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The geometry of folded tectonic shear sense indicators

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Abstract

The geometry of refolding of early stretching lineations and associated sense of shear indicators is often not fully considered and can potentially lead to grossly incorrect tectonic interpretations of orogens and orogenic events. Sense of shear is not inverted or 'flipped' in all cases of refolding by folds with closure angle $<90°$. The geometry of inversion of 'flipping' of shear sense is determined entirely by the angle (ϕ) between the stretching lineation and the latter fold axes. Folding around an axis orthogonal to the stretching lineation ($\phi = 90°$) does not result in shear sense inversion. This is a special case; if there is any degree of obliquity ($\phi < 90°$) between fold axis and stretching lineation, there is a change in the orientation of the stretching lineation on alternate limbs and if $\phi < 45°$ the sense of shear is inverted in alternate limbs. © 1998 Elsevier Science Ltd. All rights reserved.

Indicators of the sense of non-coaxial shear, such as σ-type and δ-type porphyroclasts (Passchier and Simpson, 1986; Van Der Driessche and Brun, 1987), asymmetric boudinage (Etchecopar, 1974, 1977), *S–C* relationships (Simpson, 1984) and shearbands (Passchier and Trouw, 1996) have been employed over the last 25 years in mobile belts to establish the sense of relative regional tectonic transport. However, strain is accommodated in mobile belts by folding as well as non-coaxial shear both in discrete shear zones and pervasively throughout large-scale domains. Furthermore, in many mobile belts the earliest regionally extensive and pervasive deformation is typically an intense *L–S* shear fabric which is often subsequently folded by one or more folding phases (Goscombe, 1991; Gower, 1992; Dürr and Dingeldey, 1996; Sithole et al., 1997; Goscombe et al., 1998). The stretching lineation and asymmetrical structures, employed to evaluate shear sense, are frequently formed in this earliest non-coaxial shear episode. As a result of later fold events, the early stretching lineation (thought to represent the principal relative transport vector) and shear sense indicators no longer reside in their original orientation and evaluation of regional tectonic transport can only be deduced after removing later folding effects.

Though this is a commonly recognised scenario, the geometry of refolding of shear sense indicators is often not fully considered. Most workers instinctively consider refolding, by folds with closure angles less than 90°, to always result in an inversion of shear sense on alternate limbs. It is not commonly recognised that there are geometries of tight to isoclinal folding which do not invert the sense of shear on alternate limbs. To evaluate this correctly, the acute angle (ϕ) between the refolded transport vector and the fold axis needs to be considered. This is illustrated by the two end-member geometries portrayed in Fig. 1.

1. Folding around an axis orthogonal to the transport vector ($\phi = 90°$) does not result in shear sense inversion; shear sense is the same on alternate limbs (Fig. 1a). This is a special case; if there is any degree of obliquity ($\phi < 90°$) between fold axis and transport vector, there is a change in the orientation of the transport vector on different limbs and if $\phi < 45°$ the sense of shear is also reversed.
2. Folding around an axis parallel to the transport vector ($\phi = 0°$) results in the inversion of shear sense, with opposing transport sense preserved on alternate limbs, if the closure angle is $<90°$. In this case the fold axis can be considered a 'flip axis' (Fig. 1b).

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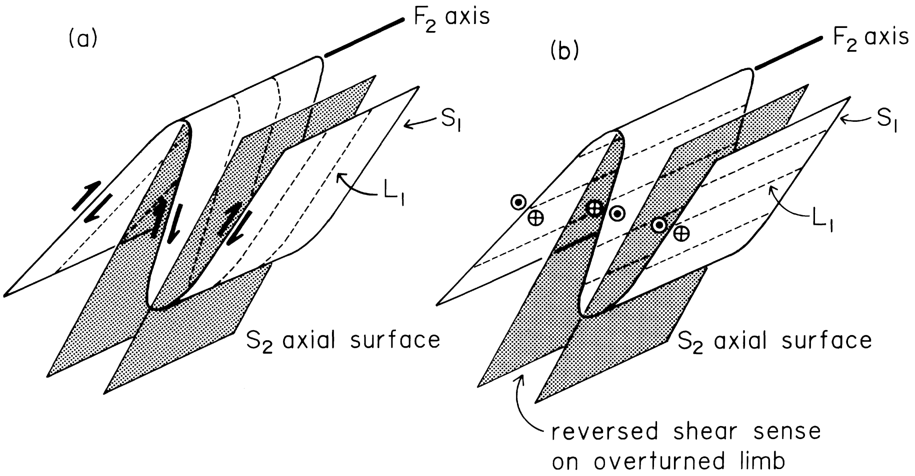

Fig. 1. The two end-member cases of folding stretching lineations and associated shear sense by later tight to isoclinal folds. (a) Shear sense remains the same on both limbs where the fold axis is orothogonal to the lineation. (b) Shear sense is inverted when fold axis and stretching lineation are co-linear.

In the two end-member cases discussed above, the orientation of the transport vector is not significantly different on alternate limbs of isoclinal folds. In all intermediate cases between these end-members, oblique folding of the transport vector results in a spread and eventually bi-modal distribution of the transport vector. Between these end-members there is a progressive increase in the change in orientation of the transport vector due to folding, with a maximum at $\phi = 45°$, giving 90° of rotation of the transport vector. For ϕ between 0° and 45°, there is also an inversion of the shear sense due to folding, if the closure angle is $<90°$. For ϕ between 45° and 90°, shear sense is the same on alternate limbs. The above relationships are best illustrated by drawing parallel arrows with arrowheads pointing in opposite directions on different sides of a piece of paper and experimenting by folding the paper in various directions relative to the arrows.

In medium- to high-grade metamorphic belts, axes of ductile fold structures and stretching lineations are

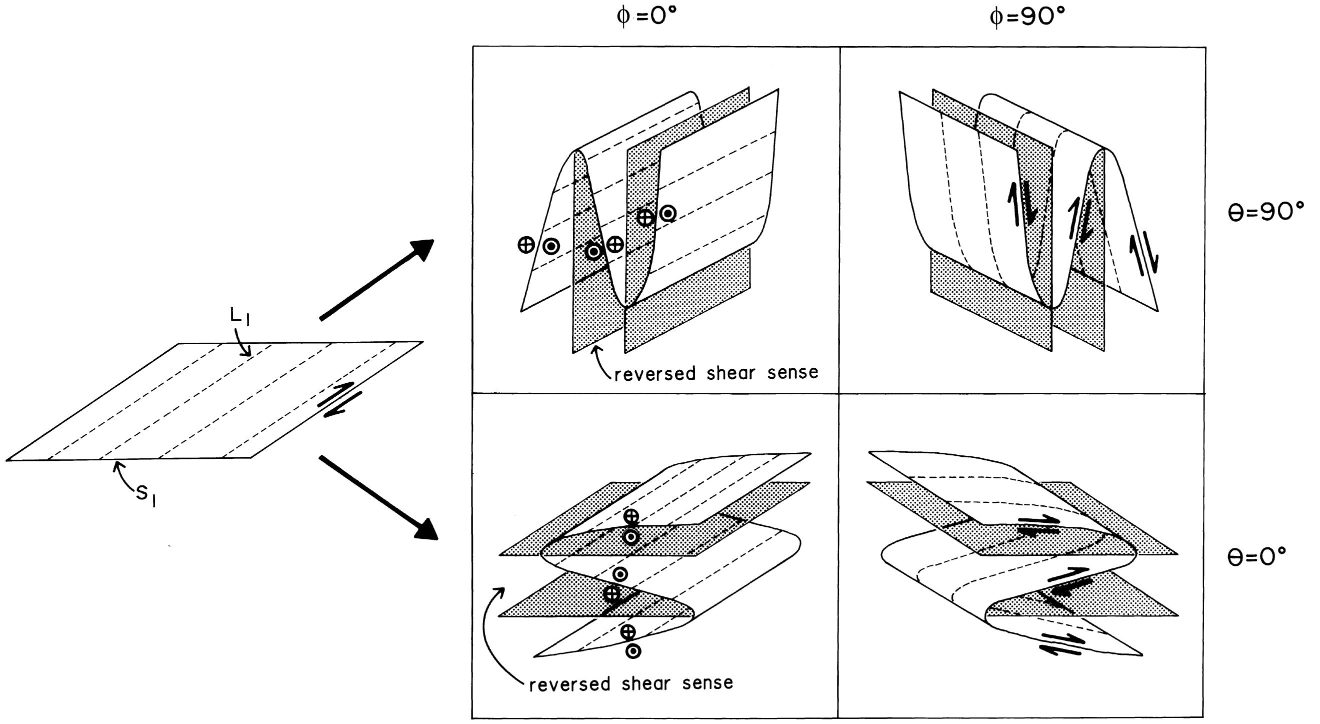

Fig. 2. Refolding of a sub-horizontal shear fabric for end-member cases of the angle (θ) between the early shear fabric and the axial surface of the later folds, and the angle (ϕ) between stretching lineation and fold axis. Note shear sense is inverted only in the end-member cases with $\phi = 0°$.

commonly co-linear, for example the Zambezi Belt (Goscombe et al., 1998; Vinyu et al., 1997; Sithole et al., 1997), the Kaoko Belt (Dürr and Dingeldey, 1996) and Arunta Block (Goscombe, 1991). In such cases, co-linearity of the early stretching lineation and later isoclinal to tight folds, results in opposing shear sense on alternate limbs. To ascertain the regional tectonic transport in these belts, the way up of the sequence needs to be known, so that over-turned limbs with inverted early shear sense can be recognised. In most high-grade metamorphic belts, way up indicators are rare or absent, thus an alternative analysis is required to decide which of the two opposing shear senses is the original tectonic transport sense.

In such cases, structural analysis of only a small portion of the orogen could very easily lead to incorrect interpretations. For example the area studied may reside wholly within the overturned limb of a mega-scale fold. Thus a consistent sense of shear in such a domain may be interpreted incorrectly as being due to crustal extension where the overall tectonic transport is in fact contractional. With the potential for such diametrically opposed tectonic interpretations of an orogen or orogenic event, sense of shear must be evaluated along a section through the entire orogen if possible, to confidently evaluate the sense of tectonic transport. To this end, and with the assumption that the over-turned limbs will be statistically shorter than the upright ones, the shear sense domain that constitutes the lowest proportion of a section through the orogen, can be assumed to be the domain with the inverted shear sense.

The above cases have considered the most common scenario, refolding of sub-horizontal regional shear fabric by later, tight to isoclinal folds. In this scenario shear sense can be inverted irrespective of the angle (θ) of the axial surface with respect to the original shear fabric, as illustrated by the two end-member cases of recumbent ($\theta = 0°$) or upright folding ($\theta = 90°$) in Fig. 2. The absence of any effect by θ with respect to inverting shear sense is further illustrated by the scenario of refolding of sub-vertical shear zones by both folds with upright or recumbent axial planes (Fig. 3). As in all previous scenarios the shear sense is inverted only if $\phi < 45°$. Thus the geometry of inversion or ‘flipping’ of the shear sense is determined entirely by the angle ϕ regardless of the angle (θ) between the early shear fabric and the axial surface of the later folds.

An entirely different situation results from upright open folding of a sub-horizontal shear fabric. Though in this case the shear sense cannot be ‘flipped’ for any

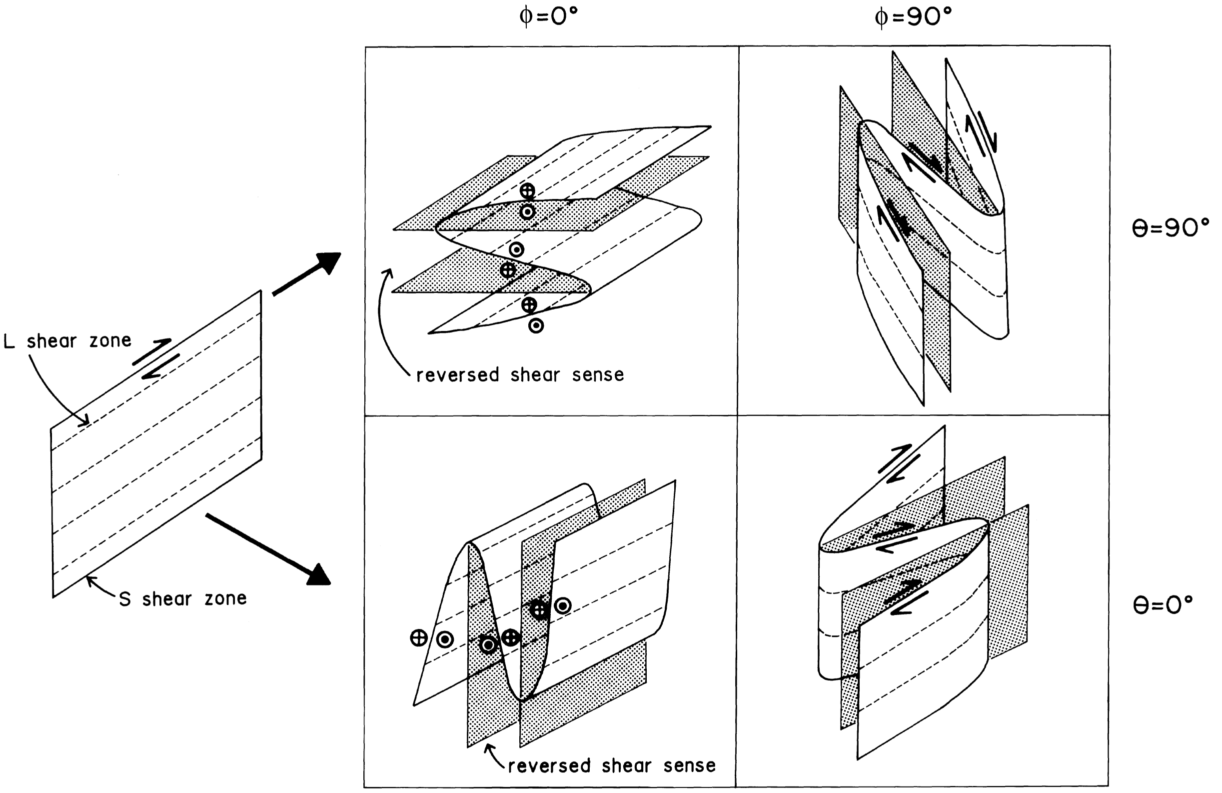

Fig. 3. Refolding of a sub-vertical shear zone for end-member cases of the angle (θ) between the early shear fabric and the axial surface of the later folds, and the angle (ϕ) between stretching lineation and fold axis. Note shear sense is ‘flipped’ or inverted only in the end-member cases with $\phi = 0°$. However, in cases with $\phi = 90°$, alternate limbs show apparent ‘normal’ and ‘reverse’ movements as illustrated in Fig. 4.

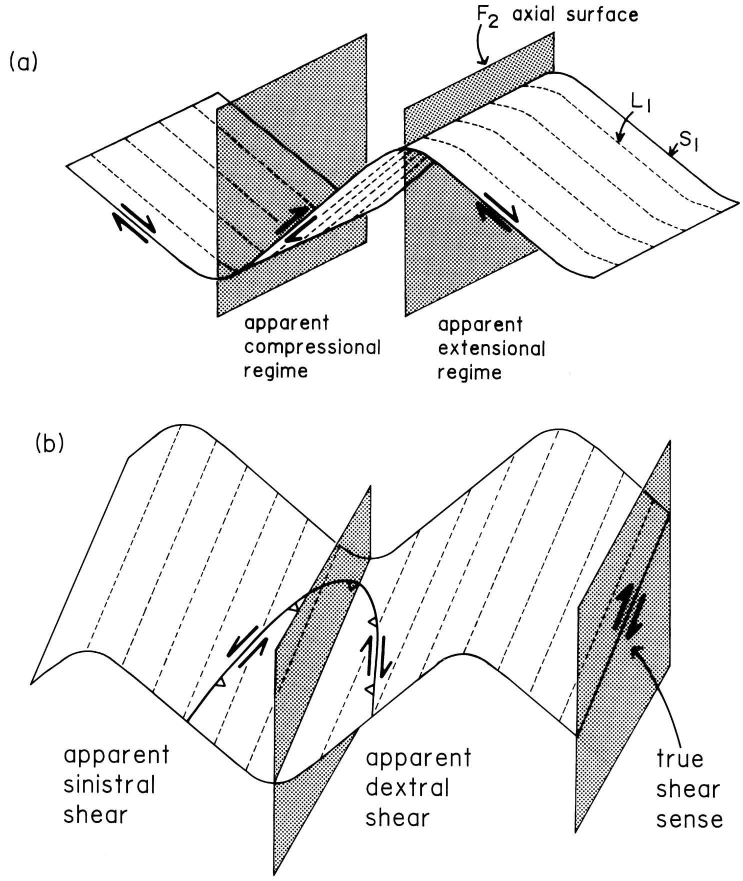

Fig. 4. Apparent change in shear sense due to open upright folding of sub-horizontal shear fabric (i.e. θ near 90°). Note shear sense has not been 'flipped' or inverted, but the apparent change in shear sense geometry could potentially result in incorrect tectonic interpretation. (a) Apparent change from thrusting to normal geometry on alternate limbs, where $\phi \neq 0°$. (b) Apparent change from sinistral to dextral shear on alternate limbs, where $\phi = 0°$.

ϕ angle, there is an apparent change from contractional to extensional geometries on alternate limbs for any $\phi \neq 0$ (Fig. 4a). The interpretation of an orogenic belt or deformational episode as either extensional or contractional is critical to evaluating tectonic setting. Thus recognition of this apparent change in shear sense is important and can only be resolved by mapping a sufficiently large area to be sure all observations are not from only one limb of an upright mega-warp. A similar misinterpretation may arise in settings with open folding around axes with $\phi = 0°$. Alternate fold limbs show either dextral or sinistral displacement on a horizontal surface (Fig. 4b). This impression of 'flipped' or inverted shear sense is only apparent, since the sense of shear has to be determined on a plane perpendicular to the shear plane and containing the movement direction. In this case, this is a sub-vertical section, along which the shear sense remains the same in both limbs.

In conclusion, any evaluation of the crustal-scale tectonic transport experienced by an orogen must consider the angular relationship between the early stretching lineation, associated with shear sense indicators, and later tight to isoclinal fold axes (i.e. ϕ). Co-linear fold axes and stretching lineations result in reversal of shear sense between alternate limbs. Incorrect interpretation of tectonic transport can result in a grossly incorrect tectonic interpretation of an orogen, as extensional for example, when, in fact, it is contractional, or vice versa. In the absence of way up indicators, and a known stratigraphy, confident evaluation of tectonic transport can be sought by domain analysis of shear sense across the entire orogen. By this method, overturned limbs, which are domains of inverted shear sense, are assumed to constitute the smaller proportion of the section across the orogen and so can be unfolded revealing the true sense of tectonic transport.

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