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Secondary cleavages in ductile shear zones

J. P. PLATT

Department of Geology and Mineralogy, Oxford University, Parks Road, Oxford OX1 3PR, U.K.

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Abstract—Secondary cleavages developed at late stages in ductile shear zones show several features that are inconsistent with progressive simple shear in the zone. These are: the orientation of a single secondary cleavage oblique to the shear zone boundaries; conjugate sets with opposite senses of shear; and multiple sets with the same sense of shear. These features can be explained if the bulk flow is partitioned into slip along discrete failure planes parallel to the primary foliation (S), coaxial stretching along the foliation, and spin.

INTRODUCTION

DEFORMED materials in ductile shear zones commonly contain more than one set of roughly planar surfaces (foliations or cleavages). One set, labelled S in Fig. 1, is defined by the preferred orientation of the long and intermediate axes of roughly ellipsoidal deformed grains and grain aggregates, and of tabular or prismatic mineral grains. If the material is initially isotropic and homogeneous, and deforms primarily by volume conservative processes, such a shape fabric can remain independent of material planes. It is then likely to correspond to the XY plane of the finite strain ellipsoid (Ramsay & Graham 1970), and will vary in orientation within a shear zone according to the strain.

The development of the S-foliation may be accompanied by formation of a set of discretely spaced surfaces parallel to the boundaries of the shear zone. These form as a result of periodic variations in the amount of shear strain, and are themselves small-scale shear zones. They may have any width and spacing between that of individual grains and that of the main zone. This fabric, labelled C in Fig. 1 after Ponce de Leon & Choukroune (1980), has also been described by Escher *et al.* (1976), Berthé *et al.* (1979), and Jegouzo (1980). They are specific to zones of simple shear, and can form because in simple shear one of the characteristic directions of the flow field (the only surfaces across which the rate of shear strain can vary without constraint) is fixed to a set of material planes. If some type of strain-softening process can operate, the finite strain can build up on these planes to define the C-zones. In any other type of flow the characteristic directions rotate through the material, and cannot become attached to a set of material planes.

S and C surfaces may develop from the start of deformation, and may therefore be regarded as 'primary' foliations. Note that the change of orientation of the S-surfaces adjacent to the C-zones does not mean that S has become an active surface in the deformation. It simply reflects the change in orientation of the finite strain axes with increasing shear strain. S and C surfaces form together and do not overprint each other. Many shear zones, however, also contain secondary planar fabrics that develop at a later stage. One or more sets of spaced, irregular and discontinuous surfaces may form obliquely to S, particularly in micaceous rocks where S is strongly developed. These fabrics, identified as 'extensional crenulation cleavages' by Platt (1979) and Platt & Vissers (1980), and referred to as 'shear-band cleavage' by White *et al.* (1980), probably result from the anisotropy of material properties caused by the intensifying primary foliations. Like the C fabric, they are essentially sets of small-scale shear zones, although there is some evidence of minor dilation (Behrmann pers. comm. 1982). Unlike the C fabric, they are normally oblique to the boundaries of the main shear zone (Platt & Vissers 1980, White *et al.* 1980). They have been shown to overprint both S and C fabrics by Ponce de Leon & Choukroune (1980), who labelled them C' in their figure. They are shown as '*ecc*' in Fig. 1. Conjugate sets of *ecc*s with opposite senses of shear, and multiple sets with the same sense of shear, have been described by Platt & Vissers (1980).

There are two major problems associated with the geometry of *ecc*s in shear zones: (1) their orientation with respect to the shear-plane and (2) the development of conjugate sets, and multiple sets with the same sense of shear, neither of which are consistent with simple shear flow.

ORIENTATION

Platt & Vissers (1980) suggested that *ecc*s may be comparable to slip-lines in plastic materials (Hill 1950).

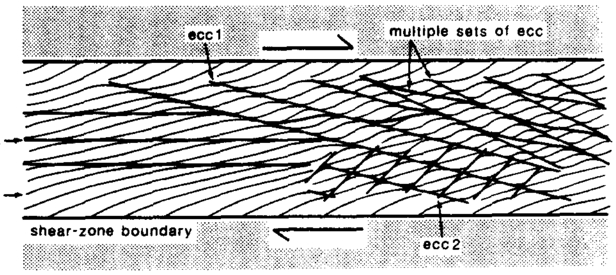

Fig. 1. Diagram to illustrate the orientations and mutual relationships of foliations in shear-zones. S, shape fabric; C, shear bands, *ecc* 1 & *ecc* 2, conjugate sets of extensional crenulation cleavages.

In isotropic incompressible plastic materials, slip lines propagate parallel to the so called 'characteristic directions' of the spatial fields of stress and strain rate. For simple shear flow, these lie normal and parallel to the plane of shear. The implications of slip-line theory for anisotropic materials are unclear, however, because the principal directions of stress and strain rate are in general not parallel. Hill (1950) suggested that slip-lines would follow the characteristic directions of the flow field (and not the stress field) in an anisotropic material, so that they would be oriented normal and parallel to the shear plane, as in an isotropic material. This provides an adequate explanation for the orientation of the *C*-surfaces, as noted above; but the two sets of *ecc* are commonly oblique to the slip plane, with the dominant low-angle set (*ecc* 1 in Fig. 1) at 15–20° to the shear zone boundaries (Platt & Vissers 1980, White *et al.* 1980). Two possible reasons for this obliquity are (a) the cleavage zones do not propagate parallel to a characteristic direction of the flow field, or (b) the flow field deviates from simple shear.

The first explanation could apply if, for example, deformation in the cleavage zones was dependent on the mean stress. In this case they would propagate in directions forming a dihedral angle of less than 90° about the maximum principal compressive stress (Odé 1960), although in an anisotropic material they would not necessarily be symmetrically disposed about this axis. This may explain the orientation of R_1 Riedel shears in fault gouges, for example (S. Hall pers. comm. 1982).

I want to explore the second possibility (that the strain deviates from simple shear) in more detail, as this may also provide an explanation for the formation of conjugate and multiple sets. Lister & Williams (1979, 1983) suggest that flow in shear zones may commonly be spatially partitioned. Such spatial partitioning presents no problems as long as the bounding surfaces between differently deforming domains stretch and rotate at the same rates. Any inhomogeneous deformation can be treated as a spatial partitioning of a bulk flow field. In an anisotropic material an obvious way for flow to become partitioned is for there to be a degree of ductile or brittle failure parallel to the plane of anisotropy (S). Bulk simple shear flow, for example, could become partitioned into three components: slip along discrete surfaces parallel to S; coaxial stretching of the whole system along S; and spin. If S is at an angle ϕ to the shear plane, bulk simple shear flow at rate Γ becomes partitioned into: (a) slip//S on discrete surfaces at an equivalent bulk rate $L^s = \Gamma \cos 2\phi$, (b) coaxial stretching of the whole system//S at $D^s = \frac{1}{2}\Gamma \sin 2\phi$, and (c) spin of the whole system at $W^s = \frac{1}{2}\Gamma(1 - \cos 2\phi)$ (see Appendix).

Structures forming in the coaxially stretching domains would then have orientations governed by the local stress and flow fields (which would be parallel), rather than by the bulk simple shear of the whole system. Conjugate sets of *ecc*s, for example, could form at 45° on either side of the foliation. For $\phi = 20°$, the cleavages would be at 65 and $-25°$ to the shear plane (Fig. 2). This model requires that there be effective failure along

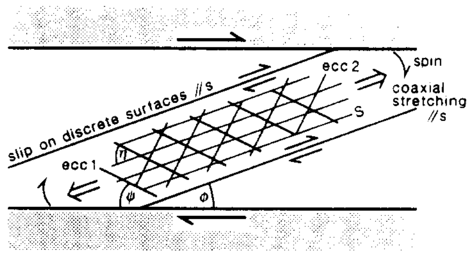

Fig. 2. Strain-partitioning model to explain extensional crenulation cleavages (*ecc*) in a shear zone.

discrete surfaces or zones parallel to S, so that the shear stress parallel to S in the intervening domains is largely relieved. Deformation in the zones of failure is not simple shear, as the coaxial stretching component is superposed.

The foliation in the coaxially deforming domains will be offset and modified by the developing *ecc*s, and will no longer track the principal plane of finite strain. The enveloping surface of S will be rotated by the spin component W^s towards the shear plane at the same rate as if it were a passive marker in simple shear flow. The *ecc*s will also rotate and evolve, as discussed below.

CONJUGATE SETS

If domains of coaxial flow develop parallel to S, as described above, either or both of the two possible sets of *ecc*s should develop equally well, although they would be confined to the these domains. In simple shear flow, by contrast, the high-angle set (*ecc* 2 in Fig. 2) rotates rapidly into an unfavourable orientation for continued slip (Platt & Vissers 1980). The presence of conjugate sets in shear zones may therefore support the flow-partitioning model outlined above. After initiation, the cleavages will rotate towards S at $\dot{\eta} = D^s \sin 2\eta$, where η is the angle between the cleavage and S.

SINGLE SETS

Many shear zones contain only a single set of *ecc*s, at a low angle to the shear plane (*ecc* 1 in Fig. 2). Their obliquity to the shear plane suggests that some degree of flow partitioning has occurred, but the absence of the conjugate set indicates that flow was not perfectly coaxial. A possible explanation is that *ecc* 1 has started to take up a proportion of the bulk shear strain, thereby amplifying this set at the expense of the other. The subsequent evolution of *ecc* 1 will then lie between the following two extremes.

(1) If the flow is fully partitioned into slip along S, stretching along S, and spin, *ecc* 1 rotates towards S at $D^s \sin 2\eta$, and therefore rotates towards the shear plane at:

$\dot{\psi} = D^s \sin 2\eta - W^s$, where ψ is the angle between *ecc* 1 and the shear plane (Fig. 2), and $\eta = \phi + \psi$.

$$\dot{\psi} = \tfrac{1}{2}\Gamma[\sin 2\phi \sin 2(\phi + \psi) - 1 + \cos 2\phi].$$

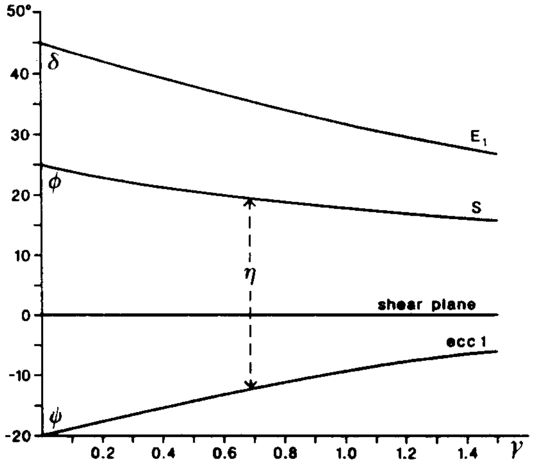

Fig. 3. Orientation of the principal post-partitioning finite extension (E_1), the foliation (S), and a low angle set of extensional crenulation cleavages (*ecc* 1) relative to the shear plane with increasing shear strain γ. *ecc* 1 is arbitrarily assumed to initiate at 45° to S, when S is at 25° to the shear plane.

An example of this evolution is illustrated in Fig. 3, assuming for the sake of argument that *ecc* 1 initiates at 45° to S, when S is at 25° to the shear plane.

(2) If flow is completely repartitioned into slip along *ecc* 1 at $\frac{1}{2}\Gamma \cos 2\psi$, shortening along *ecc* 1 at $-\frac{1}{2}\Gamma \sin 2\psi$, and spin at $\frac{1}{2}\Gamma(1 - \cos 2\psi)$, then *ecc* 1 rotates away from the shear plane as if it were a passive marker at $\frac{1}{2}\Gamma(1 - \cos 2\psi)$.

It is quite likely that the real situation will lie between these two extremes, in which case *ecc* 1 will rotate very slowly or not at all.

MULTIPLE SETS

Multiple sets of *ecc* 1 cleavages, with older sets lying at a lower angle to S and to the shear plane than younger sets, have been documented from the Betic Movement Zone by Platt & Vissers (1980), and are well developed in back thrusting zones in the French Alps (F. Peel pers. comm.). In simple-shear flow, the low-angle cleavage should rotate away from the shear plane at $\frac{1}{2}\Gamma(1 - \cos 2\psi)$, and this pattern of multiple sets should not develop. The strain-partitioning model [alternative (i) above], however, predicts that *ecc* 1 rotates towards the shear plane and S, so that it will become less favourably oriented for slip within the local coaxial flow field. As shown in Fig. 3, a set initiated at $\eta_0 = 45°$ to S, when S was at $\phi_0 = 25°$ to the shear plane, lies at $\eta = 25°$ to the enveloping surface of S after an additional increment of bulk shear strain $\Delta\gamma = 1.2$. The empirical evidence of Platt & Vissers (1980) suggests that *ecc*s become inactive when $\eta = 30°$ approximately, and may be overprinted by a younger set at a higher angle to S.

DISCUSSION

Conjugate sets, multiple sets, and obliquely oriented single sets of extensional crenulation cleavages in ductile shear zones all suggest that flow in the zone departs from progressive simple shear. The probable cause of this is a tendencyfor slip to occur on discrete surfaces parallel to the foliation, allowing the flow to become more coaxial in the intervening domains. The structures in these domains do not, therefore, directly reflect the bulk flow field, and they might in fact give a misleading impression of the bulk sense of shear. In areas where conjugate sets of extensional crenulation cleavage are common, such as the Betic Movement Zone, southern Spain, and parts of the Vanoise massif, French Alps (Platt & Vissers 1980), the two sets locally alternate, so that significant volumes of rock contain cleavages indicating a sense of shear opposed to that of the bulk flow-field.

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APPENDIX

Flow partitioning

The velocity gradients for simple shear flow at rate Γ parallel to x_1 are:

$$L_{ij} = \begin{bmatrix} 0 & \Gamma \\ 0 & 0 \end{bmatrix}. \tag{1}$$

This can be partitioned into components of shear (L^s) at $\Gamma \cos 2\phi$ along a direction at ϕ to x_1, coaxial stretching (D^s) at $\frac{1}{2}\Gamma \sin 2\phi$ in this direction, and spin (W^s) at $\frac{1}{2}\Gamma(1 - \cos 2\phi)$. Then

$$L^s_{ij} = \begin{bmatrix} -\frac{1}{2}\Gamma \sin 2\phi \cos 2\phi & \frac{1}{2}\Gamma \cos 2\phi\,(\cos 2\phi + 1) \\ \frac{1}{2}\Gamma \cos 2\phi\,(\cos 2\phi - 1) & \frac{1}{2}\Gamma \sin 2\phi \cos 2\phi \end{bmatrix} \quad (2)$$

$$D^s_{ij} = \begin{bmatrix} \frac{1}{2}\Gamma \sin 2\phi \cos 2\phi & \frac{1}{2}\Gamma \sin^2 2\phi \\ \frac{1}{2}\Gamma \sin^2 2\phi & -\frac{1}{2}\Gamma \sin 2\phi \cos 2\phi \end{bmatrix} \quad (3)$$

$$W^s_{ij} = \begin{bmatrix} 0 & \frac{1}{2}\Gamma(1 - \cos 2\phi) \\ -\frac{1}{2}\Gamma(1 - \cos 2\phi) & 0 \end{bmatrix} \quad (4)$$

and

$$L_{ij} = L^s_{ij} + D^s_{ij} + W^s_{ij}. \quad (5)$$

Rotation of ecc 1

The rotation of *ecc* 1 shown in Fig. 3 is calculated as follows. Let ϕ, ψ and η be defined as in Fig. 2. Let β be the angle between S and the principal bulk finite extension E_1, and δ the angle between E_1 and the shear plane. Then $\beta = \delta - \phi$, and $\eta = \phi + \psi$. The extensional crenulation cleavage is assumed for the sake of argument to initiate at 45° to S, when S is at 25° to the shear plane. Other initial assumptions are possible, but the evolutionary pattern does not change significantly. *ecc* 1 rotates as a passive marker, such that

$$\tan \eta = \tan \eta_0 (1/E^s)^2 \quad (6)$$

where E^s is the total post-partitioning stretch along S. If $\eta_0 = 45°$, then

$$\tan \eta = (1/E^s)^2. \quad (7)$$

But

$$(1/E^s)^2 = (1/E_1)^2 \cos^2 \beta + (1/E_2)^2 \sin^2 \beta \quad (8)$$

(Ramsay 1967, p. 66), and in simple shear

$$(E_1)^2 = \tfrac{1}{2}[\gamma^2 + 2 + \gamma\sqrt{(\gamma^2 + 4)}], \quad (9)$$

$$E_2 = 1/E_1, \quad (10)$$

and

$$\tan 2\delta = 2/\gamma$$

(Ramsay 1980). Now $\beta = \delta - \phi$, and the foliation rotates as a passive marker in simple shear, so

$$\cot \phi = \cot \phi_0 + \gamma \quad (11)$$

η is then calculated from (7) for values of γ.