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Folds with vergence opposite to the sense of shear

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Abstract—Near-similar folds with persistent NW-vergence occur in the southeast Highlands of Scotland and are interpreted to have formed in a regime of SE-directed non-coaxial shear. The sense of shear is corroborated by independent kinematic indicators. The folds are formed by a mechanism in which strongly partitioned shear produced an alternation of high strain zones, forming long limbs, and low strain zones, forming short limbs. Progressive strain results in the rotation and attenuation of strain markers in the long limbs and in the consumption of low strain zones. High strain may ultimately lead to the disappearance of the short limbs.

INTRODUCTION

Vergence, used as the direction of the sense of asymmetry of a set of asymmetric folds, is a useful tool for structural analysis in complex folded areas. In the definition of Bell (1981), widely adopted today, it was meant as a purely descriptive term. However, it is often assumed that vergence has the same direction as the 'sense of rotation' or sense of shear of the strain regime responsible for the formation of a set of asymmetric folds. Indeed this is how many geologists would instinctively interpret such a set. Part of this genetic connotation possibly results from the original German meaning of 'Vergenz', which indicated a direction of overturning or sense of movement (see discussion in Fleuty 1964). In a recent review of folding, Hudleston & Lan (1993) state that systematic asymmetry "is nearly always consistent with the sense of shear". Our aim is to show that folds with vergence opposite to the sense of shear of their strain regime do exist and that caution is required in the interpretation of the strain regime of asymmetric folds.

FOLD MECHANICS FOR NEAR-SIMILAR FOLDS

Models for similar folds dating from the 1950s and 1960s (e.g. Carey 1954, 1962, Wynne-Edwards 1963) invoked shear or slip parallel with the axial surface (Fig. 1a), in which fold asymmetry or vergence will be opposite to the sense of shear if the original layering was at high angles to the axial surface, as in Fig. 1(a).

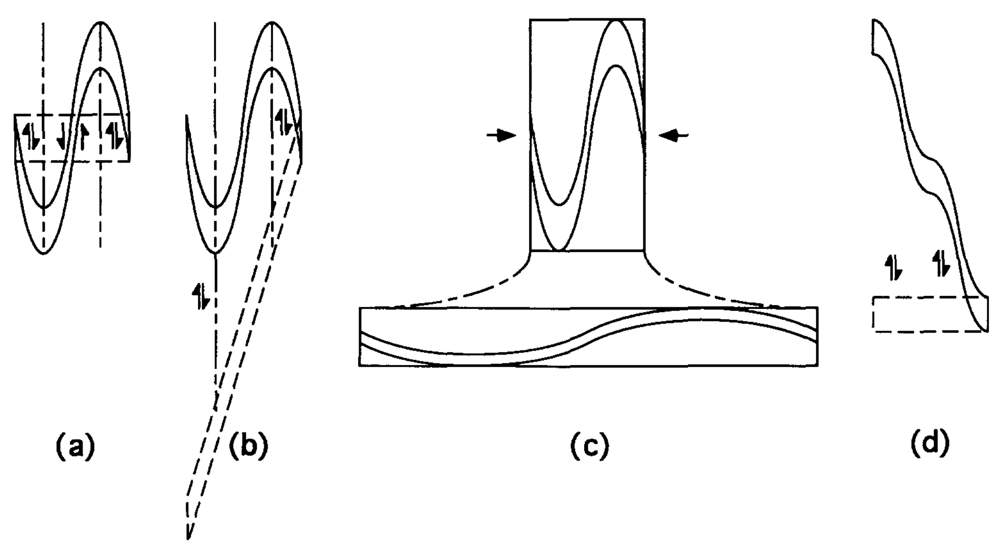

Fig. 1. Four different models of similar folding. (a) Classical shear or slip model: heterogeneous simple shear parallel to axial plane, reversal of shear sense across axial plane, sense of shear opposite to vergence. (b) Initial layer at low angle to axial plane, heterogeneous simple shear with constant sense of shear parallel to axial plane (Ragan 1969). (c) Homogeneous coaxial flattening of pre-existing parallel (buckling) folds normal to axial plane (Flinn 1962). (d) Asymmetric folds produced by heterogeneous simple shear with constant sense of shear parallel to axial plane, vergence opposite to sense of shear (this study).

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Whereas Flinn (1962, p. 425) and Hudleston (1977) pointed out that it is difficult to explain the necessary systematic reversals of shear sense across axial surfaces, Ragan (1969) proposed a model of heterogeneous simple shear with constant sense of shear, starting with a layer at low angles to the axial surface (Fig. 1b). Ragan (1969) admitted that this model requires a rather special relationship between the orientation of the initial layer, the axial surface and the shear sense (see also review by Hudleston 1977). Recent reviews of fold models no longer consider the shear or slip model (Suppe 1985, Ramsay & Huber 1987, Price & Cosgrove 1990) or reject it altogether (Johnson 1977). This is partly because of the realization that perfect similar folds are rare in nature (Ramsay 1962) and that 'near-similar' folds can be developed by homogeneous coaxial flattening (i.e. pure shear) of earlier parallel (buckling) folds (Fig. 1c, Flinn 1962, Ramsay 1962); this has subsequently been termed 'passive amplification' (e.g. Suppe 1985) or 'passive folding' (e.g. Price & Cosgrove 1990).

Although passive amplification seems to be a viable mechanism to produce near-similar folds, this mechanism can only produce large sets of asymmetric folds with constant vergence if the earlier folds were already formed with a consistent sense of asymmetry, or if the enveloping surface of the earlier folds was highly oblique to the bulk shortening direction and the bulk shortening direction cuts across both limbs of the earlier folds. Assuming a vertical bulk shortening direction, consistently asymmetric folds would result if one of the earlier fold limbs was overturned.

The problem of changing shear sense does not occur in sets of folds which show a consistent asymmetry over a large area. In this case, heterogeneous simple shear with consistent sense of shear, i.e. shear or slip model folding, is a viable fold model (Fig. 1d). As noted above, in this case the sense of shear of such folds will, in most cases, be opposite to their vergence.

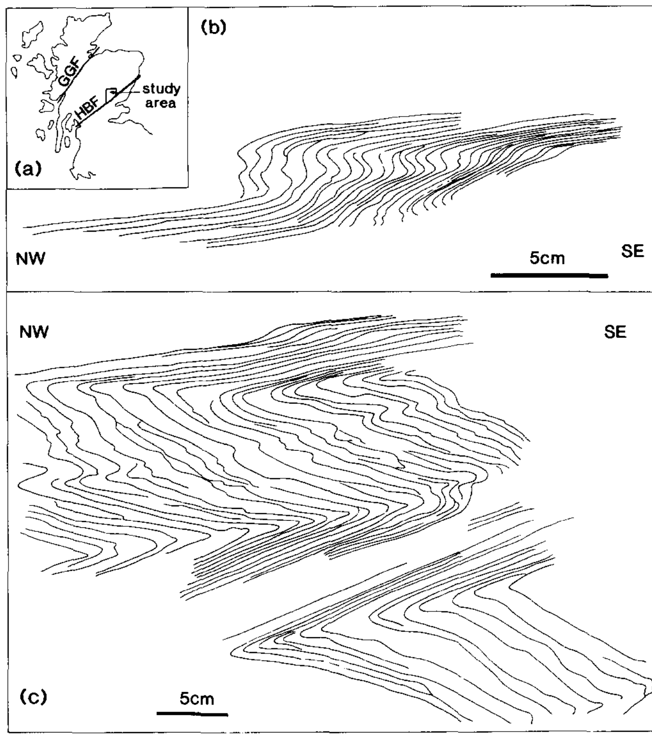

Fig. 2. (a) Sketch map indicating location of study area in southeast Scotland, GGF = Great Glen Fault, HBF = Highland Boundary Fault. (b) & (c) Accurate line tracings from field photographs of two typical D_2 folds in psammites of the Southern Highland Group. Tracings are section; the folds plunge gently to the northeast. Lines represent modified S_1 fabric, occurring as very thin micaceous films delineating quartz rich lithons. (b) This experienced higher strain than (c) as can be seen from the thinner spacing of S_1 in the long limbs, the smaller angle between S_1 (mod) and the axial plane and the higher ratio of long vs short limb. Note development of *S–C* like geometry in right part of (b). Localities: (b) NO07295157, (c) NO04354791.

ASYMMETRIC FOLDS WITH CONSISTENT VERGENCE

In the southern part of the Dalradian outcrop in Central Scotland, folds with a consistent NW-vergence occur over a large area in the inverted limb of the Tay Nappe. They deform a thick sequence of Southern Highland Group clastic metasediments, comprising mainly psammite and semipelitic schist. The following description is taken from the authors detailed observations in the area outlined in Fig. 2(a) and accords with that of Harris *et al.* (1976) working in adjacent ground to the southeast. Fine-grained, quartz-rich psammites generally show a very conspicuous spaced fabric or tectonic striping (S_1) defined by very thin (200–400 μm), micaceous laminae comprising stubby flakes of biotite and/or muscovite which separate quartz-rich lithons; in areas which escaped subsequent D_2 deformation the spacing of S_1 is about 10–30 mm. The S_1 fabric is formed by pressure solution (Harris *et al.* 1976) during a D_1 deformation which Harris *et al.* (1976) and Treagus (1987) believe—and the authors accept—produced close folds with steeply dipping axial planes. During the D_2 deformation, the S_1 fabric is intensely modified to produce tight, angular, near-similar fold structures. F_2 fold axes plunge gently to the northeast; well developed L_2 mineral stretching lineations plunge gently to the north, with a considerable narrower spread than F_2 fold hinges. Whereas S_2 is subhorizontal in places, it is more typically north to NW-dipping at up to 30 degrees. D_2 folds show a strong and consistent sense of asymmetry; virtually all (c. 90%) verge towards the northwest (Figs. 2b & c), i.e. are 'S-shaped' when viewed down-plunge. Spacing of the modified S_1 (further termed S_1 (mod)) in the long limbs is thinned (1–3 mm) with respect to the spacing in the hinges. In the long limbs S_1 (mod) is remarkably straight, whereas it is more irregular in the short limbs with parasitic folding (Figs. 2b & c). These geometries are seen in most of the outcrop of Southern Highland Group rocks in a zone at least 20 km wide and over a 100 km long. In the study area, these structures are not modified significantly by later deformation events, which only become important further north and also in the extreme southeast of the area, close to the Highland Boundary Fault.

SENSE OF SHEAR VERSUS VERGENCE

The issue addressed here is whether these D_2 folds are formed by non-coaxial strain with top to the SE sense of shear, by non-coaxial strain with top to the NW sense of shear or by coaxial flattening. Harris *et al.* (1976) postulated that D_2 folds in the Pitlochry area are shear folds which transport top to the southeast, i.e. opposite to the dominant northwest directed vergence, and Treagus (1987) arrived at the same conclusion working in Dalradian lithologies at stratigraphically lower levels. However, this view is not universally accepted (e.g. Mendum & Fettes 1985). One of our arguments demonstrates the non-coaxial nature of the D_2 folds and a further three attest to the vergence being opposite to the sense of shear.

(1) The consistent asymmetry of the folds, i.e. predominant NW-vergence is seen throughout an area of >2000 km^2 with a structural thickness of at least 5 km. The NW-vergence is therefore *regional*. If the D_2 folds were formed by passive amplification (i.e. bulk coaxial vertical shortening) this would require a pre-existing (D_1) fold stack of huge (>20 km) thickness. There is no evidence whatsoever for such a thick pile of metasediments being attenuated during D_2, in fact D_2 is synchronous with peak metamorphic conditions (Robertson 1994), i.e. during gross crustal thickening. This implies that vertical shortening cannot have been the dominant process during D_2.

The long limbs of F_2 folds are very straight and thinned with respect to the original thickness (see later). Extension in this direction without bulk vertical flattening is only possible during strong non-coaxial shear. Strong non-coaxial shear, i.e. with a strong component of simple shear, must therefore have been responsible for the F_2 folds.

(2) Quartz c-axis fabric analysis of oriented quartz-rich (>90%) samples taken from the long limbs of D_2 folds shows a girdle pattern clockwise to the normal to the axial plane of D_2 (Fig. 3a). Such a girdle pattern is indicative of non-coaxial shear with a top to the SE-sense of shear (Law 1990 and references therein) by means of dynamic recrystallization. A c-axis fabric analysis from a hinge zone of a D_2 fold shows a symmetric 'hourglass' pattern (Fig. 3b), indicative of coaxial strain (Law 1990). This suggests that different strain regimes have operated in the hinge and the limb zones of D_2 folds and rules out preferred crystallographic orientation in the long limbs as a result of D_1 deformation reorientated during D_2.

(3) *S–C* fabric geometries are recorded in both thin-section and at a larger scale in the long limbs of D_2 folds at numerous localities, all indicating a top to the SE sense of shear. In some places, *S–C* geometries are seen to be continuous with D_2 folds (e.g. Fig. 2b).

(4) D_2 is absent in the extreme southeast of the Dalradian outcrop of the study area as is the case more generally in Perthshire (Harris *et al.* 1976). In such domains the spacing of the original S_1 fabric lies in the range of 10–30 mm, whereas the spacing of S_1 (mod) in the long limbs of D_2 folds is 0.5–3 mm and in the short limbs is 3–10 mm. This suggests that the limbs of D_2 folds have been thinned rather than that the hinges were thickened with respect to the original spacing of S_1. This rules out an origin by buckling with transport to the northwest: in buckle folds one would expect thickened hinges.

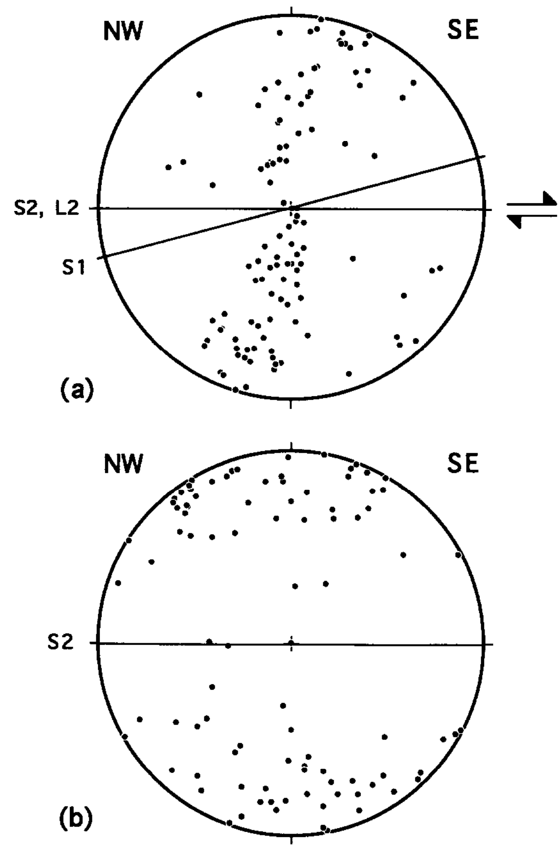

Fig. 3. Quartz c-axis fabrics from a quartz-rich (90%) sample of a long limb (a) and a hinge zone (b) of a D_2 fold. Measurements taken on an automatic U-stage, N = 111 (a) and N = 95 (b).

Thus it can be concluded that the asymmetric NW-vergent folds are generated in a strongly non-coaxial shear regime with a top to the SE sense of shear, i.e. opposite to their vergence. The prominent L_2 mineral lineation indicates the direction of movement.

FOLDING MECHANISM

The following model is proposed for the D_2 folding (Fig. 4). Originally steeply dipping S_1, produced by upright or steeply inclined folds, was subjected to a sub-horizontally directed, strongly non-coaxial shear regime. S_1 was (partly) rotated towards the long axis of the strain ellipse and was attenuated, lying in the extensional field of the strain ellipse, thus forming the long and straight limbs of the folds. The original spacing of S_1 was greatly reduced, both by rotation and by extension sub-parallel to the long limbs. This shear regime acted in a strongly partitioned way, with low-strain domains now forming the short limbs of the folds; the short limbs are, in effect, relics of steep less deformed S_1 (Fig. 4a). Progressive strain resulted in both rotation of S_1 (mod) in the long limb towards the axial plane of the folds (which is sub-parallel to the flow plane) *and* in progressive consumption of the short limbs, i.e. of the low strain zones (Fig. 4b). The latter is effectively a decrease in deformation partitioning. In other words, both the angle of rotation and the ratio of long to short limbs increased with progressive strain.

With ongoing progressive strain, the low strain short limbs may ultimately be consumed entirely resulting in a purely planar, composite S_1/S_2 shear fabric, subparallel to the flow plane (Fig. 4c), as is seen in many places most often in more pelitic lithologies. An intermediate situation results in a geometry which resembles an *S–C* fabric (Fig. 2b), although it is not an *S–C* fabric *sensu stricto*, where the '*C*' planes are the composite S_1/S_2 shear fabric and the '*S*' planes are partly sheared-out S_1 relics. Although produced by a slightly different mechanism, this geometry is indicative of the same shear sense of normal *S–C* fabrics. In this mechanism F_2 hinges reflect the intersection of original attitudes of S_1 layering and the shear surface in D_2.

Many of the garnet porphyroblasts occurring in semi-pelitic schists in the study area show straight or slightly sigmoidal internal fabric (Si = S1) at large angles to the external fabric (Se = composite S_1/S_2 shear fabric), usually with Si in different garnet porphyroblasts parallel to each other in a single thin-section. Rotation of the external S_1/S_2 fabric (cf. Bell 1985) occurs in the study area by a shear sense consistent with the observed *S–C* and quartz c-axis fabrics.

It should be noted that the resulting fold geometry is dependent on the initial orientation of S_1 and the shear regime (Fig. 4d). The folds that are the subject of this article result when the original S_1 dip is at high angles to the D_2 flow plane. If S_1 attitudes are in the extensional field and at low angles to the flow plane no tight folds will result; an *S–C* type geometry will develop and most likely evolve rapidly into a planar fabric. Alternatively, if S_1 is positioned in the compressional field throughout its evolution folds with neutral vergence or vergence in the same direction as the sense of shear will develop (Fossen & Holst 1995).

DISCUSSION

This study shows that asymmetric folds exist with their vergence opposite to the sense of shear of the strain regime and that they can be generated by heterogeneous non-coaxial shear in a shear-fold like mechanism. The folds described in this study are not necessarily formed by simple shear alone; some degree of flattening is likely (see also Treagus 1987), if only to account for the parasitic folding in the low strain short limbs. However, strongly non-coaxial shear must have been the dominant process.

Near-similar asymmetric folds with the sense of shear opposite to their vergence are reported by a few other authors, e.g. Ramsay *et al.* (1983) described such folds in the lower limb of the Morcles Nappe. In this case, however, folding started as buckle folds with vergence in the same direction as the sense of shear and only changed vergence at high shear strains ($\gamma > 6$, their fig. 4). This situation is not seen in the present study, where the D_2 folds have opposite vergence from their initiation until the folds are completely sheared out.

Further examples of folds with opposite shear sense are reported from microstructural studies of crenulation folds (Bell & Johnson 1992, Rajlich 1993). In scaling up their findings on small scale structures Bell & Johnson (1992) postulated a fold mechanism similar to that proposed here: in fact this study is a confirmation that their proposed 'deformation partitioning' model can occur where the bulk strain is strongly non-coaxial.

It should be noted that, at very high strains, e.g. those that occur in mylonite zones, the concept of vergence is of little use because of the formation of sheath folds with strongly curvilinear fold-axes. Indeed, Hanmer & Passchier (1991) caution strongly against the use of fold asymmetry as a shear sense indicator in mylonite zones.

The realization that folds with vergence opposite to the sense of shear do exist and, at least in the Dalradian of southeast Scotland, do so over a large area, has important implications for tectonic analysis. It is obviously of fundamental importance in deciphering the overall strain regime responsible for folds and, if such

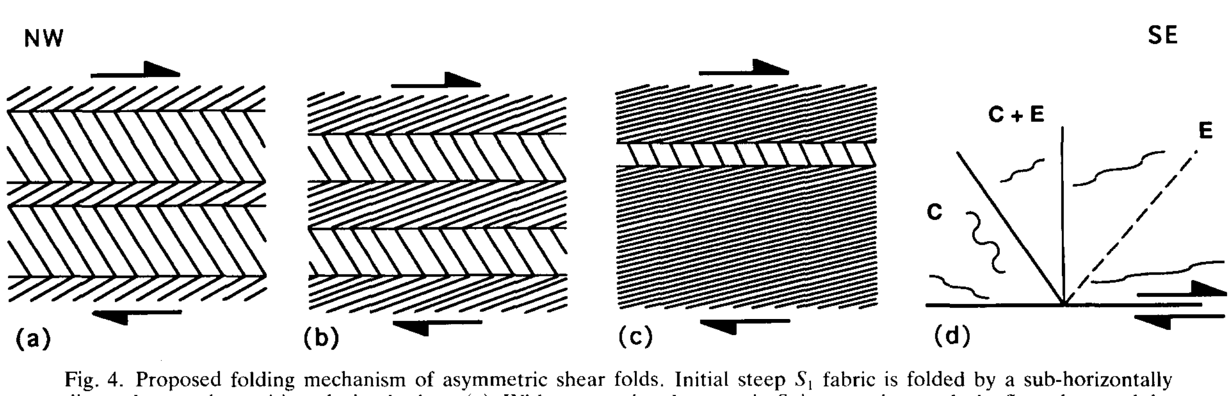

Fig. 4. Proposed folding mechanism of asymmetric shear folds. Initial steep S_1 fabric is folded by a sub-horizontally directed, strongly partitioned, simple shear (a). With progressive shear strain S_1 is rotated towards the flow plane and the low-strain zones with steep S_1 are progressively consumed by the high strain zones (b). Ultimately some low strain zones will disappear (c). A sketch showing orientation of initial strain markers, deformed by simple shear into different types of shear folds, is included (d). Fields of extension (E), compression (C) and extension followed by extension are shown (C + E). Further explanation: see text.

folds occur over a large area, this will have implications for the kinematic interpretation of such areas. In the study area, for instance, the interpretation of the Tay Nappe hinges on the correct interpretation of the asymmetric folds (e.g. Harris *et al.* 1976, Mendum & Fettes 1985, Treagus 1987).

Large scale zones of strong non-coaxial movement are widespread in orogens, both related to compressional structures (nappes) and to extensional structures (low-angle detachments) (note that a zone of simple shear in itself is neither compressional nor extensional). Often it is difficult to distinguish between compressional and extensional phases in the evolution of an orogen; it would not surprise the authors that, in view of this study, some reinterpretation of certain zones with strong non-coaxial strain might be necessary.

CONCLUSIONS

Vergence should be used to describe the sense of asymmetry of folds, without any reference to the sense of rotation or sense of shear. Fold asymmetry should not be used as an independent kinematic indicator; other indicators such as *S–C* fabrics should be used to test whether vergence is consistent with shear sense or not.

Shear or slip sub-parallel to the axial plane is a viable mechanism for near-similar folds which show a consistent vergence over a wide area.

Folds generated by this model have a sense of shear opposite to their vergence, if the original layering was at high angles to the flow plane.

Near-similar folds with their vergence opposite to their sense of shear occur in large areas subjected to bulk non-coaxial strain.

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