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Conflicting shear sense indicators in shear zones; the problem of non-ideal sections

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Abstract—Deflection of pre-existing planar structures such as foliations or veins by ductile shear zones is geometrically very similar to the curvature of newly developed shear zone-restricted foliations in zones that cut a rock with a random fabric. Sense of curvature of shear zone-restricted foliations can be used to determine shear sense, but the deflection of pre-existing planar structures is less reliable. Two examples are presented of shear zones in Australia where both types of structures seem to represent conflicting shear sense. This conflict can be attributed to a geometrical effect which causes deflection of older structures in an opposite direction to shear sense on outcrop surfaces oblique to the displacement vector. If the orientation of the displacement vector cannot be accurately determined in shear zones, e.g. because of limited outcrop or unclear lineations, most shear sense indicators can still be used to determine shear sense, but pre-existing planar structures are notoriously unreliable.

INTRODUCTION

Determination of shear sense in shear zones is an important tool in the tectonic analysis of deformed terrains. Structures such as shape fabrics, mantled porphyroclasts, and shear band cleavage in ductile shear zones have different geometry, but their idealised three-dimensional shape shares a monoclinic symmetry with a two-fold rotation axis (Ramsay & Huber 1987, Hanmer & Passchier 1991, Passchier & Trouw 1995, p. 110). This shape-symmetry is thought to reflect the monoclinic symmetry of non-coaxial flow in the ductile shear zone (refs cit.). It is the dextral or sinistral 'sense' of monoclinic symmetry (also referred to as asymmetry) of fabric elements in outcrop that is used to determine sense of shear (refs cit.). Sections normal to the monoclinic symmetry axis (the 'ideal section') show the 'asymmetry' of structures to greatest advantage.

If a gradient of increasing strain exists towards the centre of a ductile shear zone that transects rocks with an originally random fabric, associated rotation of the finite strain ellipsoid towards the zone boundary orientation produces a characteristic curvature of the shape fabric in ideal section (Ramsay & Graham 1970) that is now one of the most commonly used shear sense indicators. We refer to the planar and linear elements of this shape fabric as shear zone restricted (SZR) foliation and lineation, respectively.

In a parent rock that contains an older foliation or set of dykes, the older planar structure is rotated towards the shear zone boundary orientation and develops a curved shape very similar to that of SZR-foliations. Because of this similarity, it is tempting to use this geometry to determine sense of shear as for SZR-foliations. However, as pointed out by Wheeler (1987), deflected older planar fabrics may give the wrong shear sense if they are interpreted in this way: two examples of such structures are presented in this paper. We investigate the problem of oblique sections through shear sense indicators in some detail to see if other structures may also be problematic, and how such 'problematic' structures can be recognised.

CONFLICTING SHEAR SENSE INDICATIONS

Robbies Well Pluton

The Robbies Well Pluton is a porphyritic biotite monzogranite that intrudes a greenstone belt at Mount Ross in the northern part of the late Archaean Eastern Goldfields Province of the Yilgarn Craton, Western Australia (Australian Map Grid 3140-090240; Williams 1989; Passchier 1990). Observation of the pluton is restricted to flat pavement-outcrops. In the boundary zone of the pluton, a biotite foliation can be traced into aplite-, pegmatite- and microgranite veins that lie at a high angle to the foliation. One of the pavement outcrops contains a set of 10–60 mm wide anastomosing mylonite zones (Figs. 1 and 2). A shape fabric in the zones defined by elongate quartz lenses lies oblique to the shear zone boundary (Figs. 1 and 2a—inset) and is locally slightly sigmoidal, both indicating a sinistral shear sense. This shape fabric is probably related to the same deformation event that formed the external biotite foliation, and the shape fabric in the zones is therefore interpreted as an SZR-fabric. Pegmatite veins are cut by one of the shear zones and most of these have apparent dextral offset and dextral deflection of the veins close to the shear zone margin (Figs. 1 and 2a). However, the internal quartz-shape fabric between dextrally offset segments indicates *sinistral* shear sense as described above (Fig. 2a, inset). Because of the planar nature of the outcrop, dip values on most veins are inaccurate (exposed steep fractures at a high angle to the veins are rare and give only 10–20 mm of relief) and no lineations were observed. However, since vein 5 in Fig. 1 has a very small horizontal apparent displacement, the displacement vector must be nearly parallel to the intersection of the shear zone and this vein.

Mulgandinnah shear zone

A similar situation is found in the Shaw Batholith of the Early Archaean Pilbara Craton, Western Australia. Along the western contact of the Shaw Batholith, granitic and granodioritic rocks are affected by a major early Archaean transcurrent subvertical shear zone up to 5 km wide, the Mulgandinnah shear zone. In the southern part of the shear zone at Tambourah (Australian Map Grid 2754-315919), the mylonitic foliation (S_m) is subvertical, a linear shape fabric plunges gently north, and δ-type mantled porphyroclasts (Passchier & Simpson 1986) indicate a sinistral sense of shear (Fig. 2b, inset). S_m and deformed pegmatite veins that lie subparallel to S_m are locally cut by shear bands, exposed on horizontal pavements with little relief (Fig. 2b), and are offset *dextrally*. Casual observation could lead to the conclusion that late reversal of shear sense took place in the Mulgandinnah shear zone, or even that mantled porphyroclasts are unreliable and show the wrong shear sense.

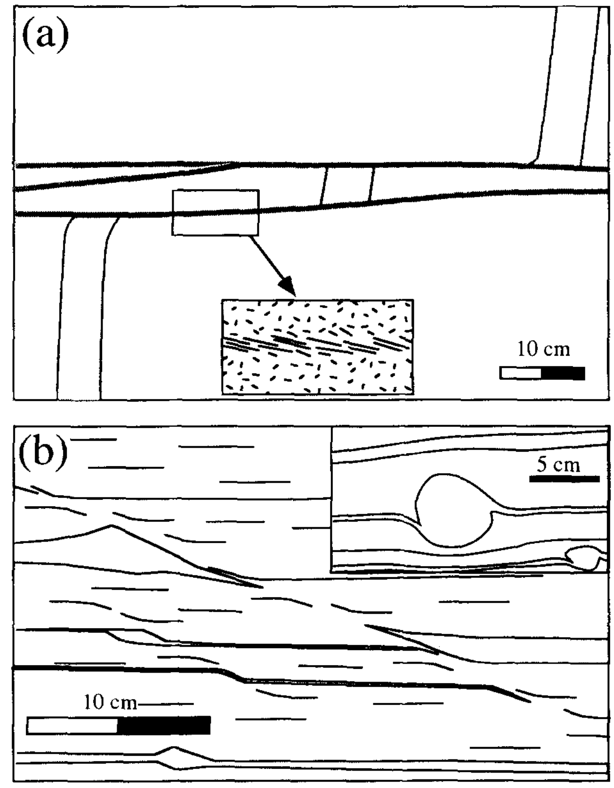

Fig. 2. Field sketches of conflicting shear sense indicators on horizontal pavement outcrops in the Robbies Well Pluton (a) and the Mulgandinnah shear zone (b), Australia. (a) A pegmatite vein is displaced dextrally and seems to indicate a dextral shear sense. The inset shows an enlarged part of the same shear zone with a foliation defined by quartz lenses slightly oblique to the shear zone boundary, indicating a sinistral shear sense. In fact, shear sense is sinistral on the shear zones. (b) Granite mylonite with sinistral shear sense as indicated by δ-type mantled porphyroclasts (inset). The mylonite is cut by a shear band, apparently indicating a dextral shear sense. In fact, shear sense is also sinistral in this band, as explained in the text.

EXPLANATION

The observed conflicting shear sense indications can be explained as an effect of the orientation of deflected markers with respect to the true displacement vector and the observation section (Wheeler 1987). The conflict arises because deflection of a pre-existing planar marker by a shear zone will lead to monoclinic shape symmetry only if the intersection line of marker and shear zone is parallel to the vorticity vector of flow in the zone (usually normal to the stretching lineation developing in the zone, except for transpression, and some other non-plane strain shear zones; Fossen & Tikoff 1993); in all other cases the resulting geometry will have a triclinic- or lower symmetry and 'sense' of asymmetry in certain sections can be opposite to that expected from the true shear sense in a shear zone.

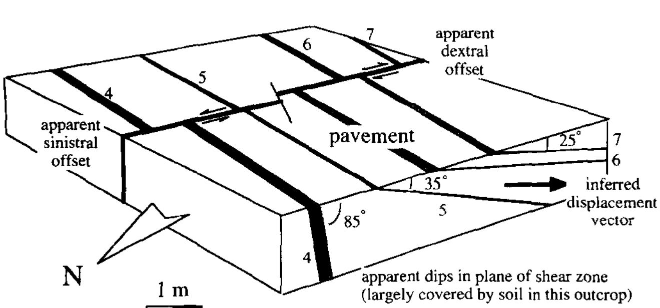

Fig. 1. Schematic isometric diagram of a pavement-outcrop in the Robbies Well Pluton showing the orientation of pegmatite veins and the shear zone. Offset of veins on the pavement is both sinistral and dextral. Slight sinistral offset of vein 5 on the pavement compared to larger offset of other veins implies that the displacement vector (bold arrow) of the ductile shear zone (and possibly a stretching lineation) must be slightly shallower (35–30°) than the apparent dip of vein 5 in the plane of the shear zone. Sinistral sense of shear in the plane of the pavement as determined from curved quartz lenses in the shear zone (Fig. 2a) is correct, despite the apparent dextral offset of veins 6 and 7.

Deflection of a planar fabric element as observed in a planar outcrop section depends on the orientation with respect to an external reference frame of the following elements: (1) the planar fabric element; (2) the shear zone; (3) the displacement vector in the shear zone; and (4) the surface of observation. The effect of these variables is shown in Figs. 3(a–c), inspired by Fig. 3 of Wheeler (1987). In these diagrams the surface of observation is chosen as horizontal, and the shear zone as trending EW. The shear zone is either vertical or dipping to the south, and the upper block moves to the south, southwest or west (normal sinistral movement). Sense of shear is defined as the sense of the horizontal displacement component of wall rocks as seen in the plane of observation, looking down. A 45° great circle segment (grey) illustrates the spread in orientation of poles to deflected SZR-foliations in a strain gradient within a shear zone developing by simple shear. SZR-lineations (stretching, or mineral lineations) plot on the same great circle but orthogonal to these poles. At very high strain, the SZR-lineation approximately coincides with the displacement vector.

If the deflection direction of planes of different orientation in this setting is investigated for variable plunge of the displacement vector and dip of the shear zone, the following patterns emerge (Wheeler 1987):

(1) Two pole-position domains of planes can be distinguished in space: a 'concordance domain' where sense of deflection of a planar fabric as observed on outcrop surface corresponds to sense of shear, following the behaviour of SZR-fabrics (Ramsay & Graham 1970) and a 'discordance domain' where both are conflicting (Fig. 3a). The discordance domain is bounded by the plane normal to the intersection line of the shear zone and the observation surface, and the plane normal to the displacement vector (Fig. 3a).

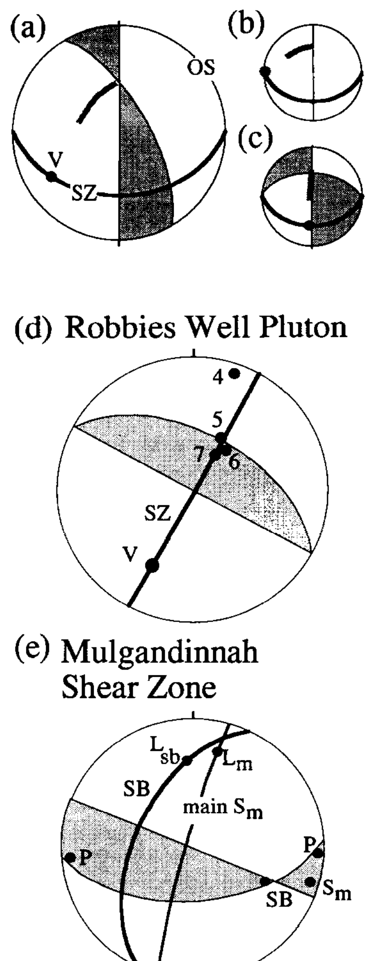

Fig. 3. Stereograms showing the relation of fabric elements for different orientation of a shear zone (SZ) and displacement vector (V), inspired by fig. 3 of Wheeler (1987). The observation surface (OS) is horizontal. Grey curves—set of poles of shear zone related (SZR) foliations. Grey fields—discordance domains of shear sense. White fields—concordance domains of shear sense. (a–c) Examples of three different orientations of SZ and V discussed in the text. (d) Orientation of structures around the ductile shear zones in the Robbies Well Pluton. Only planar surfaces whose poles plot in the concordance domain show consistency of displacement and shear sense. Numbers refer to numbered pegmatite veins in Fig. 1. (e) Orientation of structures around the ductile shear zones in the Mulgandinnah shear zone; only the discordance domain of a shear band (SB) is shown. S_m—mylonitic foliation. L_m—stretching lineation in main mylonite. L_{sb}—stretching lineation in shear band. P — pegmatites.

(2) A discordance domain is absent only if the displacement vector coincides with the intersection line of the shear zone and the surface of observation (Fig. 3b). Ideal sections will therefore *always* give a concordance relationship and pose no problem in the establishment of shear sense. In all other cases, orientations may be found where conflicting relationships occur. In the diagrams of Fig. 3 where the surface of observation is a horizontal pavement, only shear zones with pure transcurrent movement will in all cases give true relations (Fig. 3b). If the displacement vector is not horizontal, a discordance domain may occur.

(3) The size of the discordance domain approaches 50% of space when the displacement vector and the intersection line of the observation surface and the shear zone are close to orthogonal (Fig. 3c). However, if they are truly orthogonal, no shear sense is defined in the plane of observation (perfect dip-slip or normal fault) and *all* deviations from SZR-fabric orientations will give an apparent sinistral or dextral shear sense. This case is well known from the technique for determining sense of normal fault movement by apparent offsets of dipping stratigraphy.

(4) Poles to SZR-foliation plot on a segment of a great circle that lies in the concordance domain for most situations. Only if the displacement vector is normal to the intersection line of the planar fabric and the surface of observation, does the great circle segment lie on the boundary between the concordance and discordance domains and shear sense observation may be non-conclusive (Fig. 3c). SZR-foliations will therefore give true relations on most outcrop surfaces, and are reliable shear sense indicators, contrary to other planar fabric elements.

We have checked the model for the two geological examples given above (Figs. 3d, e). Concordance and discordance domains were drawn based on the orientation of the shear zone, the observation surface and a displacement vector that was reconstructed from vein displacement sense (Fig. 3d) or projection of the stretching lineation on the plane of the shear zone (Fig. 3e). In the Robbies Well Pluton, the dextral displacement of veins 6 and 7 can be explained by a vein dip that is shallower than the displacement vector in the shear zone (Fig. 3d); these veins then plot in the discordance domain. The foliation defined by quartz aggregates, however, corresponds to a SZR-foliation and plots in the concordance domain; shear sense is therefore sinistral, as indicated by the SZR-foliation. For the Mulgandinnah shear zone (Fig. 3e) it is also clear that the deflected veins plot in the discordance domain. Nevertheless, stretching lineations in shear bands and main mylonite lie close together; shear sense is therefore sinistral on the shear bands, and it is likely that the shear bands and main mylonitic foliation formed as part of a single event of sinistral transcurrent movement.

It may seem surprising that deflection of foliation and layering can create such problems in the establishment of shear sense, while for brittle faults with the same geometric arrangement, few problems exist in practice. This is mainly due to three effects:

(1) Observations are commonly made on pavements or other planar outcrop surfaces with little control on the three-dimensional orientation of structures;

(2) Observations are made in rocks that do not split along a foliation plane in the ductile shear zone (contrary to brittle faults), and therefore no stretching- or mineral lineation in the shear zone can be measured; this is the case in many igneous or high-grade metamorphic rocks;

(3) Observation of well exposed structures on planar outcrop surfaces leads to the false expectation that the section is a true section, even if no evidence has been found to this effect.

Since deflected planar fabrics can give the wrong shear sense, it is interesting to see how oblique transection of structures such as SZR-foliation, mantled porphyroclasts, shear band cleavage, and stair stepping (Hanmer & Passchier 1991, Passchier & Trouw 1995) affects shear sense determination. Since the idealised three-dimensional geometry of these structures has a monoclinic shape symmetry, their two-dimensional geometry on outcrop surfaces at an angle of less than 90° to the ideal section will show different geometry, but identical asymmetry as the ideal section; only if an outcrop surface is nearly normal to the ideal section can small deviations in orientation cause conflicting relations. Consequently, all these structures can be used confidently as shear sense indicators even if cut obliquely.

Deflected older planar structures are the exception to this rule and can give conflicting relationships since their three-dimensional geometry differs from a monoclinic shape symmetry, or has a symmetry axis oblique to the ideal section. In principle, the same problem could occur for other shear sense indicators that develop in parent rocks with an older planar structure: however, such shear sense indicators are usually observed in the core of a shear zone, and have therefore been subject to high strain. It is therefore likely that they will approach a monoclinic shape symmetry. It is possible, however, that such structures indicate the wrong shear sense if they occur in the low strain margin of a ductile shear zone.

CONCLUSIONS

Although shear sense should be established on 'ideal sections' (usually outcrop surfaces parallel to a stretching lineation and normal to the shear zone), planar outcrop surfaces in non-ideal orientation can be used to determine shear sense for most shear sense indicators. However, older planar structures such as foliations, bedding or intrusions that are deflected by ductile shear zones may show conflicting relations and can give the wrong shear sense in some cases. It is therefore essential to distinguish them from SZR-foliations, even though their geometries are very similar. Deflected older planar structures are best to be avoided as shear sense indicators, or should be interpreted with great care. One possible way of using them is to draw concordance and discordance domains as described above, and to check where the poles to planar structures plot. The displacement direction, needed to draw domain boundaries, can usually be determined from a stretching or mineral lineation by projecting it on to the plane of the shear zone in a direction normal to this plane.

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