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Geometry of transecting, anastomosing solution cleavage in transpression zones

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The recognition of transpression (Harland 1971) as a common deformation mode, and the results of current investigations into transpression geometry (Sanderson & Marchini 1984) emphasize that even moderately deformed rocks in convergence zones are likely to have suffered significantly non-coaxial strain histories. I suggest how these developments might lead to some further insight into the geometry of non-axial planar cleavage and the relationship of slaty cleavage to its low grade, non-penetrative precursors.

The outstanding problem regarding slaty cleavage is simply stated. Numerous strain studies have shown that slaty cleavage is formed perpendicular to the shortest axis of the finite strain ellipsoid (Ramsay & Huber 1983, p. 181). The implication is that slaty cleavage tracks the *XY* principal plane through each increment of the cleavage-forming strain episode. On the other hand, it is widely accepted that penetrative cleavage fabrics often develop via spaced types which involve solution mechanisms, with or without crenulation. These, and the less perfect varieties of slaty cleavage, are in detail domainal, or take the form of discrete seams or folia. Such material discontinuities cannot be developed parallel to *XY* and then maintain parallelism with that plane except during a strictly coaxial strain history (Hobbs *et al.* 1976, chap. 5; Ghosh 1982). In the general non-coaxial situation, they can only become effectively parallel to *XY* (finite) by passive rotation after large strains.

Transpression, which can be defined as simple shear plus shortening across the shear plane, involves non-coaxial incremental strains. Of interest in the present context is the recognition that transpression is the characteristic deformation mode in the late Caledonian slate belts the British Isles (Sanderson *et al.* 1980, Soper & Hutton 1984). Here early stages of cleavage formation can be observed at moderate strain states and low metamorphic grades. The dominant form of cleavage in the lower Palaeozoic arenaceous turbidites and volcanogenic sediments is 'rough cleavage' (Gray 1978, Onasch 1983), in which irregular, anastomosing folia define a statistical planar fabric parallel to which detrital quartz grains are sometimes weakly oriented. This fabric grades into uncleaved rock on the one hand and into more continuous but still anastomosing pressure solution seams on the other.

An important geometrical feature of the Caledonian slate belts is the manner in which the cleavage transects the folds, almost always in a clockwise sense, at angles of 10° or more (see Soper & Hutton 1984 for references and Stringer & Treagus 1980, fig. 5c, for a good illustration). Contemporaneous transecting cleavage can be produced by coaxial strains imposed on bedding not initially parallel to a principal strain plane (Borradaile 1978, Treagus & Treagus 1981), or by non-coaxial strains on originally orthogonal bedding (Sanderson *et al.* 1980), or by a combination of these two end member geometries. Criteria for the recognition of non-coaxial strains include the presence of regionally curvilinear tectonic trends, particularly where these show sigmoidal 'shear-zone' type geometry; the obliquity of folds and cleavage to displacement directions derived from independent criteria, for example contemporaneous thrust faults; and the association of folds and cleavage with strike-slip faults.

In the Southern Uplands–Down accretionary complex, transection may result from oblique accretion. The Silurian turbidites of N England and E Ireland (Soper & Moseley 1978, Murphy 1985) contain contemporaneous upright folds and steep cleavage of early Devonian age which were apparently imposed on originally subhorizontal bedding. The association of these structures with sinistral shear zones and strike-slip faults establishes the sinistral transpressive nature of the deformation.

The general review of transpression by Sanderson & Marchini (1984) does not address the problem of transection specifically, but does provide an analysis of the special case of *Simple Transpression* (Fig. 1a) which represents a good initial model for deformation in the slate belts. Following this analysis and assuming that fold axes initiate parallel to the *XY*—bedding intersection at the first strain increment and then rotate passively without hinge migration, the angle between fold axis (F) and the *XY* plane in simple transpression can be calculated. Figure 1(b) shows this for $\beta = 45°$. It is evident that for strains appropriate to the slate belts ($0.2 < S < 0.6$, $0.25 < \gamma < 1.5$) and over a range of β values ($45° < \beta < 90°$) $\angle FXY$ does not exceed 4°. The model has oversimplifications, for example it neglects the possibility of non-synchronous initiation of buckling and cleavage, but the conclusion can be drawn that in

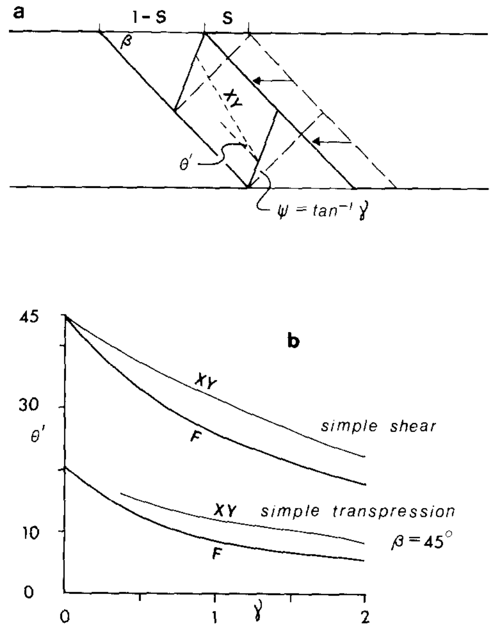

Fig. 1. (a) Geometry of Simple Transpression (Sanderson & Marchini 1984) envisaged as the deformation of ductile material between rigid blocks whose boundaries are inclined at an angle β to the displacement direction. S is the shortening displacement. In constant volume deformation, reduction in area of the deformed zone is compensated by extension normal to the plane of the diagram. (b) Angle between the XY plane and fold axis in simple shear and simple transpression, assuming the fold to develop as a material line during the first increment of deformation and then rotate passively.

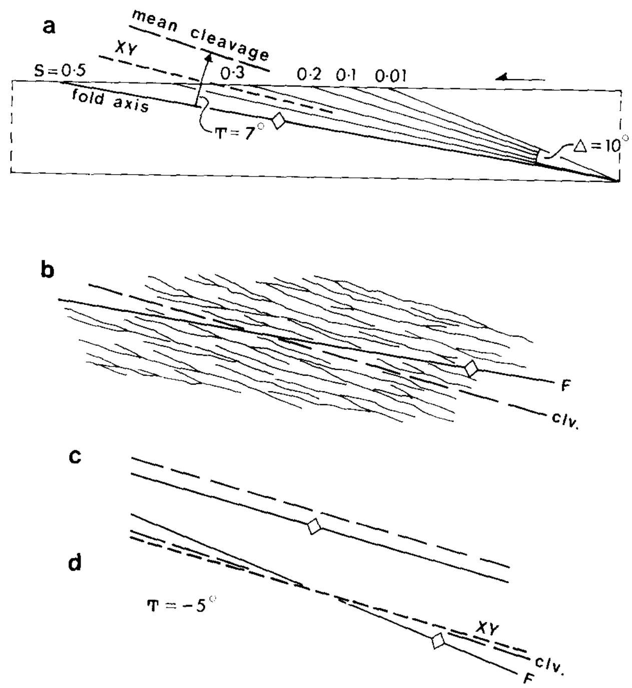

Fig. 2. Cleavage dispersion and transection in sinistral simple transpression. (a) Fold is generated during the first deformation increment and rotates passively. Cleavage starts to develop parallel to XY incremental after 10% shortening, continues to develop through successive strain increments and rotates passively. (b) Dispersion and clockwise transection geometry produced by model (a). (c) Axial planar cleavage produced when buckling takes place half-way through the period of cleavage formation. (d) Anticlockwise transection produced in sinistral transpression when the cleavage is formed by layer-parallel shortening before buckling.

regions of moderate transpression where transection angles of 10° and more are common, the cleavage on geometrical grounds alone is unlikely to represent the XY finite strain plane.

The dominant cleavage-forming mechanism in these low-grade turbiditic sediments is undoubtedly diffusive mass transfer in the presence of pore fluids. Important among the physical and chemical controls of pressure solution (Durney 1976, McClay 1977) is the stress component normal to grain contacts. Solution seams are therefore likely to develop preferentially normal to the principal compressive stress, σ_1, and Onasch (1983) has shown this to be true of low grade 'rough cleavage' in arenites. The other important grain-shaping process is the plastic deformation of clastic quartz grains by crystallographic slip and this too is controlled by the orientation of σ_1. Since incremental stress is reflected by incremental strain, a geometrical model for solution cleavage not associated with microcrenulation would be that solution seams are preferentially initiated parallel to the XY incremental strain plane at some stage in the deformation history, and if the strain is non-coaxial thereafter rotate passively as material discontinuities.

Support for this view is provided by a feature of cleavage in low grade arenites which is commonplace, but has not hitherto attracted much attention. Many examples of first generation solution cleavage, at both thin section and outcrop scale, show the solution seams to be irregular and anastomosing, with individual seams meeting at angles of up to 20° or more (see Fig. 2b). Numerous illustrations in the literature show this feature in sections normal to bedding or parallel to the profile plane of a fold (e.g. Ramsay 1967, fig. 7-69; Borradaile *et al.* 1982, figs. 117, 137, 222) but it is also commonly seen on bedding surfaces (e.g. Borradaile 1978, fig. 13; Stringer & Treagus 1980, fig. 4a; Borradaile *et al.* 1982, figs. 71, 212B, 233C). Note that none of these examples of anastomosing cleavage can be interpreted as either crossing crenulations or S–C fabrics. The angular range between extreme orientations of seams can be defined as the dihedral angle between them, but for the present purpose we can simply recognize a dispersion angle ($\triangle$), measured between seam traces on a surface such as bedding or the profile plane of a fold. Frequently, solution seam traces appear to have a bimodal distribution of orientations, imparting a trapezoidal appearance to the fabric.

Two factors may be important in controlling the non-planar nature of solution seams. One is rock anisotropy, either on the grain scale, so that seams wrap around and anastomose between individual detrital grains (e.g. Gray 1978, fig. 3) or on a larger scale as, for example, the anisotropy produced by numerous small sand volcanoes illustrated by Stringer & Treagus (1980, fig. 4a). The other factor is a non-coaxial stress history. This is exemplified by studies of folded multilayers which contain solution seams and for which the principal stress orientations can be independently determined (see the excellent brief review by Onasch 1983, p. 79). Seams formed during layer-parallel shortening show σ_1 parallel to bedding around the fold, those formed during buckling show stress orientations oblique to bedding and those related to late flattening show σ_1 normal to the fold axial plane. A few recent investigations have identified distinct generations of cleavage produced during a single sequence of layer-parallel shortening, buckling and finally flattening (e.g. Boulter 1979) but the geometrical relationship of anastomosing cleavage to this typical 'first deformation' sequence has yet to be studied.

Non-coaxial deformation may be responsible for a component of the cleavage dispersion seen on folded bedding surfaces in transpression zones, where it is also commonly associated with a transection angle (T), defined as the angle between fold axis and mean cleavage plane (Borradaile 1978). The models illustrated in Fig. 2 assume simple transpression with $\beta = 45°$. Figures 2(a) and (b) show a situation where buckling instability occurred after an unknown amount of layer-parallel shortening had been accommodated by some process such as dewatering or grain boundary sliding which imparted no fabric on the rock. Values of S in Fig. 2(a) refer to shortening as defined in Fig. 1(a) after the initiation of buckling. The fold axis initiated parallel to the incremental Y axis, and then acted as a material line, rotating passively through successive strain increments. After a further 10% shortening, early solution seams began to develop parallel to the incremental XY plane and thereafter rotated passively. Further seams were initiated parallel to incremental XY at similar intervals and after 50% post-folding strain reached the positions shown. The transection angle $T = 7°$ is associated with a dispersion angle $\triangle = 10°$. Note that the XY finite plane lies between the fold axis and mean cleavage but within the cleavage dispersion angle. If with further strain other prograde processes were to supersede pressure solution so that no further seams developed, $\triangle$ and T would diminish by passive rotation and finite XY would assume a position close to the mean cleavage.

It is improbable that solution would cease across the earliest formed seams as soon as they rotated away from their position of initiation. Indeed, the concentration of insoluble impurities along developing seams may enhance solution and thus inhibit the initiation of new seams. If further seams did not develop until late in the strain history, then the characteristic bimodal distribution would result. Figure 2(b) shows a bimodal distribution based on the geometry shown in Fig. 2(a).

An important geometrical feature of the model is that the time relationship between buckling and cleavage initiation determines not only the transection angle but also the sense of transection. Figures 2(c & d) show that both axial planar and anticlockwise transecting cleavage can be produced by sinistral transpression. If solution cleavage were initiated during layer-parallel shortening and continued to be developed after the onset of buckling, a mean cleavage orientation parallel to the fold axis could result (Fig. 2c). If cleavage development were confined exclusively to the layer-parallel shortening stage, before buckling occurred, sinistral transpression would result in anticlockwise transection (Fig. 2d). In studies of transpression zones it is therefore necessary to establish the sense of transpression independently of transection criteria. The apparent association of clockwise transection with sinistral transpression in the British slate belts lends support to the traditional 'flattened buckle' model for the folding in that region.

In order to generalize the model it would be necessary to consider more realistic buckling mechanisms which might involve hinge migration, the sequential initiation of folds on different scales during the same deformation episode, fold propagation through a multilayer at different rates depending on size, and related complexities. Intuitively, fold hinge migration during transpression can be seen as the decreasingly successful attempt by a tightening fold to accommodate to the rotational finite strain field; as the fold tightens and finally locks, its hinge behaves more and more as a material line and undergoes passive rotation as in the simple model proposed above. In Fig. 2(a) an element of early hinge migration would therefore produce a fold axis orientation closer to finite XY, and in general hinge migration would lead to smaller transection angles. The geometrical relationship of cleavage to folds on different scales which were initiated sequentially during transpression (e.g. Sanderson & Marchini 1984, fig. 9) can in principle be accommodated by the model but detailed consideration of this and other complexities is beyond the scope of a short essay.

The model is being tested and developed in the Caledonian cleavage arc of NW England, where sinistral transpressive strains predominate but orthogonal and perhaps dextral strains also occur. Preliminary results suggest a systematic variation in transection angle around the arc, but the determination of meaningful dispersion angles presents difficulties. Useful independent strain markers are uncommon in the Silurian rocks, but it is necessary to concentrate on these to avoid the complication of intra-Ordovician deformation episodes. I would welcome comments and criticisms based on experience in other areas.

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