1994; Nelson 1995). Early-formed structures are preserved in areas not affected by subsequent folding, such as in coastal exposures between Cape Freycinet and Redgate (Fig. 12b). In this area, the S_1 gneissic foliation parallels compositional layering. Both are isoclinally folded by F_2 folds with sub-horizontal axial surfaces (e.g. location A in Fig. 12d). An axial planar foliation (S_2) is locally observed in F_2 fold hinges. The horizontal to shallowly dipping composite S_1/S_2 foliation is displaced and deflected into normal ductile shear zones striking between 150° and 170° and dominantly dipping ENE (e.g. location A in Fig. 12f and locations A and B in Fig. 12h). Whilst generally discrete, narrow structures, some broad shear zones are also developed (e.g. location C in Fig. 12h). Open folds were formed between shear zones (e.g. location B in Fig. 12d) due to a combination of planar back-rotation and drag into shears. Shear related folds refold F_2 isoclinal folds. Single-wavelength, inclined to overturned folds (e.g. location C in Fig. 12d and B in Fig. 12f) are interpreted as having formed by greater amounts of back-rotation between normal shear zones. Multiple wavelength folds at locations E and F in Fig. 12h represent buckling of back-rotated layers.

3. Discussion

3.1. Factors enhancing folding during back-rotation

Back-rotation of a foliation displaced by shear zones has been previously noted in diverse situations (as summarised in Section 1.2), but in these examples back-rotation has seldom been sufficient to produce asymmetrical folds as described in Section 2. Clearly there must be reasons why, in some cases, back-rotation is inhibited and asymmetric folds do not develop, whereas in the examples described in Section 2, back-rotation was accentuated. A range of factors appears to determine why some rock packages may undergo a large amount of back-rotation whereas others do not. As noted by Jiang and White (1995), (i) it is essential to differentiate between displacements related to shear zone boundaries and the response of the intervening rock, and (ii) knowing the nature of the boundary displacements does not constrain the kinematics of structures within the deforming zone.

Johnson (1999) suggests that by back-rotation during crenulation cleavage development, the foliation being crenulated may dilate so that quartz dissolved from along the crenulation cleavage (i.e. along a zone undergoing contraction) may be redeposited. Johnson (1999) contends that back-rotation beyond orthogonality with cleavage seams would no longer favour this process and that deformation must proceed by one or more different mechanisms


110°E
120°E
130°E
20°S
30°S
Western Australia
Perth
area enlarged in (b)
400 km
(a)
115°E
116°E
33.30°S
34.00°S
Indian Ocean
Leeuwin Complex
Redgate
Bob's Hollow
Cape Freycinet
Margaret River
Dunsborough Fault
Perth Basin
Darling Fault
Yilgarn Craton
10 km
Augusta
(b)
(c)
ENE
WSW
A
B
C
5 cm
(d)
(e)
NE
SW
A
B
C
5 cm
(f)
(g)
NE
SW
A
B
C
D
E
F
5 cm
(h)
foliation
shear zone
quartz-feldspar-garnet-biotite gneiss
pegmatite

that progressively shorten the micro-fold hinges for further back-rotation to occur. A process of dissolution similar to that described by Johnson (1999) is, however, unlikely to occur under high-grade metamorphic conditions. Whereas cleavage in low-grade rocks is a plane undergoing contraction subject to volume loss due to pressure solution, the presence of pegmatites along shear bands bounding back-rotated folds in gneiss suggests that they are dilatational structures. In some areas of migmatitic gneiss, partial melt has also migrated to form foliation-parallel pegmatites in back-rotated domains where the maximum extension direction was at a large angle to the foliation. Formation of partial melt in migmatites results in a positive volume change and an increase in melt (pore-fluid) pressure (Davidson et al., 1994). Melt generated in situ will migrate towards dilatational sites. The presence of partial melt greatly weakens rocks, and strain is temporarily concentrated within melt-bearing zones (Davidson et al., 1994). In addition, the effective normal stresses are reduced by an amount equivalent to the melt pressure (as illustrated by Davidson et al., 1994). Increased ease of shear displacement along these zones may result in greater backward rotation of the zone between shears. Variable extension across a package of layers due to volume changes during partial melting in migmatitic gneiss (Bons, 1999) may also be a factor enhancing increased back-rotation (R. Gabrielsen, pers. comm.).

Geist et al. (1988, fig. 8) and Ghosh (1993, p. 453) show how the width of a zone cut by parallel faults increases, and the angle faults make with the maximum extension direction decreases, during domino- or bookshelf-style faulting. In domino-style faulting, back rotated layers remain planar and of constant length. A similar mechanism may operate under high-grade metamorphic conditions where parallel ductile shear zones displace a gneissic foliation or compositional layering. Apart from drag folding on shear zone margins, folds as described in Section 2 would not form by this mechanism, as back-rotation of layers is accommodated by increasing spacing between shear zones. Layer-parallel shortening during back-rotation between two shear zones is, however, a geometrical necessity where the distance between shear zones does not increase sufficiently with progressive deformation to accommodate the length of back-rotated layers. Similarly, shortening of back-rotated layers must also occur when shear zones converge (as in shear-bounded lozenges similar to those shown in Fig. 2).

In the examples described in Section 2, folding due to back-rotation between shear zones has taken place in anisotropic gneiss with alternating felsic and mafic layers. Cobbold (1976) has shown that the effective rheology of an anisotropic material changes as it rotates with respect to the flow field. If there is a strong mechanical anisotropy, folds may initiate in the back-rotated layers due to internal buckling instabilities (Biot, 1965; Cobbold et al., 1971; Carreras et al., 1977). A rotated domain may deform at a rate different to that of the surrounding material causing amplification into a fold (Platt, 1983). Open folds may develop if the rotated layer lies in the extensional field (Platt, 1983) and tighter folds will form if the layer lies in the contractional field. Alternatively, if there is no mechanical contrast between layers, they may passively increase in thickness in the back-rotated zone. Folds develop and/or amplify during rotation of the bounding shear zones, as well as the reoriented layering between them, towards the $X-Y$ (flattening) plane. Foliations that have been rotated into the shortening field will undergo further layer-parallel shortening and thus buckle (given suitable viscosity contrasts, length of the segment between shears and width of layers). Folding during back-rotation may be facilitated when extension is inhibited in one direction (e.g. due to a nearby more competent object such as an intrusive body).

In addition to back-rotation and buckling, some folds illustrated from Bremer Bay and Kanakapura may have formed due to differing amounts of displacement (but with the same shear sense) along parallel shear zones similar to Gleitbretter folds, as described in Section 1.

3.2. Situations in which folding during back-rotation between shear zones may occur

It has been shown in Section 2 that folds formed by back-rotation may occur in high-grade gneiss between discrete transcurrent, transpressional and normal ductile shear zones. Strain in broad ductile shear zones may also be partitioned into bands of intense shear and into intervening lithons of less intense shear within which, however, rotation may still take place (see Simpson and De Paor (1993) and citations therein). It is therefore also likely that folds overturned in the opposite sense to the bulk shear sense may develop within ductile shear zones between C-surfaces (Berthé et al., 1979a,b), either parallel or oblique to shear zone margins (Jiang and White, 1995), at thin-section to regional scales. Back-rotation may also occur between antithetic (C″, ecc2) extensional or normal-slip crenulation cleavages (Berthé et al., 1979a,b; Platt and Vissers, 1980; Dennis and Secor, 1990) and reverse-slip crenulation cleavage (Dennis and Secor, 1990) within ductile shear zones.

3.3. Criteria to distinguish folds formed by back-rotation

Criteria that help distinguish folds formed by back-rotation between shear zones from 'drag folds' that record an asymmetry consistent with the bulk shear sense are as follows:

1. Presence of pegmatites sub-parallel to fold axial surfaces. Shears that displace overturned fold limbs formed by 'drag folding' during shear sub-parallel to a layer

Fig. 12. The Leeuwin Complex, Western Australia. (a,b) Location maps. (c–h) Photographs and corresponding line drawings (traced from enlarged photographs) of vertical cross-sections of folds developed by back-rotation between normal shear zones at Bob's Hollow. See text for description.

generally lie in the contractional field of the incremental strain ellipse (e.g. thrusts during regional shortening of initially shallowly-dipping layering). As such, they are unlikely to dilate (except within dilatational bends or jogs along them), and hence do not act as sites towards which fluids migrate. Veins or pegmatites are, therefore, unlikely to occur along these shear zones. In contrast, pegmatites commonly occur along shear zones on the long limbs of back-rotated folds (e.g. Figs. 6–8). In migmatitic gneiss, pegmatites along shear zones are formed due to migration of melt generated in situ (e.g. B in Fig. 4c; Fig. 6b). As their margins are commonly diffuse, such pegmatites may partly obliterate evidence for shearing. Pegmatites formed along shear zones rotate towards parallelism with the regional foliation. A range in fold styles from open overturned folds to transposed folds with foliation-parallel pegmatites may be present. Note that other mechanisms to produce axial planar leucosomes in folded high-grade rocks, such as high fluid pressure, transitory relaxation of stresses, boudinage and dilational jogs, have been described by Vernon and Paterson (2001).

2. Refolded, transposed folds developed in a single deformation/metamorphic event.
3. Concentration of folds into localised packages (as seen in Fig. 8b). A regional foliation may be consistent in orientation outside zones of intense folding.
4. Coexistence of folds with opposite asymmetry (as shown schematically in Fig. 9f) in an area that has not experienced polyphase folding, and that cannot be explained as parasitic folds about a larger fold closure or as box folds.
5. Overturned limbs that are thicker than the upright limbs (e.g. centre of Fig. 6b). Note, however, that in folding due to shear sub-parallel to a layer, as illustrated by Fossen and Rykkelid (1990) and Fossen and Holst (1995) and in kink- and shear-band folds (Plotnikov, 1994, figs. 3.21 and 6.1), the short, forward-rotated fold limb will also undergo initial thickening prior to thinning.
6. Shear zones with the same sense of displacement on both limbs of folds. This contrasts with shear zones with opposite senses of displacement along attenuated limbs of folds formed by intense regional shortening, such as described by de Wit et al. (2001, fig. 3).

Examples of vorticity partitioning in shear zones have been presented by Lister and Williams (1983). Comparison of their fig. 7b (a photograph showing variable amounts of overturning of folds along a zone inclined to the regional foliation) with folds portrayed in Figs. 6–8 and 11 suggests that they may have formed by either (a) back-rotation between sinistral shear zones, or (b) as drag folds in a dextral shear zone, as interpreted by Lister and Williams (1983). Identical fold geometries may result from the opposite sense of displacement on bounding shears, depending on whether there has been forward- or back-rotation between shears. The mechanism of folding due to back-rotation between shear zones therefore poses additional constraints on the use of fold asymmetry as a kinematic indicator to those previously noted by Ghosh (1966) and Ramsay et al. (1983).

4. Conclusions

Folds with the opposite sense of asymmetry to the bulk shear sense may form in high-grade rocks by back-rotation between shear zones combined with buckling of reoriented foliations. The bounding shear zones and back-rotated foliations may also rotate towards the shortening (X–Y) plane of the finite strain ellipsoid, resulting in additional buckle folding and development of transposed folds. This mechanism of folding can be especially difficult to identify in migmatitic gneiss where shear zones between fold packages may be obliterated by pegmatites with diffuse margins. Pegmatites sub-parallel to the axial surfaces of folds are, however, difficult to explain in classical models for folding where dilation along the axial surface is not likely (unless fluid pressure exceeds the applied stress). Folds due to back-rotation and subsequent buckle folding at outcrop to regional scales may have previously been misinterpreted as drag folds, resulting in the opposite sense of tectonic transport being deduced. Back-rotation between normal shear zones provides a mechanism for folding of sub-horizontal foliations in extensional terrains.

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