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The association of folds and veins in shear zones

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Abstract—Paired hook-shaped asymmetric folds, with shared limbs cut by axial planar veins, dikes or fractures are common in glaciers and rocks. The sense of offset across the vein or fracture is characteristically opposite to that expected from the sense of fold asymmetry. The kinematics of development of the folds and the relationship of the folds to the fractures or veins can be understood by considering the nature of glacial flow and by utilizing simple clay experiments.

In zones of simple shear, dilational fractures may form at about 45° to the shear zone boundaries. The perturbation of strain around such a fracture during its development and subsequent rotation and closure under continued deformation causes layers or pre-existing foliation cut by the fracture to become folded. Thus folding is a consequence of the fracturing, and not vice versa. The precise shape of the fold depends on the nature of the perturbation, and particularly whether or not the fracture remains for a time open or fluid filled and thus has walls unable to sustain a shear stress during vein rotation.

Paired hook folds provide evidence for non-coaxial strain and are good sense-of-shear indicators. However, not all folds with veins parallel to their axial surfaces form in the way described in this paper. In some cases vein emplacement occurs late during fold development or post-dates folding; in these cases offsets along the veins are consistent with fold asymmetry.

INTRODUCTION

VEINS are found in rocks deformed under a wide range of crustal conditions, common examples being quartz veins in slates and other low-grade metamorphic rocks, and leucocratic veins in migmatites or other high-grade rocks. They have been used in a number of ways to help determine the deformational history of rocks, both on a small scale (e.g. Ramsay & Huber, p. 235) and on a regional scale (e.g. Fitches *et al.* 1986). Perhaps the most familiar example on a small scale are planar and sigmoidal en échelon veins which, from their orientation and shape, can be used to determine sense and amount of shear in shear zones (Durney & Ramsay 1973, Ramsay & Huber 1983). However, it is clear that not all sigmoidal en échelon veins or dikes are associated with shear zones (Pollard *et al.* 1982, Nicholson & Pollard 1985) although, whether developed in a shear zone or not, most workers interpret échelon cracks or veins to be extensional cracks propagating in a plane normal to the least compressive stress. In quite a different use of veins, the folds and boudins developed in a suite of veins of various orientations can provide information about the symmetry and orientation of the strain ellipsoid (Talbot 1970).

It is not uncommon to find veins developed parallel to the axial surfaces of folds, prompting questions about the origin of both folds and veins (Fig. 1a). Besides occurring in rocks, this close association of the two structures is very common in a number of glaciers I have studied, in which the deformational history is easily established. The examples in ice provide strong evidence that the two are closely linked genetically in a rather simple way. It involves the development of extensional fractures in an otherwise ductile shear zone. These fractures form rapidly, and are treated here as forming instantaneously. Certainly, the time of formation is very small compared to the time for any finite rotation of a fracture. Continued deformation leads to the rotation of the fractures, which typically dilate and subsequently close up or become infilled to form veins, and the simultaneous development of the folds, as described below. Thus the folding is a consequence of the fracturing and vein formation, not vice versa. The purpose of this paper is to describe the mechanics of this process, with reference to natural examples developed in rocks and ice, and to discuss the use of the structures as sense-of-shear indicators.

MECHANISM OF VEIN DEVELOPMENT AND FOLDING

Folds in glaciers

Folds of the kind shown in Figs. 1(b) and 3 are very common in the highly foliated marginal ice of several valley glaciers in northern Sweden. They consist of asymmetric pairs of *hook folds* with the common limb apparently sheared out and occupied by a vein. The folds plunge steeply and are of 'S' symmetry on one side of the glacier (adjacent to the left bank following the flow) and of 'Z' symmetry on the other, with the sense of asymmetry on both sides consistent with the sense of shear in the marginal ice. Sense of offset along the sheared-out limb is often difficult to determine because of lack of marker horizons, but where discernible is always of the *opposite* sense to that of the sense of shear known from the flow of the glacier and predicted by the fold asymmetry. Where the veins end, the folds die out also. Where there are multiple veins the pattern is more complicated (Fig. 2b).

The veins are typically manifest as bands of clear ice cutting across bands of foliated ice—with foliation marked by variations in grain size and size and frequency of bubbles (Hooke & Hudleston 1978). In well recrystallized ice, there is often little difference in grain size between vein and host. There is sometimes a line of bubbles along the center of a vein (Fig. 2b), suggesting syntaxial infilling (Ramsay & Huber 1983, p. 241).

It is known that the marginal ice in glaciers, like the basal ice, undergoes large shear strains (Hambrey & Milnes 1977, Hudleston & Hooke 1980) and thus, unless the veins formed late in the deformational history, both folds and veins have been subjected to this shear, which approximates simple shear near the glacier margins. There is good reason to suppose that the veins did not form as a direct response to shear in their present positions: the present shear affecting the vein walls is of the wrong sense to produce the observed offsets.

Observations suggest the following origin for the veins. There are numerous extensional fractures (crevasses and smaller cracks) that form at roughly 45° to the margins of the glacier. They become progressively rotated, nearly closed up and infilled to form veins. There is no direct evidence that individual fractures begin to close up before being infilled to form veins, but most open fractures (crevasses) are much wider than any of the veins found. One must bear in mind that where best seen in the ablation zones of glaciers (e.g. Fig. 2a) ice is being removed by ablation as the fracture/vein rotates thus exposing different levels of the structures with time. Because crevasses get narrower with depth, it is hard to separate closing with time from narrowing with depth. Veins formed by the infilling of fractures are a major component of the strong marginal foliation in glaciers (Hooke & Hudleston 1978). The sequence of formation, rotation and infilling of fractures can clearly be traced, using cross-cutting relationships, in ice exposed in the ablation zone of the glaciers in the summer. It is such fractures that eventually become the veins in the shared limbs of folds of the kind shown in Figs. 1(b) and 3.

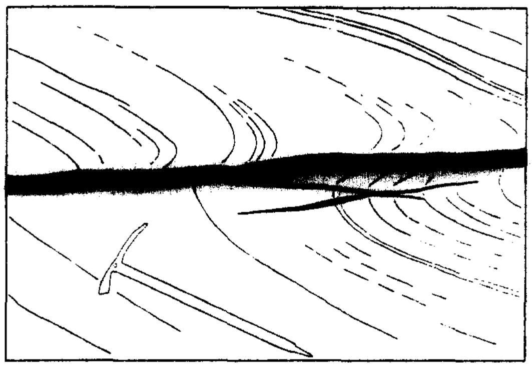

Fig. 3. Line drawing of Fig. 1(b) to clarify the pattern of folds and veins (black) in glacial ice.

Experiments

The progressive development of the veins and folds can be demonstrated in several ways. In Fig. 4 are shown the results of very simple experiments done with Plasticene, a modelling clay with strongly non-linear rheological properties (McClay 1976). In one set of experiments, rectangular blocks of the material, about 8 × 2.5 × 1.5 cm, were prepared with straight central lines marked along the lengths of the blocks on the upper surfaces to represent the 'pre-existing foliation' (developed under the strong shear strains that are assumed to have preceded this stage). Thin cuts (a few mm deep) at 45° to the line and block margins were then made with a penknife to simulate fractures. The initial state in the experiments (Fig. 4a) can be compared to the initial state in a glacier (Fig. 2a). The blocks were subjected to shear along their edges (using pieces of wood with rough edges to reduce slip between wood and clay). The results are shown in Figs. 4(b) & (c), which are drawings of different models subjected to different amounts of total shear. To prevent slippage between wood and clay a certain amount of compression across the block was required, so the strain is actually one of transpression. Despite the strong edge effects at the ends of the block of clay (as evidenced by the curling over of the 'layer' at the ends of the block in Fig. 4c), the rotation of the fracture and concomitant development of the fold are very nicely shown. Blocks sheared without a fracture develop no folds and show homogeneous strain in their central parts.

In a second experiment, a rectangular grid was marked on the upper surface of the block prior to deformation. The appearance of the block and rotated and partly closed fracture is shown in Fig. 5. The deformation associated with the overall strain and the perturbation

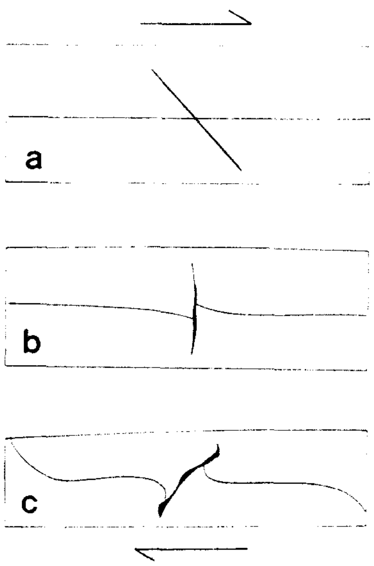

Fig. 4. Line drawings of photographs of Plasticene blocks used in experiments to show fold development adjacent to fractures. (a) Initial state with central marker drawn parallel to the shear zone boundaries and a cut at 45°. (b) After shear strain (dextral) of about 1. (c) After shear strain of about 2. The ends of the blocks are not shown.

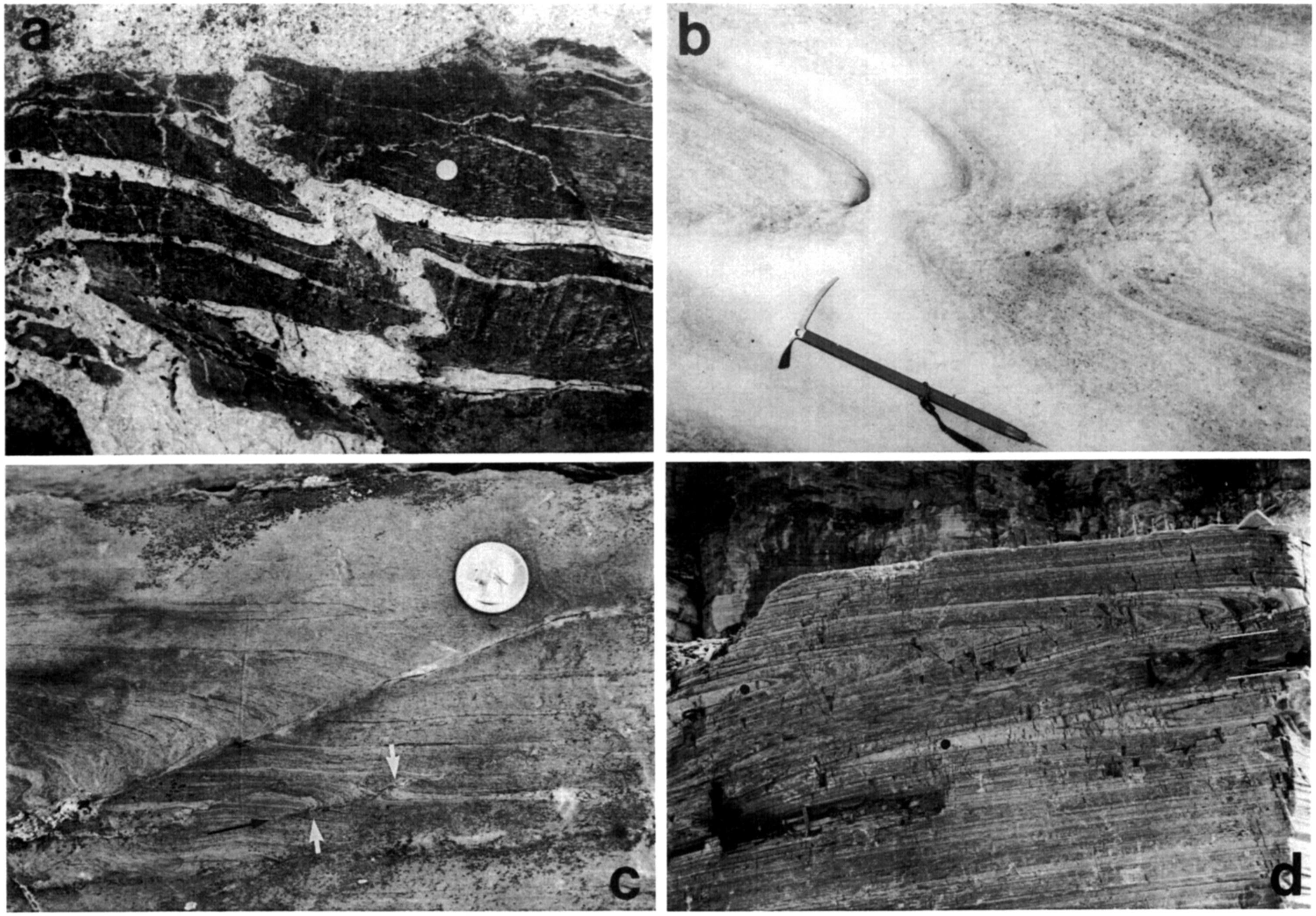

Fig. 1. (a) Folds in granitic veins in biotite schist, cut by second generation granitic vein parallel to the fold axial surface (Archean rocks exposed at the southern end of Burntside Lake, Minnesota). (b) Asymmetric paired folds in foliated ice, with veins occupying the central limb (Storglaciär, Lappland, Sweden). Glacial flow produced dextral shear. (c) Structures in Archean schist in dextral strike-slip fault zone (near International Falls, Minnesota). Note the larger asymmetric 'Z' fold and small paired hook folds in the lighter band (white arrows) separated by a fracture with sparse vein infilling (black arrow). (d) Very tight paired folds in psammitic schists separated by strongly sheared mafic dike (margins shown in white at the right of the photograph). Matching hinges are indicated by black dots (Eidsvoll quarry, near Oppdal, Norway). The hammer at the bottom left gives the scale.

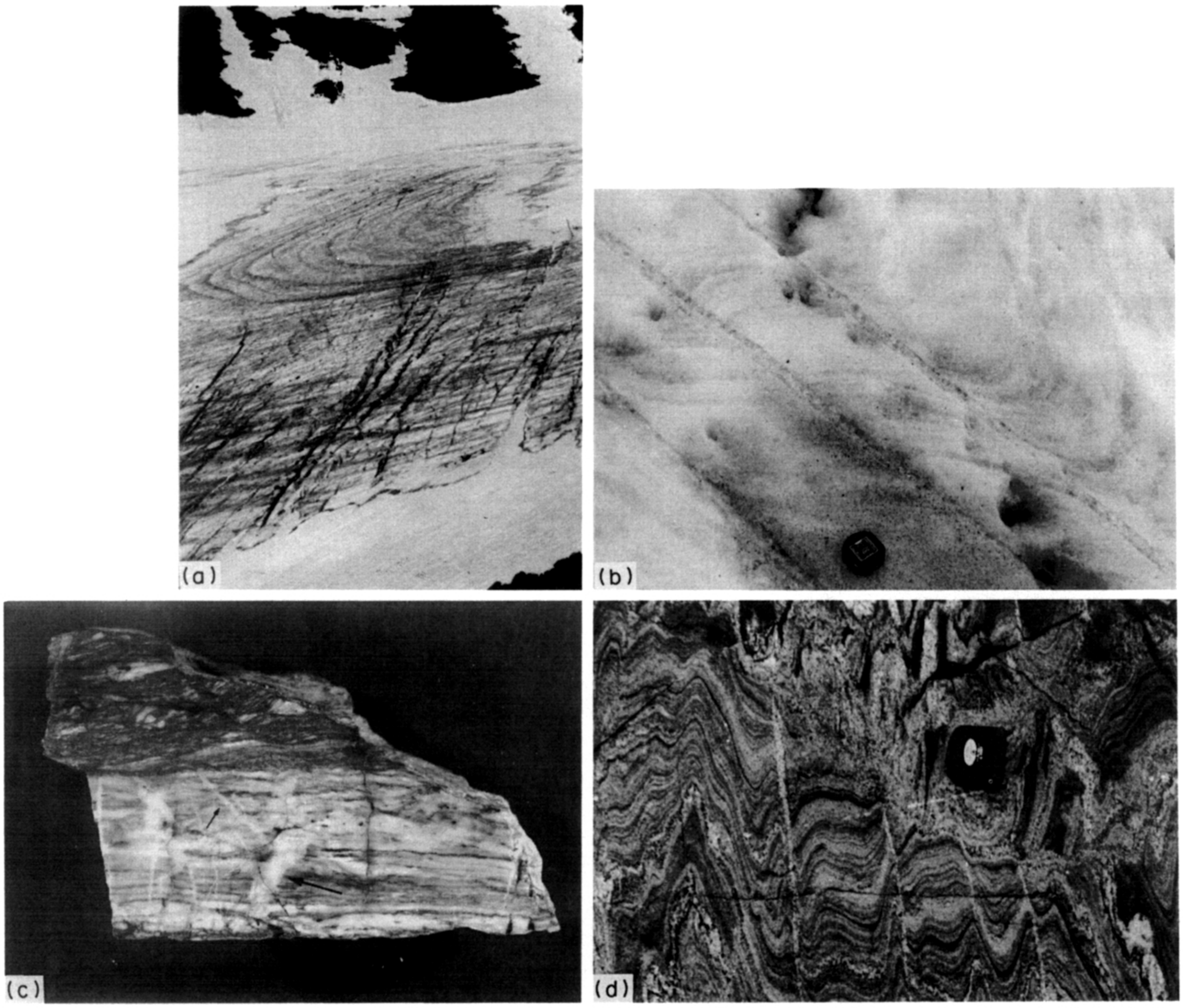

Fig. 2. (a) Foliation cut by marginal crevasses (Rabots Glacier, Lappland, Sweden). The arcuate structure at the center of the glacier is sedimentary stratification. Flow is to the left. The crevassed zone is about 150 m wide. (b) Folds in foliated ice with several axial planar veins (Storglaciär, Lappland, Sweden). The veins are of clear ice with indistinct lines of bubbles in their centers. (c) Quartz/chlorite mylonite cut by a sequence of quartz veins (lower part of picture). The youngest vein (small arrow) lies at about 45° to the mylonitic foliation; an older vein (large arrow) lies at a higher angle to the foliation. Shear bands in the upper part of the specimen indicate dextral shear (Precambrian rocks, Wasatch Mountains, Utah). The specimen is 11 cm long. (d) Folds in Moine Series metasedimentary rocks with leucocratic veins parallel to the axial surfaces (Loch Monar, Scotland).

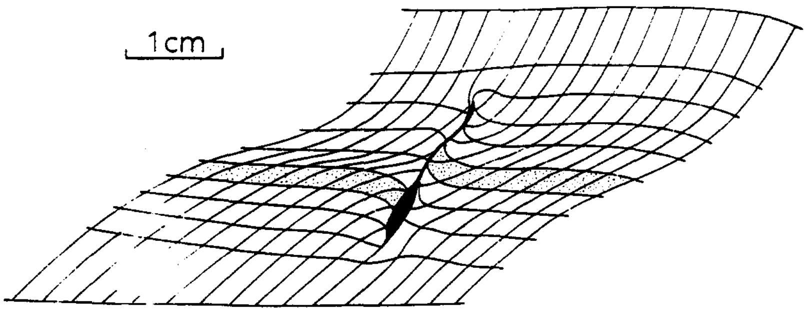

Fig. 5. Line drawing of photograph of the central part of a Plasticene block to show deformation around a deformed fracture (black). The grid was originally rectangular, with square elements, except for the top and bottom rows. One row is stippled to show offset.

due to the presence of the fracture can be seen from the deformed grid. A number of features should be noted. First, the overall shear strain in the block is least at the margins and greatest near the center, indicating strain softening. Second, the zone of perturbation due to the presence of the fracture has dimensions about half the fracture length either side and beyond the tips of the fracture (the rigid walls may have inhibited further propagation in the latter directions). Gentle folding of the horizontal grid lines occurs just beyond the tips of the fracture. The axial surfaces of these folds are at a high angle to the shear zone boundaries, and the folds 'face' in the opposite sense to the imposed shear. They are gentle 'S' folds. They would be expected to die out passively with continued bulk dextral simple shear or transpression. The strain gradients are most intense near the tips of the fracture (where the stresses are highest). Near each tip the longitudinal strain parallel to the wall is extensional on one side of the fracture and contractional on the other.

Other experiments showed the same basic features, but the shear strain profiles across the blocks were quite variable, from nearly constant to sigmoidal, with strain concentrated near the center of the block, as in Fig. 5. The free surface of the block clearly influenced deformation in the vicinity of the fractures. In some instances there was a slight buckling of the surface and in others, when the fracture closed, one wall overthrust the other slightly (as near the center of the fractures in Fig. 5). These effects modified but did not change in any fundamental way the pattern of perturbation strain around the fracture.

Analysis

The development of the folding in the experiments and in glacier ice is clearly a consequence of (i) the strain in the host material that accommodates the initial 'fracture' and/or of (ii) the perturbation from simple shear (or transpression) of further deformation created by the presence of an open (at least for a time), partly healed or filled fracture. The second effect can be considered as one of four types, depending on the nature of the vein filling: (1) the filling has the same rheological properties as the host, as is almost the case in ice; (2) there is no filling (as in the experiments and initially in ice); (3) the filling is less stiff than the host; and (4) the filling is stiffer than the host.

(1) *No competence difference between vein and host.* In this situation, there is no perturbation of the strain from simple shear, after fracture formation and infilling, and so the effect of the strain that accommodates the initial fracture can be evaluated. This is illustrated schematically in Fig. 6. Let a brittle crack develop by pure dilation in an otherwise ductile shear zone, causing a pre-existing 'marker' foliation trace to be separated by normal displacement across the crack as shown in Fig. 6(a). Let the crack immediately fill to become a vein and the rock and vein be further passively deformed in simple shear. The effect of increasing homogeneous shear on the initial disturbance that accommodated the fracture is shown in Figs. 6(b)–(e). Paired hook folds occur as in the experiments, but they are much less

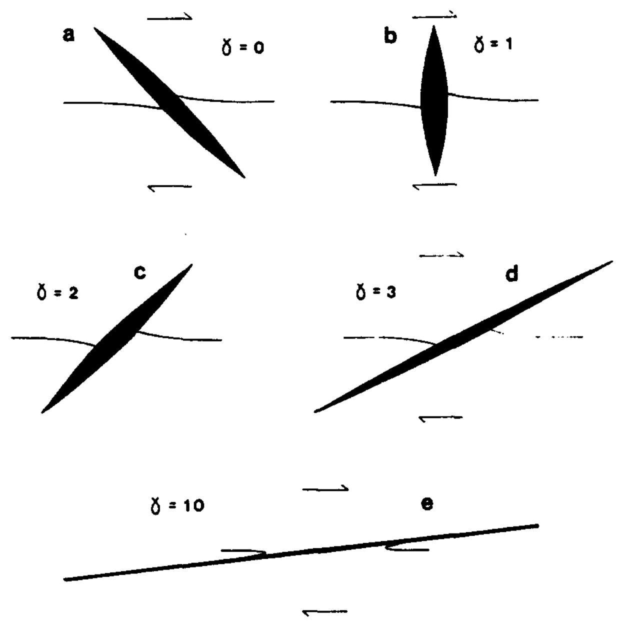

Fig. 6. Idealized case of fold development in which the deformation after instantaneous dilation and vein formation is homogeneous simple shear. Thus the folding is entirely passive. (a) Initial state. (b–e) Deformed states. The vein is shown in black; only part of it is shown in (e).

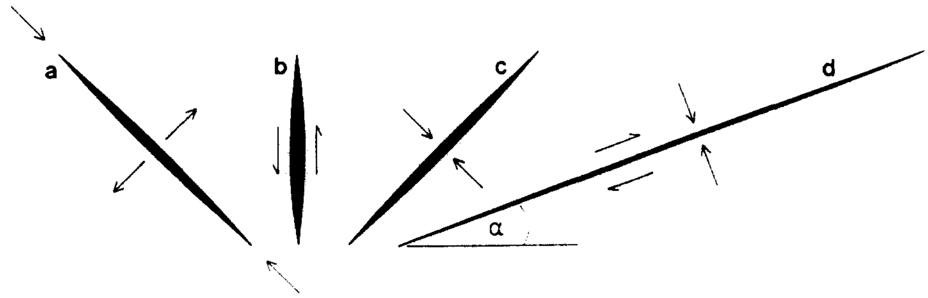

Fig. 7. Diagram to illustrate the stress components normal and parallel to a vein in a matrix of the same composition (i.e. the vein is a passive marker) subjected to homogeneous dextral simple shear. (a) A fracture opens and immediately fills to form the vein. Principal stress orientations are shown. There is no shear stress on the walls. (b) Position of maximum (sinistral) shear stress. (c) Position of zero shear stress. (d) Shear stress of dextral sense. Between (a) and (b) normal stresses across the vein are extensional. From (b) onward, normal stresses across the vein are compressional, with a maximum at (c). Note that the stress state is the same in all figures; only components normal or parallel to the vein are indicated.

pronounced (compare Fig. 4c with Fig. 6c at roughly the same shear strain). Strains of $\gamma > 5$ are needed to form tight folds in this instant-fill, passive further-strain model. The precise shapes and locations of the hinges of the folds depend on how the strain accompanying crack dilation is distributed.

(2) *No fracture (or low viscosity fluid) filling.* The contribution to fold development of passive amplification of the disturbance accompanying fracture formation and dilation, as described above, is minimal in the experiments. The reason that the folding is more pronounced in the experiments than in the passive model is because the fracture does not instantly heal, but remains a plane of zero or low shear resistance during the deformation. The effect of this can be illustrated by reference to Fig. 7, and by contrast with the case just discussed. If the fracture forms and immediately heals to become identical in composition to the host rock (as in the previous section), shear stress on the plane of fracture increases from zero in the initial position ($\alpha = 45°$, Fig. 7a) to a maximum with the vein at 90° to the shear zone (Fig. 7b), and then diminishes again to zero at $\alpha = 135°$ (Fig. 7c), beyond which it again increases but in the opposite sense. (This is equivalent to considering the stress components on planes of varying orientation at a point in a body, e.g. Ramsay & Huber 1987, fig. E-6.) These are the 'base state' stresses associated with the homogeneous simple shear. If the fracture remains open (or fluid filled) between stages a and b (Fig. 7), there can be no (or only very small) shear stresses along the fracture walls, and this must cause a perturbation in the strain field (from that of simple shear) around the fracture. The situation, away from the complications associated with the fracture tips, is rather like the partitioning of strain in a shear zone into coaxial strain in microlithons separated by slip planes (Lister & Williams 1979, fig. 14), only in this case there is only one plane of 'slip'—the fracture itself. The other sides of the two 'microlithons' grade into the host material undergoing homogeneous shear. The angle between the foliation and the fracture surface at the fracture wall (initially 45°) changes in response to shear stress and longitudinal stresses parallel to the wall. In the absence of shear stresses, the angle will change much less than in Fig. 6 (cf. Figs. 4 and 6). It will increase between the positions shown in Figs. 7(a) & (b), due to vein-parallel shortening, and decrease between the positions shown in Figs. 7(b) & (c) due to vein-parallel extension. To accommodate the perturbation in strain resulting from the lack of shear stress along the fracture wall, a fold must form in the foliation away from the wall. Also, because there is no resistance to movement between the walls of the fracture, except at the tips, the two sides of the foliation marker will become separated. There will be left-lateral slip (in a dextral shear zone as in Fig. 7) along the walls of the fracture. Thus the effect of having an open fracture or reduced resistance to slip along the fracture walls is to accentuate the folding. The deviation of the experimental conditions from simple shear do not alter this conclusion: the angles of zero and maximum shear stress shown in Fig. 7 will however be modified by amounts that depend on the magnitude of the compression across the shear plane (the values of α at the transition positions shown in Fig. 7 will be increased).

One difference between an open fracture and a fluid-filled fracture is that the former is likely to close up much more rapidly than the latter. It seems unlikely that open fractures, of the kind seen in glaciers and simulated in the experiments, occur in rocks undergoing ductile shear.

(3) *Vein softer than host.* In this case, the values of the shear stresses along the walls during vein rotation will be between those existing for planes of the same orientation due to simple shear alone (as in Fig. 7) and zero, which they must be for a hole. They can be evaluated for elliptical viscous inclusions of any aspect ratio and viscosity (expressed as viscosity ratio of inclusion to host) using equations developed by Donnell (1941) for elastic materials, making use of the correspondence between constitutive relations for elastic and viscous materials. The maximum shear stress acting on the walls of elliptical inclusions can be expressed as a fraction of the corresponding maximum shear stress in simple shear (for positions $\alpha = 0$ and 90° in Fig. 7). Calculations show that for an inclusion of aspect ratio 100 and a viscosity ratio of 1000, the maximum shear stress will be 5% of

that for an inclusion of the same viscosity as the host (i.e. homogeneous simple shear). If the inclusion is a fluid or melt with viscosity many orders of magnitude less than that of the host material, the shear stress on the inclusion wall will be negligible. In such cases the strain perturbation will be almost identical to that for an inviscid fluid (case 2 above). This will be true whether the host material is Newtonian, as in the calculations, or non-Newtonian, as in the experiments. The details of the perturbations in Newtonian and non-Newtonian hosts will, however, differ.

(4) *Vein stiffer than host.* If the vein filling the fracture is stiffer than the layer then immediately after formation it will tend to buckle, and subsequently as it rotates tend to unfold and boudinage in the manner described by Ramsay (1980, fig. 13). The perturbation of flow due to buckling and boudinage will be superimposed on the perturbation due to fracture opening, and will dominate. If the vein is short and very stiff, it may rotate more rapidly than a passive vein in the manner described by Gay (1968), and the extra perturbation of flow due to the rotation will generate folding in the adjacent layering. Van Den Driessche & Brun (1987, fig. 11) illustrated this effect beautifully for flow around rigid rectangular objects. The folds they produced are similar to the paired hook folds described herein, but they possess two hinges, a tight one close to the inclusion and an open one further away.

Discussion

The geometric properties of three idealized models of predicted fold development with increasing strain are shown in Fig. 8, together with the results of four Plasticene model tests. The plot is followed from left to right with increasing deformation. Curve A represents the change in interlimb angle for the passive folds developed in Fig. 6. It assumes the initial dilation associated with the fracture produces a very gentle fold with interlimb angle of 170°. Curve B represents the situation in which the initial angle (45°) between vein and pre-existing foliation is fixed throughout deformation. This is only likely to occur if the layering adjacent to the vein is incorporated in a stiff 'pressure shadow'. Curve C represents the situation in which deformation adjacent to the vein wall is coaxial plane strain shortening or stretching parallel and normal to the vein, with length changes being determined by the angle of the vein to the shear zone. It is exactly equivalent to the coaxial strain in microlithons shortening or extending in a simple shear zone as described by Lister & Williams (1979, fig. 14). As might be expected, most of the data for the Plasticene models fall close to curve C until $\alpha \approx 60°$. For smaller values of α, and particularly for $\alpha < 45°$, the fracture becomes closed by normal stresses (Fig. 7c) and thus able to support shear stresses. Further changes in the angle between the vein and the foliation will thus be less than predicted by curve C. The scatter in the experimental data is quite large—up to 40° difference in interlimb angle at the same value of α. This reflects in part the rather crude nature of the experiments, but also the sensitivity of the perturbation around the 'veins' to the geometry of the initial cuts that represent them and the fact that the cuts do not close uniformly. In some experiments, the interlimb angle in the same layer on either side of the vein differed by as much as 40°.

EXAMPLES IN ROCKS

Syntectonic veins are common in sheared rocks. Unlike the situation in glacier ice, most ductile (crystal–

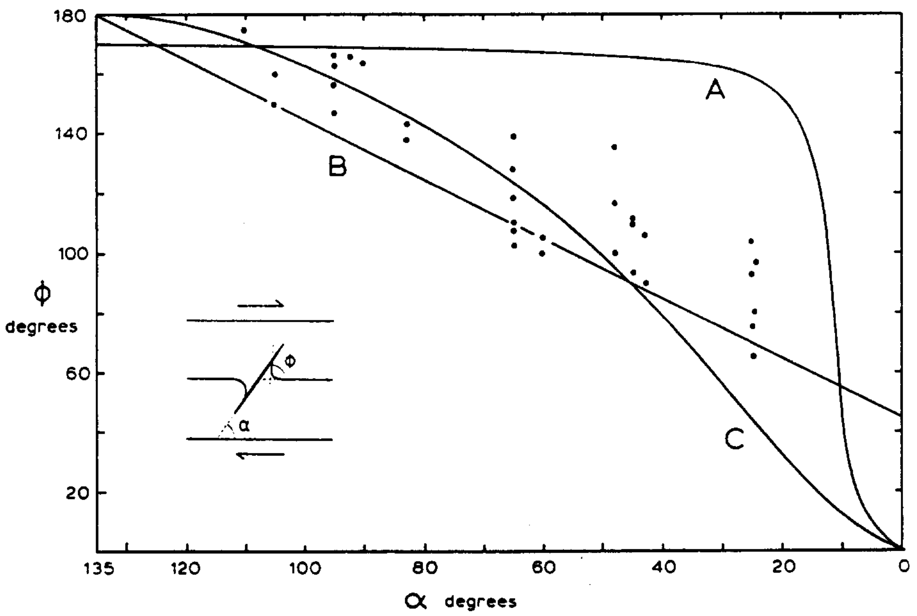

Fig. 8. Change in interlimb angle, ϕ, with angle, α, that the fracture/vein makes with the shear zone boundaries. Curve A is for the case shown in Fig. 5, curve B for the case in which the angle between the vein and the marker horizon ($\phi - \alpha$) is constant, and curve C for the case in which the wall rock adjacent to the vein undergoes a coaxial strain history (see text). Dots are results from the Plasticene block experiments.

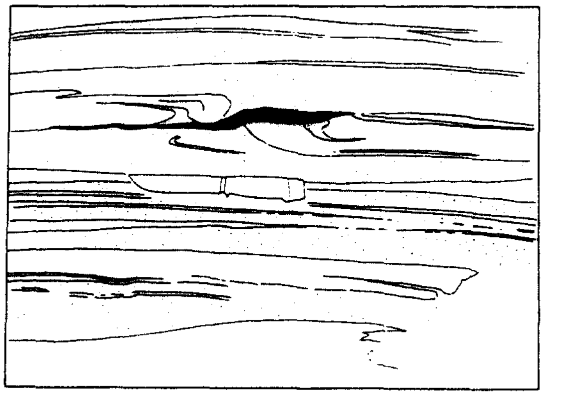

Fig. 9. Line drawing of folds in leucocratic veins in migmatitic hornblende gneiss, Finland (after Van Staal & Williams 1983, fig. 7). Stippled layers—hornblende gneiss; clear layers—leucocratic veins; black layer—leucocratic vein separating paired folds, with matching hornblende seam heavily stippled. Knife for scale.

plastic) deformation in rocks occurs under high confining pressures, which tend to inhibit the development of extensional fractures. For such fracturing to occur, fluid pressure must be high enough to overcome the high normal stresses within the crust and thus allow hydrofracturing to occur. This is especially likely to happen during prograde metamorphism of sedimentary rocks.

Good examples of hook folds with the characteristic 'contradictory' senses of offset and asymmetry are shown in Figs. 9 and 1(c). In Fig. 9, paired hook folds are developed in banding in a migmatitic hornblende gneiss. It seems very likely that these were produced during strong (dextral) shear during which an extensional leucocratic vein developed obliquely across the gneissose banding and earlier leucocratic veins. As in glacial ice, the production of the gneissose foliation itself almost certainly involved large shear strains (Hooke & Hudleston 1978). In Fig. 1(c), hook folds in a quartz vein are separated by an unfilled (but now closed) fracture. In this case (analogous to Fig. 4) the regional setting is known to be a large ductile transcurrent dextral fault zone. In the same outcrop there are folds of 'Z' symmetry and back-rotated boudins (Hanmer 1986), both confirming dextral shear.

The wall rock dikes emplaced or subsequently involved in shear zones may develop folds similar to those found in association with veins. For example Gayer *et al.* (1978) described close to gentle folds in the walls of dikes affected by Caledonide deformation in northern Norway. They showed clearly that the folds post-dated emplacement of the dikes, and found a systematic relationship between the interlimb angles of the folds and the angle of discordance between dike wall and layering in the host metasediments (Gayer *et al.* 1978, fig. 4). Such a relationship is predicted by the models of fold development described in this paper. Gayer *et al.* considered two models for the development of folds, one involving frictional slip along the margins of relatively rigid dikes and the second (better able to explain their observations) of quasi-plastic rotation of dykes and metasediments. The latter model is similar to that proposed here, except that they considered the folding to be due to flexural-slip or flexural flow, whereas folds in my model are purely passive. Certainly the folds illustrated in their paper are similar (i.e. class 2 of Ramsay 1962) in style, suggesting passive layer behavior (Gayer *et al.* 1978, fig. 5), and an origin similar to that described here for the folds adjacent to veins is likely. The critical feature for their development is the low frictional resistance along the dike walls, perturbing the flow from homogeneous shear (although note that for short rigid dike segments, with high friction along the boundaries, well-developed passive folds will form due to the spin of the rigid segment and associated strain partitioning—see Van Den Driessche & Brun (1987). This does not appear to be the situation for the Scandinavian dikes). Although in the examples shown by Gayer *et al.* and described here layering behaved passively, it may also behave in a mechanically active way, in which case the fold shapes will be modified. The possible nature of such modifications will not be discussed here.

A good example of hook folds along dike margins is shown in Fig. 1(d), in which very tight folds developed under very large shear strains involved in thrusting in the central Norwegian Caledonides. These dikes are in fact much more deformed equivalents of those described by Gayer *et al.* (1978). They have been used further east, where deformation is less intense, to help establish deformation profiles in the Särv thrust sheet of the Swedish Caledonides (Gilotti & Kumpulainen 1986).

It is clear that the presence of paired hook folds provides excellent evidence for sense-of-shear in shear zones. Unlike some sense-of-shear indicators, they are also clear indicators of non-coaxial strain, provided the vein formed in the same deformational event as the folds. Extensional veins open normal to σ_3, the least compressive stress. If strain is coaxial such veins will not rotate after formation. It is only in non-coaxial strain that they will rotate. Other sense of shear indicators, such as asymmetric folds or rotated porphyroblasts need not reflect a non-coaxial strain history (see for example Ramsay 1962).

The paired hook folds described in this paper are not the same as the 'fish-hook' folds described by Ramsay & Huber (1987, fig. 17.11) The latter occur as en échelon fish hooks in a train. Those rather enigmatic features appear to be modified buckle folds of some sort, probably involving non-coaxial bulk strain.

Folds do not have to develop in association with formation and rotation of veins in order for the veins to provide good sense-of-shear information. Folds may fail to form because there is no good foliation to become folded, because the initial perturbation was slight and the fracture healed quickly, or because the deformation has not been great enough. In Fig. 2(c), showing quartz veins in a quartz mylonite, one vein is very clearly defined with straight edges, whereas a neighbor has much more irregular edges. I interpret this to indicate that the straight vein is the latest formed, and the ragged vein formed earlier (they do not cross-cut). This is consistent with the fact that the straight vein lies at almost 45° to the mylonitic foliation. The other vein was presumably once straight and has rotated some 45° since formation, becoming distorted and ragged in the process (see Figs. 4b & c for comparison), perhaps in part due to buckling. Shear bands in the phyllitic layer just above the quartz mylonite in Fig. 2(c) provide independent evidence of the required dextral sense of shear. None of the veins in Fig. 2(c) have undergone sufficient rotation to form significant folds (compare Fig. 2c with Figs. 4 and 6).

It is clear that not all veins associated with folds can have formed in the manner described above. The fold of Fig. 1(a) does not show the characteristic 'wrong' offset that hook folds display. This may be an example of a vein being emplaced preferentially in a fold limb because it has well-developed foliation and is thus a plane of weakness. Another type of vein found associated with folds is illustrated in Fig. 2(d). These veins occur in the limbs or hinges of, and are parallel to the axial surfaces of, multilayer folds produced under near-migmatitic conditions. Some process appears to have induced local melting or segregation of leucocratic material in planes parallel to the schistosity and the axial surfaces of associated folds, destroying the previous fabric and producing a vein. In this case, the offset of a marker horizon along the vein is 'correct' for the asymmetry of the fold.

As discussed in the Introduction, not all en échelon veins are formed in zones of simple shear. It is equally likely that not all veins in shear zones formed by the process of dilational fracturing as described above. Sawyer & Robin (1986) describe veins formed by subsolidus segregation during prograde metamorphism of metasedimentary rocks. It is quite likely, as they suggest, that such veins can form in an environment of simple shear. Most of the veins they describe are layer-parallel and are not associated with folds. It has also been suggested that en échelon veins in shear zones form as shear fractures (e.g. Hancock 1972, Beach 1978, Rickard & Rixon 1983). For the purpose of using the folds as sense-of-shear indicators, it is not necessary to know the exact angle at which the veins formed with respect to the shear direction, or indeed to know whether the fractures were of pure extensional origin or involved shear. Most information can be gained about the vein system, however, if veins are preserved at various orientations to the shear direction and with folds in various stages of development.

There is no doubt that extensional veins can develop to great depths in the crust and that they often develop in rocks simultaneously undergoing ductile deformation. Characteristic, often 'rootless', hook folds will develop if a suitable layering is present in the host rock and the strain is large. The symmetry and offset of these, or simply the cross-cutting relationships and appearance of veins where no folds are developed, provide good criteria for determining sense of shear in rocks.

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REFERENCES

Beach, A. 1975. The geometry of en-échelon vein arrays. *Tectonophysics* **28**, 245–263.

Donnell, L. H. 1941. Stress concentrations due to elliptical discontinuities in plates under edge forces. In: *Theodore von Karman Anniversary Volume*. Pasadena, 293–309.

Durney, D. W. & Ramsay, J. G. 1973. Incremental strains measured by syntectonic crystal growths. In: *Gravity and Tectonics* (edited by DeJong, K. A. & Scholten, R.). Wiley, New York, 67–96.

Fitches, W. R., Cave, R., Craig, J. & Maltman, A. J. 1986. Early veins as evidence of detachment in the Lower Palaeozoic rocks of the Welsh Basin. *J. Struct. Geol.* **8**, 607–620.

Gay, N. C. 1968. Pure shear and simple shear deformation of inhomogeneous viscous fluids. 1. Theory. *Tectonophysics* **5**, 211–234.

Gayer, R. A., Powell, D. B. & Rhodes, S. 1978. Deformation against metadolerite dykes in the Caledonides of Finnmark, Norway. *Tectonophysics* **46**, 99–115.

Gilotti, J. A. & Kumpulainen, R. 1986. Strain softening induced ductile flow in the Särv thrust sheet, Scandinavian Caledonides. *J. Struct. Geol.* **8**, 441–455.

Hambrey, M. J. and Milnes, A. G. 1977. Structural geology of an Alpine glacier (Greigsgletscher, Valais, Switzerland). *Eclog. geol. Helv.* **70**, 667–684.

Hancock, P. L. 1972. The analysis of en-échelon veins. *Geol. Mag.* **100**, 269–276.

Hanmer, S. 1986. Asymmetrical pull-aparts and foliation fish as kinematic indicators. *J. Struct. Geol.* **8**, 111–122.

Hooke, R. Le B. & Hudleston, P. J. 1978. Origin of foliation in glaciers. *J. Glaciol.* **20**, 285–299.

Hudleston, P. J. & Hooke, R. Le B. 1980. Cumulative deformation in the Barnes Ice Cap and implications for the development of foliation. *Tectonophysics* **66**, 127–146.

Lister, G. S. & Williams, P. F. 1979. Fabric development in shear zones: theoretical controls and observed phenomena. *J. Struct. Geol.* **1**, 283–297.

McClay, K. 1976. The rheology of plasticene. *Tectonophysics* **33**, T7-T15.

Nicholson, R. & Pollard, D. D. 1985. Dilation and linkage of echelon cracks. *J. Struct. Geol.* **7**, 583–590.

Pollard, D. D., Segall, P. & Delaney, P. T. 1982. Formation and interpretation of dilatant echelon cracks. *Bull. geol. Soc. Am.* **83**, 1291–1303.

Ramsay, J. G. 1962. The geometry and mechanics of formation of "similar" type folds. *J. Geol.* **70**, 309–327.

Ramsay, J. G. 1980. Shear zone geometry: a review. *J. Struct. Geol.* **2**, 83–99.

Ramsay, J. G. & Huber, M. I. 1983. *The Techniques of Modern Structural Geology. Volume* 1: *Strain Analysis*. Academic Press, New York.

Ramsay, J. G. & Huber, M. I. 1987. *The Techniques of Modern Structural Geology. Volume* 2: *Folds and Fractures*. Academic Press, New York.

Rickard, M. J. & Rixon, L. K. 1983. Stress configurations in conjugate quartz-vein arrays. *J. Struct. Geol.* **5**, 573–578.

Sawyer, E. W. & Robin, P.-Y. F. 1986. The subsolidus segregation of layer-parallel quartz–feldspar veins in greenschist to upper amphibolite facies metasediments. *J. metamorphic Geol.* **4**, 237–260.

Talbot, C. J. 1970. The minimum strain ellipsoid using deformed quartz veins. *Tectonophysics* **9**, 47–67.

Van Den Driessche, J. & Brun, J. P. 1987. Rolling structures at large shear strain. *J. Struct. Geol.* **9**, 691–704.

Van Staal, C. R. & Williams, P. F. 1983. Evolution of a Sveccofennian-mantled gneiss dome in SW Finland, with evidence for thrusting. *Precambrian Res.* **21**, 101–128.