Trabajos de Geología, Universidad de Oviedo, 29 : 74-77 (2009)

Oviedo (Spain) 1-3 July 2008 International Meeting of Young Researchers in Structural Geology and Tectonics
YORSGET

Unravelling patterns of folding in high-strain zones

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Abstract: The careful recording of fold and fabric geometries permits evaluation of shear zone kinematics. Directions of shearing may be calculated via the *Axial-planar Intersection Method* (AIM) which incorporates analysis of minor fold vergence with axial-planar rotations. The geometry of sheath fold pairs may also be used to determine shear sense with sheaths closing in the transport direction typically displaying greater hinge-line curvature. Cross sections through the noses of sheath folds display *cats-eye folds* where the ellipticity of closures increases towards the centre of the eye, and *bulls-eye* folds where closures become less elliptical towards the centre, and reflect variations in bulk strain type from simple shear to constriction respectively.

Keywords: shear zones, kinematics, sheath folds, flow perturbations.

Patterns of folding within high-strain shear zones are typically found to display highly variable orientations and geometries. Such folds may be broadly separated into a) those folds which initiated with variable hinges and axial planes as a consequence of variable flow within the shear zone, resulting in "flow perturbation folds" and b) folds which subsequently develop extreme hinge curvilinearity as a consequence of progressive shearing resulting in "sheath folds". These two types of shear zone-related fold will now be briefly summarized.

Flow perturbation folds

Flow perturbation folds are generated by flow patterns in underlying high-strain zones (see Coward and Potts, 1983). Such perturbations are typically transient features resulting in variable fold shapes and orientations. Leading edges of flow cells may be marked by contractional folds, whilst the trailing edge is a zone of local extension (Fig. 1). Minor "Z" fold hinges (looking down plunge) display a clockwise obliquity relative to the mineral lineation (Ln) defining the transport direction in simple shear dominated shear zones, whilst "S" folds are developed in an anticlockwise sense to Ln (see Alsop and Holdsworth, 2004, 2007). In addition, within dip-slip dominated shear zones, the strike of Z and S fold axial planes are also clockwise and anti-clockwise of Ln respectively. The dip of fold axial planes systematically increases as their strike becomes subparallel to transport (Ln) resulting in a 3-D statistical fanning arrangement centred about the transport direction. Thus mean S- and Z-fold axial planes intersect parallel to the transport lineation and this Axial-planar Intersection Method (AIM) therefore potentially provides a means of determining transport directions and shear sense in cases where lineations are poorly preserved or absent (see Alsop and Holdsworth, 2004; Strachan and Alsop, 2006 for details).

Sheath folds

Sheath folds are typically considered to form by gently curving hinge-lines becoming increasingly stretched and

Figure 1. Flow perturbation folding developed in the Moine Thrust Zone of Sutherland, northern Scotland. Contractional folding is developed above a detachment and towards the left of the photograph (west). The contraction is balanced by extension of this layer towards the right (east). 15 mm diameter coin for scale.

rotated towards the transport direction during intense ductile shearing (Cobbold and Quinquis, 1980; Ramsay, 1980; Alsop and Carreras, 2007) (Fig. 2). In detail, minor Z and S folds may form both clockwise and anticlockwise obliquities to Ln depending on if they are on the upper or lower limbs of larger-scale sheath folds, and if hinge-line curvatures are greater or less than 90 degrees (Fig. 3). Within dip-slip dominated systems, strike-normal reversals in minor fold vergence define the axial surfaces of larger folds, whilst strike-parallel reversals in minor fold

Figure 2. Sheath folding developed within mylonitized quartz layers, Cap de Creus, Spain. The fold is exposed in 3-D and displays 160 degrees of hinge-line curvature to define an upward closing sheath. The return fold to the left of the 15 mm diameter coin also displays a curvilinear hinge.

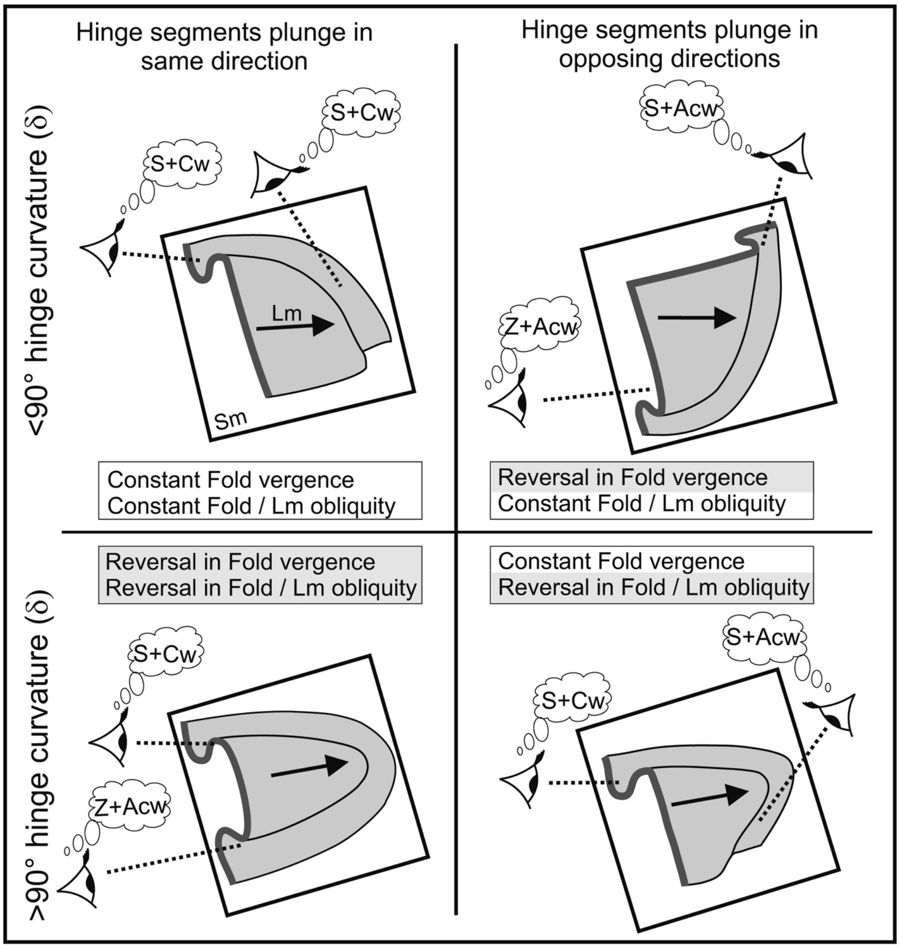

Figure 3. Schematic diagrams illustrating how an observer views variations in S and Z fold patterns depending on the plunge of hinge segments and if hinge curvature (δ) is greater or less than 90°. Folds may be described as clockwise (Cw) or anti-clockwise (Acw) of the mineral lineation (Lm) defining tectonic transport within the mylonitic foliation (Sm).

vergence define the culmination/depression surfaces of larger (curvilinear) folds. Careful analysis of such patterns permits patterns of fold hinge-line vergence to be established whereby the hinge-lines of larger folds display long and short segments which define an asymmetry (or vergence) towards major culminations.

A common misconception within the literature is that sheath fold closures "point" in the direction of shearing and can thus be simply used to determine shear sense (e.g. Van der Pluijm and Marshak, 2004). However, analysis of 100% exposed sheath fold pairs reveals that both hinges of the fold pair become markedly curvilinear with increasing strain and are therefore in this basic sense unreliable as shear criteria (Alsop and Carreras, 2007). However, greater hinge-line curvilinearity is commonly preserved in the sheath closing in the shear direction (reflecting original buckle fold patterns) and this may be of value in helping to determine shear sense.

Cross sections through the noses of sheath folds frequently display the classic elliptical closure patterns described as eye-folds (Ramsay, 1962) (Fig. 4). Recent analysis has divided such closed patterns into cats-eye folds where the ellipticity of closures increases towards the centre of the eye, and bulls-eye folds where closures become less elliptical (and even circular) towards the centre (Alsop and Holdsworth, 2006). Such eye-fold patterns are considered to reflect the bulk strain regime during deformation, with cats-eye folds typically forming during simple shear or general shear (where a component of flattening has also operated across the shear zone). Conversely, bulls-eye folds which typically have much lower elliptical ratios are representative of constrictional deformation. Such relationships thus enable bulk strain types to be easily and quickly determined across a range of scales, materials and environments (e.g. Alsop *et al.*, 2007; Searle and Alsop, 2007).

Conclusions

Flow perturbation and sheath folding typically results in variable fold orientations and geometries which may be linked to the same kinematic regime of

Figure 4. Eye-fold developed within psammites of the Moine Nappe in Sutherland, northern Scotland. The photograph is looking directly into the transport direction and shows elliptical closures which define an overall cats-eye fold pattern associated with general shear deformation. The camera lens cap is 60 mm in diameter.

deformation and need not reflect separate "events" within the shear zone. Initial fold and fabric obliquities are extremely resilient and difficult to destroy, meaning that they may be modified although not reversed during continued deformation. Flow perturbation folds and sheath folds therefore typically provide consistent results which allow a variety of techniques to be reliably employed such as the Axial-planar Intersection Method (AIM) to determine shear direction, and cats-eye or bulls-eye fold analysis to deduce bulk strain types. Such techniques may be applied to high strain zones in a wide range of environments and settings and provide a predictive and testable methodology.

References

ALSOP, G. I. and CARRERAS, J. (2007): Structural evolution of sheath folds: a case study from Cap de Creus. *J. Struct. Geol.*, 29: 1915-1930.

ALSOP, G. I. and HOLDSWORTH, R. E. (2004): Shear zone folds: records of flow perturbation or structural inheritance? In: G. I. ALSOP, R. E. HOLDSWORTH, K. J. W. MCCAFFREY and M. HAND (eds): *Flow processes in faults and shear zones. Geol. Soc. London Spec. Publ.*, 224: 177-199.

ALSOP, G. I. and HOLDSWORTH, R. E. (2006): Sheath folds as discriminators of bulk strain type. *J. Struct. Geol.*, 28: 1588-1606.

ALSOP, G. I. and HOLDSWORTH, R. E. (2007): Flow perturbation folding in shear zones. In: A. C. RIES, R. W. H. BUTLER and R. D. GRAHAM (eds): *Deformation of the Continental Crust: The legacy of Mike Coward. Geol. Soc. London Spec. Publ.*, 272: 77-103.

ALSOP, G. I., HOLDSWORTH, R. E. and MCCAFFREY, K. J. W. (2007): Scale invariant sheath folds in salt, sediments and shear zones. *J. Struct. Geol.*, 29: 1585-1604.

COBBOLD, P. R. and QUINQUIS, H. (1980): Development of sheath folds in shear regimes. *J. Struct Geol.*, 2: 119-126.

COWARD, M. P. and POTTS, G. J. (1983): Complex strain patterns developed at the frontal and lateral tips to shear zones and thrust zones. *J. Struct. Geol.*, 5: 383-399.

RAMSAY, J. G. (1962): Interference patterns produced by the superposition of folds of similar type. *J. Geol.*, 70: 466-481.

RAMSAY, J. G. (1980): Shear zone geometry: a review. *J. Struct. Geol.*, 2: 83-99.

SEARLE, M. P. and ALSOP, G. I. (2007): Eye to eye with a mega-sheath fold: A case study from Wadi Mayh, northern Oman Mountains. *Geology*, 35: 1043-1046.

STRACHAN, L. J. and ALSOP, G. I. (2006): Slump folds as estimators of palaeoslope: A case study from the Fisherstreet Slump of County Clare, Ireland. *Basin Res.*, 18: 451-470.

VAN DER PLUIJM, B. A. and MARSHAK, S. (2004): *Earth Structure: An introduction to Structural Geology and Tectonics*, 2nd Ed, W.W. Norton and company, New York, 672 pp.