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Transected folds and transpression: how are they associated?

S. H. Treagus and J. E. Treagus

Department of Geology, University of Manchester, Manchester M13 9PL, U.K.

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Abstract—Folds transected by cleavage are a distinctive structural feature in the Caledonian–Appalachian orogenic belt. With the advent of a tectonic model of transpression for this belt, there has been an assumption that transected folds are a symptom of transpressive deformation: in particular that clockwise transection signifies sinistral transpression. We examine this tenet, and conclude that there is no unique explanation for folds transected by a synchronous cleavage. Explanations can be found for either clockwise or anticlockwise transection, for sinistral (or dextral) transpression, each requiring assumptions about the inclination of bedding to the transpression vector, or requiring that cleavage does not track the finite *XY* plane. A further explanation, which may fit the regional data best, requires a non-constant transpressive deformation, with initial pure-shear-dominated deformation giving way to increasing transcurrent movement in time. None of these models can be assumed to be right, without supporting data on the incremental and finite strain histories of such regions.

INTRODUCTORY REVIEW

Several recent papers concerned with the relationships between structural field observations and regional tectonics of the Caledonian–Appalachian organic belt have equated the transection of folds by cleavage with transpressive deformation (e.g. Soper & Hutton 1984, Soper *et al.* 1987, Woodcock *et al.* 1988). In particular, the common observation of folds whose hinge lines are transected by cleavage in a clockwise sense (e.g. Fig. 1) is increasingly assumed to indicate sinistral transpressive closure in the British sector of Iapetus.

Harland (1971) first introduced the terms "transpression" and "transtension" to describe the form of deformation imposed by obliquely converging or opening plates. Sanderson & Marchini (1984) have rejuvenated these terms, and documented finite strain in 'simple transpression', and the strain paths for incremental transpression. For simple transpression, the strain ellipsoid is of the flattening kind ($k<1$), and for most geometries except those quite close to transcurrent simple shear, the principal extension, X, is vertical. Neither Harland (1971) nor Sanderson & Marchini (1984) make any association between transpression and folds with transecting (non-axial-planar) cleavage. Transpression, like simple shear, does not provide an immediate theoretical explanation for folds transected by synchronous cleavage. So how did clockwise-transected folds in Britain begin to be seen as indicators of sinistral transpression?

Sanderson *et al.* (1980) described three scenarios whereby folds with clockwise-transecting cleavage might develop in a zone of transcurrent simple shear, model 1 associated with dextral shear, and models 2 and 3 sinistral. Each requires the initiation of folds which are not perpendicular to the shortening direction in the layer, whereas the cleavage planes track the finite *XY* planes, and so cross-cut the folds. Murphy (1985) subsequently used this reasoning to relate clockwise-transected folds in Ireland to the presence of sinistral strike-slip deformation, and possibly sinistral transpression.

The association of *clockwise* transection of folds with a regional *sinistral* transpression model for the British Caledonides came with the introduction of a three-plate closure model (Soper & Hutton 1984). Regional considerations led these authors to reject the earlier two-plate model of Dewey (1969) and Phillips *et al.* (1976),

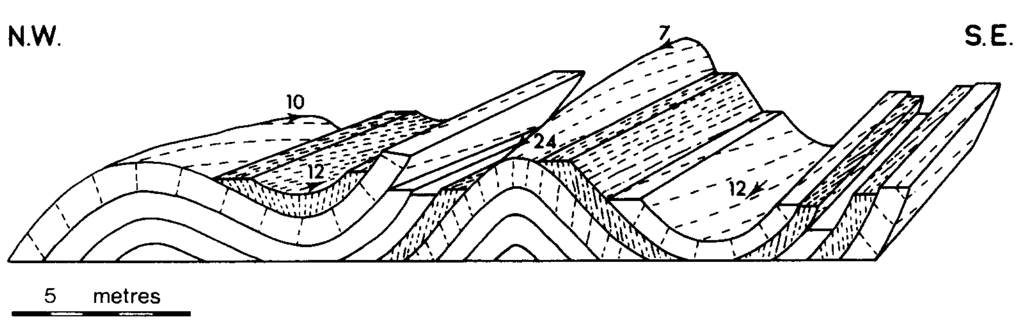

Fig. 1. Typical geometry of folds and associated clockwise-transecting cleavage in the lower Palaeozoic turbidites of the British Caledonides. Cleavage (broken lines) is shown in the profile view to fan around folds, and refract through beds of greywacke (wide-spaced lines), siltstone and mudstone (denser lines), giving variable plunges of intersection on the fold limbs. Arrows show plunge values of fold hinges. This fold train (from Stringer & Treagus 1980, fig. 2) is at Corseyard Point (grid reference NX 5835 4865) in Silurian rocks of the Southern Uplands of Scotland.

with its E–W closure (giving dextral transpression). Instead, Soper and Hutton proposed a N–S closure with consequent sinistral movements on pre-existing or new shear zones parallel to the zone margin. In support, they quote abundant evidence for late Caledonian strike-slip displacements in Britain. However, they also use the clockwise transection (quoting Sanderson *et al.* 1980, and Sanderson & Marchini 1984) as supporting evidence for sinistral simple shear imposed upon regional coaxial deformation (pure shear), although as we have stated, these papers do not provide any independent evidence for making such associations.

A more persuasive rationale for the link between clockwise transection and sinistral transpression came from Soper (1986). He argued that the domainal anastamosing cleavage common to many lithologies of the British Caledonides is the product of a series of pressure solution cleavage increments. In sinistral transpression, early cleavage surfaces are rotated sinistrally, and later increments superimposed in a clockwise sense. This is the explanation for the anastamosing nature of the cleavage, and could explain the transection of folds by up to about 7°. However, Soper (1986) chose to define the fold axis as the material line perpendicular to the *initial* shortening in the layer (deformed passively thereafter): it is not a finite fold axis in the sense of being perpendicular to the *finite* shortening of the layer. With this assumption, Soper could model a range of transection angles of 10° or more between the first and last shortening increments. Thus, his model requires specific assumptions regarding the nature of both folding and cleavage development, for a transpressive (non-coaxial) deformation history. If Soper's (1986) model is to be used widely to explain the association of clockwise transpression with sinistral transpression (and anticlockwise with dextral), and most importantly, if it is to be used as the basis for *deducing* sinistral transpression from clockwise-transected folds, its assumptions and microstructural implications must be fully justified.

Soper's model is used to explain the association of clockwise transection with sinistral transpression in the English Lake District (Soper *et al.* 1987) and in the Welsh Basin (Woodcock *et al.* 1988). In both regions a steep cleavage transects low plunging folds by angles up to 10°, and the stretching direction, where it can be determined, is approximately down-dip on cleavage.

The clockwise-transected folds in the above areas possess similar features, in our experience, to the transected folds in the Scottish Southern Uplands (Stringer & Treagus 1980) (Fig. 1). Here, the nature of the cleavage in a variety of lithologies affected by folding led us (also in Treagus 1972, Treagus & Treagus 1981) to conclude that the folds, and their non-axial planar but refracting and fanning cleavages, were the product of a single deformation. The morphology of these folds and their cleavage support the traditional equation of cleavage with the *XY* plane of the finite strain ellipsoid; cleavage fanning and refraction through different lithologies show similarities with models (analogue and theoretical) of finite strain in folds (Dieterich 1969). The *only* factor which differs from the 'norm' is that cleavages are oblique to fold axial planes, so that cleavage–bedding intersections are not parallel to fold hinges (Fig. 1).

We explained (Stringer & Treagus 1980, Treagus & Treagus 1981) the transection in the Southern Uplands by the simple assumption that folding layers which are oblique to all three principal axes of a strain ellipsoid will have axes (of folding) oblique to the *XY* trace on the layer (Flinn 1962, Borradaile 1978). Treagus & Treagus (1981) gave examples of different degrees of transection for different layer orientations to the ellipsoid, and different ellipsoid shapes. Lisle (1986) considered the same process in terms of the degree of non-coaxial two-dimensional straining in the layer compared to a three-dimensional coaxial strain. Perhaps the emphasis placed on the geometry in terms of pure shear has led some authors to consider this a 'pure shear model' (e.g. Woodcock 1990), when it is simply a property of surfaces in three-dimensional strain, regardless of the strain *history*. Exactly the same feature of obliquity of shortening axes (fold axes) to principal planes (*XY*) will hold for oblique layers in finite strain arising from simple shear, pure shear or transpression. The only distinction will come when we consider history-sensitive processes.

Stringer & Treagus (1980) attributed the clockwise sense of transection to folding of oblique layers in a zone of *dextral* shear, in keeping with the prevailing tectonic model (Phillips *et al.* 1976). However, the Southern Uplands have now been included in the general transpressive model for the British Caledonides (see review, Soper 1988). In common with the English Lake District and Wales, the clockwise-transected folds are taken to indicate *sinistral* transpression, although the evidence (Soper & Hutton 1984) comes from the Irish equivalent of the Southern Uplands, rather than from Scottish data.

The Appalachian fold belt also has clear evidence of transected folds, although there is debate as to whether these are the products of a single deformation, as in the Southern Uplands, perhaps related to transpression, or the cross-cutting effects of superimposed or protracted deformations: see Stringer (1975), Gray (1981), Blewett & Pickering (1988, 1989), Lafrance (1989, 1990), Lafrance *et al.* (1989), Blewett (1990) and van der Pluijm (1990).

In this paper, we wish to clarify the geometry of strain in transpressive deformation, and consider theoretical aspects of fold and cleavage development. Our aim is not to comment on the regional structures, but to question objectively whether the sense of cleavage transection can, or should, be used as an indicator of sense of transpression.

MODELS FOR FOLDS IN TRANSPRESSION

Geometry of transpressive deformation

The geometry of simple transpression is illustrated in the familiar horizontal plane of view in Figs. 2(a) & (b),

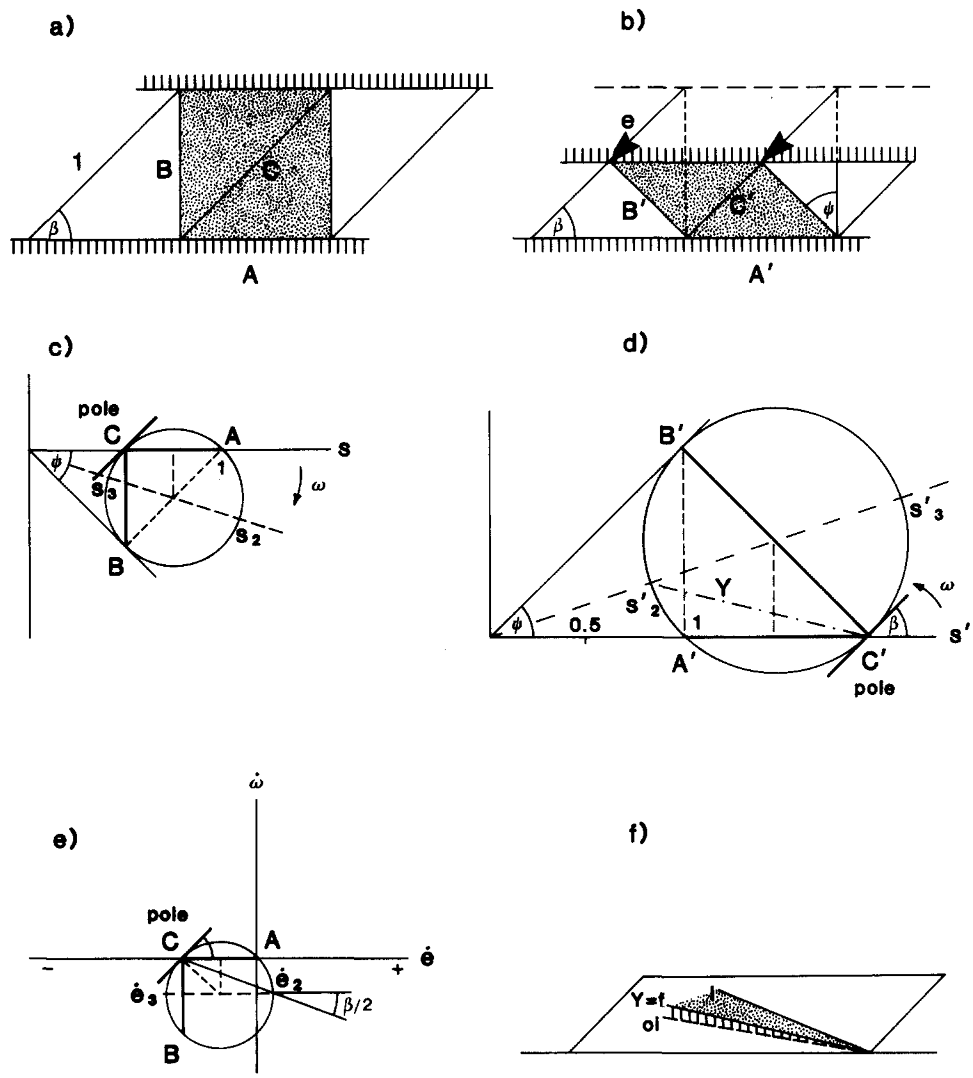

Fig. 2. Transpressive deformation, with $\beta = 45°$ and $e = 0.5$, in two-dimensional (horizontal) view. (a) & (b) The square region (shaded) in (a) deforms to the parallelogram in (b). The transpression zone margins are shown by ticked lines, and the transpression vector by arrows. The Mohr circles are (c) stretch and rotation, (d) reciprocal stretch and rotation, and (e) instantaneous flow. Bold lines show directions A, B, C (or A′, B′, C′) using the Mohr-circle pole (= C). See text for explanation. (f) shows for the deformed state the directions of finite extension, f (tectonic Y), current incremental extension, i, and the deformed first incremental extension, oi. These are used in discussion of Soper's (1986) model.

after Harland (1971), Sanderson & Marchini (1984), McCoss (1986) and Soper (1986). It is assumed the material between two moving plates deformed homogeneously (shaded square to parallelogram) according to the external oblique plate motion (arrow), and that a principal vertical stretch compensates for the area loss. Our example in Fig. 2 is the same geometry as Soper's (1986) example: transpression angle $\beta = 45°$, and shortening $e = 0.5$.

Three material lines (A, B, C in Fig. 2a) can be used to constrain the deformation of simple transpression. Line A remains fixed parallel to the margin of the rigid plate, so is neither rotated nor stretched. Line B rotates according to the angular shear, ψ (Fig. 2b). Line C is parallel to the movement vector, so shortens (by e) but does not rotate. (It is the diagonal of the initial square only for this $\beta = 45°$ example.)

These known stretches and rotations for lines A, B and C invite the use of polar Mohr circles for stretch vs rotation (Means 1982, 1983, De Paor 1983) for the principal horizontal plane. It is useful to consider two types of circle, after Means (1982): Fig. 2(c) shows stretch vs rotation and represents lines (A,B,C) and angles in their unstrained orientation, and Fig. 2(d) is reciprocal stretch vs rotation, representing the lines in their final deformed positions (A′,B′,C′). For both types of circle, we use a sign convention which allows us to use a Mohr pole and represent lines in real space (Figs. 2a & b) (Mohr circles of the 'first kind'; De Paor & Means 1984). Thus the line labelled Y in Fig. 2(d) is the true orientation of the elongation axis for the horizontal plane (ellipsoid axis, Y). Note that both Mohr circles are *off-axis*, which reveals the vorticity of the deformation. Instead of a single tangent point, as for the Mohr circle for simple shear deformation (in the XZ plane), or a symmetric on-axis circle as for pure shear, this is a partially off-axis circle cutting the abcissa at A and C.

The Mohr circle for flow (Lister & Williams 1983) in incremental transpression at constant angle β is shown in Fig. 2(e). This is a Cartesian Mohr graph of $\dot{e}$ vs $\dot{\omega}$, which shows simply that the principal axis ($\dot{e}_2$ in the ellipsoid) is fixed at $\beta/2$ to the zone (see also McCoss 1986). The flow for incremental transpression is a Type II dilatant flow (Passchier 1991), where the kinematic vorticity number (W) is sin β, and the dilatancy number (A) is cos β.

These three Mohr circles (Figs. 2c–e) allow us to determine all the vital information on transpression geometry and strain, by construction. Figure 2(f) compiles this information for the deformed state (cf. Fig. 2b), and shows the finite strain axis (f), the instantaneous extension axis (i), and the material line which was the initial extension axis (oi), for this example. Lines in the ruled sector contain earlier finite extension directions (e.g. the material line which was Y for $e = 0.3$). Returning to Soper's model example, his fold axis would be line 'oi' (not f) and his cleavage increments (traces) would occupy the dotted and ruled sectors, with the last increment at position i.

In this example, the principal extension (X) is vertical (=2). In many other examples we have examined (e.g. $\beta = 45°$ and $e = 0.3$ or 0.7; $\beta = 30$ or 60° with $e = 0.5$), the X direction is also vertical, and so the XY plane is vertical with vertical stretching. Thus we conclude that for a range of geologically reasonable strains and transpression directions, X should be expected to be vertical, not horizontal. However, horizontal stretching will occur for transpressive deformations approaching simple shear, and/or with a high ψ component (Sanderson & Marchini 1984, fig. 3).

Folding in horizontal layers in simple transpression

The example in Fig. 2 allows an immediate assessment of the bulk strain for a horizontal layer in horizontal transpression. Harland (1971, fig. 3) illustrated the important features for transpressive deformation of horizontal layers: folds would initiate oblique to the converging plate margins, and progressively rotate towards parallelism as they tightened. It is not apparent whether this process was considered to be the 'passive' rotation of material hinge lines, or 'active' hinge migration tracking the finite strain axis for the layer; the difference (according to our examples) may only be 1° or 2°.

Sanderson & Marchini (1984) considered a different process for folding, whereby folds initiated in the incremental direction ($\beta/2$: i in Fig. 2f) and deformed passively, while new folds initiated later, also at $\beta/2$. Earlier folds would be cross-cut by later folds (in a clockwise sense for sinistral transpression) within the same deformation. Thus, like Soper's model discussed earlier, folds and fold hinges are considered to be markers of small (initial) increments of strain. We instead would argue (from both theoretical and experimental modelling viewpoints) that no fold would be visible after a small strain increment, and that folds will develop progressively with accumulating finite strain. Only after considerable layer shortening to establish moderate to high limb dips, and fold hinges 'fixed' by considerable curvature, might folds become 'passive' in their subsequent deformation. We suggest that shortening up to about 50% will be accompanied by 'active' buckling and accompanying hinge migration (Cobbold 1976, Stewart & Alvarez 1991). Thereafter the fold axes might rotate as a material marker, and thus lie slightly closer to the zone margin than the XY trace. This argument cannot account for folds cross-cut by XY planes by as much as 10°.

Horizontal layers which are folded in transpressive deformation should therefore be expected to fold on horizontal axes at a small angle to the converging plate margins, to have vertical axial planes and to have vertical XY planes (X vertical, Y parallel to fold axis). Thus if folds and cleavage are synchronous, and cleavage is parallel to the XY plane of finite strain, folds with axial-planar (non-transecting) cleavage should be expected. As we discussed above, two explanations have been given to explain transecting fold–cleavage relationships in transpression, although neither of these specifically requires transpressive deformation.

(1) *Folds do not initiate or develop perpendicular to finite shortening directions of layers.* Sanderson *et al.* (1980) considered an initial obliquity of fold axes to shortening, whereas Sanderson & Marchini (1984) and Soper (1986) considered folds to initiate in the first increment of shortening, with subsequent passive deformation.

(2) *Cleavage is not parallel to the* XY *plane of finite strain.* This is a wider issue than one simply concerning transpressive deformation (see Williams 1976, 1977 and reviews in Treagus 1983, 1988), but the problem of whether cleavage fabrics maintain parallelism with XY when these are non-material planes, as in non-coaxial deformations, is relevant to this discussion. Clearly, cleavages which do not develop synchronously with the whole of a deformation may be oblique to the finite XY plane, and therefore transect folds. For example, Borradaile (1981) proposed that cleavage might develop only in later deformation increments. Soper's (1986) model for transecting cleavage assumes that it developed progressively and serially, parallel to instantaneous increments of shortening. Thus he equates cleavage with stress increments, so these cleavage orientations should be compared with theoretical stress trajectories in folding layers (e.g. Dieterich & Carter 1969), rather than finite strain trajectories.

As we discussed above, the characteristic patterns of the transected folds we have studied in Britain show all the traditional fanning and refraction patterns which have long been compared to strain in folding (Ramsay 1967, p. 403), as illustrated in Fig. 1. These features, where cleavage significantly transects fold hinges in a range of lithologies from mudstone to greywacke, do not seem to be adequately explained for horizontal layers in horizontal transpression.

Inclined layers in simple transpression

In earlier work (Treagus 1973, 1983, Treagus & Treagus 1981) we have examined features of folding and straining of oblique layer systems, within the conceptual

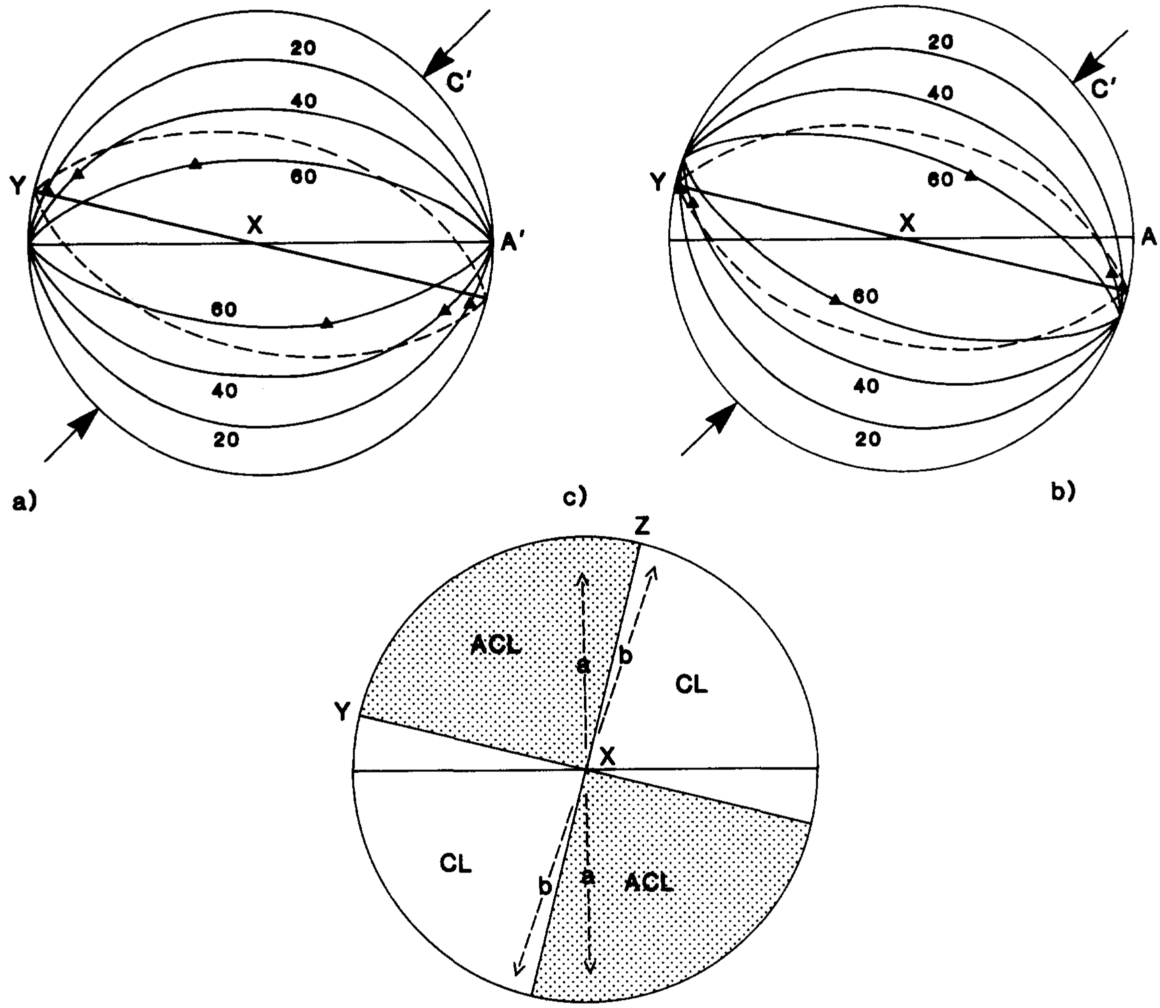

Fig. 3. Orientations of directions perpendicular to finite shortening, for planes of varying orientations with respect to the sinistral transpression deformation in Fig. 2. Transpression vector is bold arrow, transpression zone margin (A) east–west. Solid line is *XY* plane, broken curves circular sections. (a) Planes striking parallel to zone margin, dips 20°, 40° and 60° (labelled). Fold axes (triangles) are cut anticlockwise by the *XY* plane. (b) Planes striking 20° to the zone margin, otherwise as (a). Fold axes are transected clockwise. (c) Fields for which bedding poles would have anticlockwise transection of fold axes by *XY* plane (ACL, shaded), and clockwise (CL, blank). Positions for examples in (a) and (b) indicated by broken lines, labelled a, b.

framework that rock layers are unlikely to be deformed in exact layer-parallel compression/extension. If this *were* the case, and all principal displacements were horizontal or vertical, all fold axes would be horizontal, the overall sheet-dip horizontal, and axial planes and cleavages vertical. There can hardly be any fold belts which satisfy these criteria.

Consider, then, two classes of inclined layers in simple transpression: case 1 are layers striking parallel to the converging plate margin, with varying initial dips; case 2 are layers oblique in strike and dip. Examples are given for each in Fig. 3, using the same sinistral transpressive deformation as Fig. 2, and the Biot–Fresnel method of determining principal axes in the layer using circular sections (Treagus & Treagus 1981).

Case 1. Figure 3 (a) shows planes after deformation, considered to represent the sheet-dips (enveloping surfaces) of folded layers. For all these cases, the *XY* plane trace is *anticlockwise* of the finite strain axis (fold axis) in the plane of consideration. With greater layer dip, the discordance angle is more measurable, and fold axes have significant NW or SE plunges. The only examples where this form of layer obliquity can give rise to clockwise transection for sinistral transpression would be for deformation which has finite *X* horizontal: i.e. close to simple shear (not illustrated).

Case 2. Dipping layers which strike oblique to the rigid plate margin can show a range of discordance angles and trends between expected fold axes and the *XY* trace (e.g. Fig. 3b). The sense of layer strike to the *XY* plane is critical, and divides fields of anticlockwise, axial-planar and clockwise cross-cutting relationships. Actual values are less important, as these reflect the chosen transpression geometry and layer orientations, but the *senses* of the results are significant.

Figure 3(c) compiles the senses of transection for both classes of oblique layers in sinistral transpression. According to the layer pole orientation, both clockwise-transected and anticlockwise-transected folds can be explained, in theory. The question that arises is which orientation of layering is likely to be 'normal' for transpressive closure of sedimentary basins or accretionary prisms. We think it quite probable that layering would strike subparallel to plate margins; therefore, from the above discussion, we would expect clockwise transection of folds in inclined layers to be a more likely association of dextral transpression.

Deformation history and models of folding in transpression

In all the examples so far, we have considered simple transpression, and assumed homogeneous deformation arising as a single oblique-closure event. Figure 2 compared initial and final states, without requiring any particular deformation path. The deformation could have been a constantly directed progressive transpression, a pure shear followed by simple shear, simple shear followed by pure shear, or a more complex history. The net strains and rotations (Figs. 2c & d) are the same, but the histories are very different and therefore geological structures which are history-dependent (rather than finite strain markers) should be very different.

Figure 4 shows three schematic movement paths which each give rise to finite transpression. Path (a) is constant incremental (simple) transpression (Sanderson & Marchini 1984), and increments of flow for this were shown in Fig. 2(e). Paths (b) and (c) are not constant-vector paths, and their increments of transpression will vary in time, as the progressive β angle changes. Path (b) begins in dominantly pure shear and progresses gradually into transcurrent shearing, and path (c) has a reverse

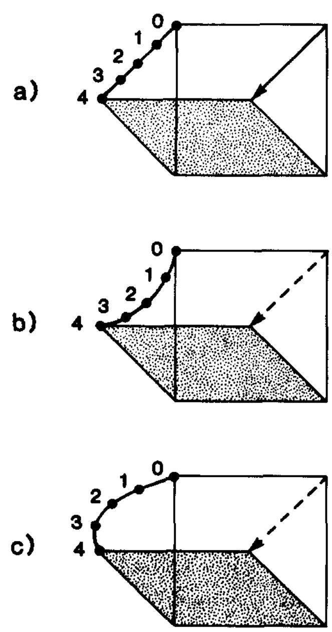

Fig. 4. Three deformation histories shown by displacements paths with time points 1–4, for an identical finite transpression (arrowed line, as Fig. 2). (a) Linear movement path; incremental simple transpression. (b) and (c) curved movement paths. (b) Smooth gradient from initial pure shear to later simple shear (increasing transpression). (c) An opposite gradient (decreasing transpression), with a final reversal of shear direction.

progression. We emphasize that all paths end up with the same finite strain (Fig. 2b), but at frozen time intervals the increments and the finite stages will be very different.

We must ask what evidence exists to place constraints on transpressive histories in the Appalachian–Caledonian belt. Arguments for sinistral transpression arising from the three-plate model (Soper & Hutton 1984) seem to focus on two lines of evidence: evidence from regional plate tectonics for western Europe, and structural evidence which comprises (a) presence of strike-slip faults (with late strike-slip movements), and (b) transected folds. Without far more data, both for regional tectonic movement paths and for incremental strain history, we consider it an oversimplification to assume that the British Caledonides either side of the Iapetus suture deformed in constant incremental transpression. The evidence that does exist suggests that sinistral transcurrent movements were relatively late in the deformation history, which may suggest a movement history like Fig. 4(b).

We have argued earlier for progressive development of folds with finite strain, and for cleavage keeping track with the *XY* plane. Our exception has been to consider a stage after which fold axes become 'fixed' and thereafter rotated as material lines. This distinction has been shown to be insufficient to explain fold transection by more than *ca* 2°. However, for a different deformation history, such as transpression where pure shearing is increasingly replaced by transcurrent shearing (Fig. 4b), different relationships will be seen. Here, we would expect folding to initiate *subparallel* to the plate margin (model 3 of Sanderson *et al.* 1980). If folding ceased to proceed actively after say 50% shortening, while cleavage retained subparallelism to the finite *XY* plane, we could expect transection of 10° or more (see orientation of *Y* to A in Fig. 2c). This would be clockwise transection for sinistral transpression. Moreover, this considerable degree of transection would occur in subhorizontal layers with horizontal plunge, so would not require the interdependence of sheet dip and fold plunge sense shown in Fig. 3.

CONCLUSIONS

There is no obvious explanation for transected folds in horizontal layers in incremental simple transpression, without requiring special pleading for the development of folds, and/or cleavage not parallel to *XY* planes. However, layers of different inclinations and strikes with respect to simple transpression should have fold axes cross-cut by *XY* planes, and thus this provides the most obvious geometrical explanation for transected folds. Significantly, some layer orientations will develop a clockwise transection sense, and others anticlockwise, for a particular transpressive sense. Thus the 'oblique layer model' does not predict that all transection would be clockwise for sinistral transpression. Diagnostic features would be characteristic associations between sheet dip inclination (layer), fold plunge and transection sense, as illustrated in Fig. 3.

An alternative explanation invokes a non-constant transpressive deformation history. Such a history, particularly one with early pure shear giving way to later simple shear (e.g. Fig. 4b), favours formation of folds subparallel to the converging plate margin, and cleavage having a characteristic crosscutting sense (clockwise for sinistral transpression). The diagnostic features would be subhorizontal fold axes, and microstructural evidence of a history of early coaxial straining and increasingly significant non-coaxial deformation later.

We conclude that there is no simple association between cleavage-transected folds and transpressive deformation. A clockwise sense of transection should not be used as sole indicator of sinistral transpression (nor anticlockwise for dextral), without supporting structural data.

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