Geological Society of America Bulletin

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Geological Society of America Bulletin 1983;94;1281-1288
doi: 10.1130/0016-7606(1983)94<1281:AEOCTD>2.0.CO;2

An evaluation of criteria to deduce the sense of movement in sheared rocks

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ABSTRACT

Some of the most useful criteria for the deduction of the sense of shear are summarized for use in areas where unequivocal field evidence is lacking. Apparently conflicting evidence from rotated pressure-shadow regions around porphyroclasts and porphyroblasts is clarified. The use of quartz-crystallographic fabric asymmetry to deduce the shear sense in the bulk rock should be treated with caution and used only together with detailed microstructural observations.

INTRODUCTION

The simplest model of a shear zone is that of a highly strained rock between planar and parallel-sided boundaries, outside which the rock remains unaffected by the shear deformation (Ramsay, and Graham, 1970; Ramsay, 1980). From study of the geometry of the schistosity at shear-zone margins, and of deflected marker horizons such as veins or dikes, it is possible to establish not only the sense, but also the amount of displacement across the zones (Ramsay and Graham, 1970; Ramsay and Allison, 1979; Ramsay, 1980). However, within very wide shear zones and mylonitic belts of regional significance, it often is not possible to find the boundaries of these shear zones, and offset marker horizons may be rare or absent. In such cases, other criteria for the deduction of displacement sense are required, the most useful of which are outlined below.

By sense of shear and shearing direction, we do not imply deformation by strictly simple shear. We merely refer to the sense of shear (vorticity) along a continuous non-coaxial or rotational strain path. The existence of a large-scale shear zone must be established beforehand by geological mapping. In some cases, structures similar to those outlined below may be produced by noncontinuous multiphase deformation. Before applying any shear sense criteria, this latter case must be excluded by independent geological evidence.

It is important to make observations in regard to the shear sense, using oriented thin sections cut parallel to the shear direction and perpendicular to the flattening plane. In general, this corresponds to a section parallel to the lineation and perpendicular to the foliation. The criteria that have been found to be the most useful in determining shear sense are asymmetric augen structures; composite planar fabrics; asymmetric pressure shadows; displaced broken grains; oblique, elongate, recrystallized grains and subgrains; and crystallographic fabric asymmetries. Each of these criteria will now be discussed in turn.

ASYMMETRIC AUGEN STRUCTURES

Within many shear belts, mylonitic gneisses occur that contain larger and relatively flow-resistant grains, commonly referred to as porphyroclasts or augen, within a more ductile and fine-grained matrix. Such larger crystals are typically feldspars (Fig. 1); larger, not yet fully recrystallized, quartz grains (Fig. 2); or micas (Fig. 3). Foliation planes are asymmetrically distributed around the porphyroclasts so that the grains have a retort shape with tails of finer-grained recrystallized material of the same

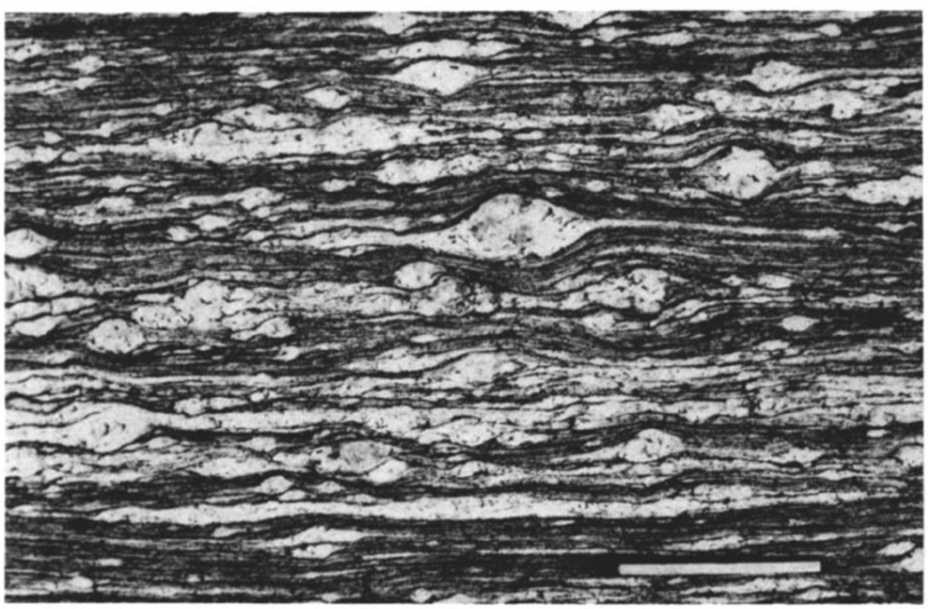

Figure 1. Asymmetric feldspar augen in a granitic gneiss (Monta Rosa granite gneiss, Val d'Ossola, Italy) indicating dextral shear. Matchstick approximately 4 cm long.

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Geological Society of America Bulletin, v. 94, p. 1281–1288, 11 figs., November 1983.

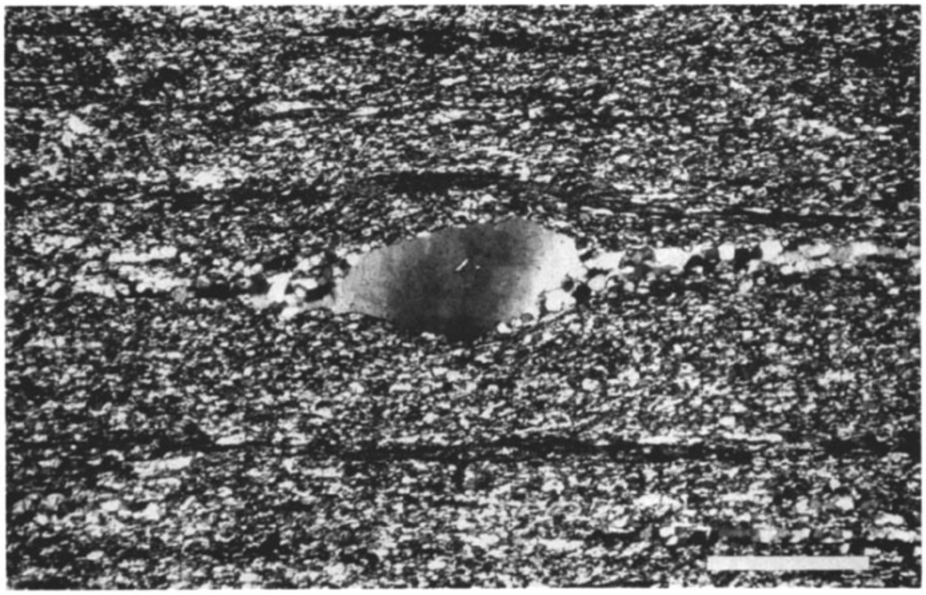

Figure 2. Quartz porphyroclast with asymmetric tails of dynamically recrystallized quartz in a feldspathic groundmass (mylonitized Corvatsch granite, Engadine, Switzerland) indicating dextral shear. Scale bar = 0.5 mm, crossed nicols.

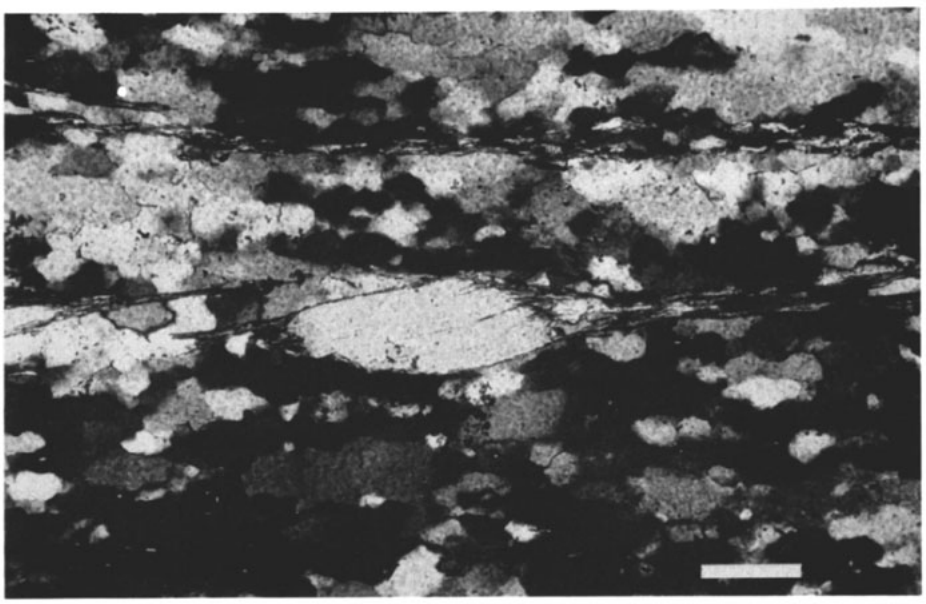

Figure 3. Porphyroclast of white mica (mylonite at the Insubric line, Val Loana, Italy) indicating dextral shear. Scale bar = 0.1 mm, crossed nicols.

composition as the porphyroclast extending along the foliation plane in the direction of shear (Fig. 4A). Such augen or retort-shaped crystals have been used to deduce the sense of shear in foliated rocks (Eisbacher, 1970; Choukroune and Lagarde, 1977; Etchecopar, 1977; Lister and Price, 1978; Berthé and others, 1979a).

Contrary to the genetic implications of the term "porphyroclast," invoking a grain-size reduction by cataclastic processes, the fine-grained material within the tails is usually the product of dynamic recrystallization. This reduction in grain size is generally associated with strain softening (White and others, 1980). In a shearing environment, the weaker material within the tails has a higher rate of rotation into parallelism with the over-all foliation in the rock, whereas the less deformable porphyroclasts rotate more slowly, so that their long axes remain oblique to the foliation in the surrounding matrix. However, grains such as elongate feldspar phenocrysts that have undergone very little or no dynamic recrystallization and that have passively rotated in a ductile matrix may give ambiguous results. This problem is discussed in more detail in the following section.

ASYMMETRIC PRESSURE SHADOWS

Where a high ductility contrast occurs between a rotated grain and its matrix within a foliated rock in a shear zone, it is generally possible to ascertain the sense of rotation of the grain and, hence, the shear sense. However, observations of the over-all symmetry of the pressure shadows with respect to the porphyroclast and foliation may lead to apparently contradictory results, especially where dealing with round or equidimensional grains such as garnets. Ghosh and Ramberg (1976) conducted a series of experiments in which they studied the reorientation of elongate, rigid inclusions that were embedded in silicon putty and subjected to simple shear deformation. They found that with the same bulk deformation, some inclusions showed a finite rotation with respect to that of passive marker lines in the same sense as the simple shear rotational component. Other inclusions, in different initial orientations and with different axial ratios, showed a finite rotation with respect to passive marker lines in the opposite sense to that of the simple shear component; in other words, the passive marker lines rotated faster than the rigid inclusions. However, in all cases of simple shear deformation, the inclusions themselves rotated with the same sense as the shear component with respect to an external co-ordinate system.

Schoneveld (1977), in his "rotated garnet and string" model, showed that the pressure-shadow "wing" on the right-hand side of a grain within a dextral shear zone should be uppermost when viewed in profile (Figs. 4B and 4C). The foliation outside the garnet forms a small microfold at the point of entry into the grain. Taking a reference point in the core of the microfold and looking toward the point of maximum curvature of the foliation (in the direction of the thin

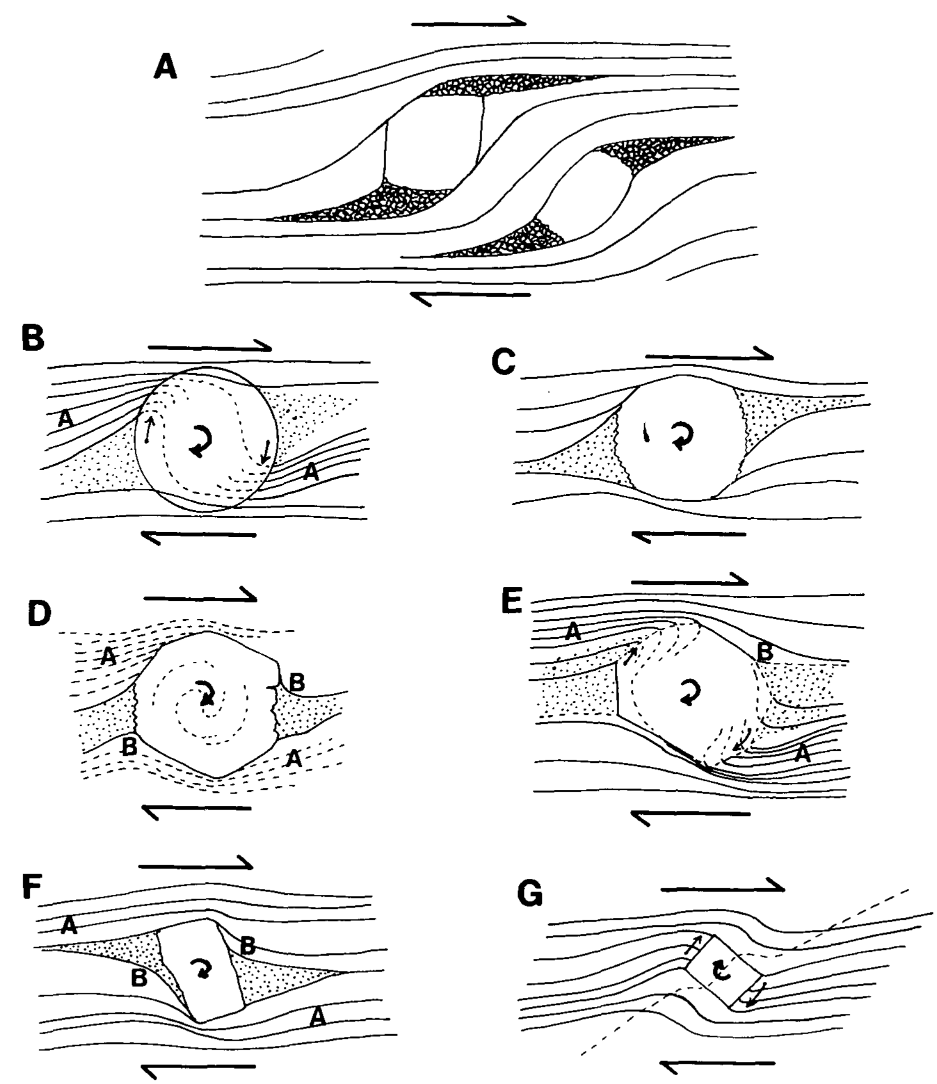

Figure 4. A. Schematic diagram of asymmetric augen structures within foliation planes. The "tails" of the retort-shaped grains are composed of fine-grained material of the same composition as the host porphyroclast, extending along the foliation plane in the direction of shear. B. Rotated porphyroblastic garnet model, modified after Schoneveld (1977, Fig. 2; 120° clockwise rotation). The foliation outside the garnet forms a small microfold at the point of entry into the grain. Arrows indicate the direction of rotation of the grain. Pressure-shadow "wings" are stippled. Points A and B, see text. C. Rotated porphyroblastic garnet and associated pressure shadows marked with stipple ornament (modified after Schoneveld, 1977, Fig. 12). D. Rotated garnet porphyroblast and associated pressure shadows (modified after Powell and Vernon, 1979, Figs. 4c and 4d). Scale bar, 1 mm. Points A and B, see text. E. Rotated garnet porphyroblast and associated pressure shadows (modified after Powell and Vernon, 1979, Fig. 9, no. 6). Scale bar = 1 mm. Points A and B, see text. F. Rotated feldspar with associated pressure shadows from a thin section of foliated gneiss in the center of a dextral shear zone in granite, Maggia Nappe, central Swiss Alps. Scale bar = 2 mm. Points A and B, see text. G. Rotated rigid inclusion and passive marker lines in silicon putty subjected to simple shear deformation (modified after Ghosh and Ramberg, 1976, Fig. 26; here reproduced in mirror-image form to facilitate comparison with Figs. 4B to 4F).

arrows in Fig. 4B) gives the direction of rotation of grain. Powell and Vernon (1979), in a study of rotated garnet porphyroblasts, illustrated pressure-shadow "wings" that are symmetrically positioned with respect to the foliation planes on either side of the grain (see Fig. 4D, after Powell and Vernon, 1979, Figs. 4c and 4d). They also illustrated a rotated garnet with pressure-shadow "wings" showing the opposite sense of asymmetry (Fig. 4E, after Powell and Vernon, 1979, Fig. 9, no. 6). In Figure 4F, a rotated feldspar crystal has been sketched from a thin section of a foliated gneiss in the center of a shear zone in deformed granite. In this example, an earlier aplite dike is displaced in a dextral sense across the shear zone, but at first sight the pressure shadows around the feldspar grain give the opposite sense of shear.

Despite the superficially conflicting geometry of the pressure shadows around the rotated porphyroblasts and porphyroclasts illustrated in Figures 4B to 4F, each of the examples shows the same two diagnostic features. The first of these diagnostic features is the occurrence of microfolds in the foliation at the edges of the rotating garnets (compare Figs. 4B and 4E) that consistently record the direction of crystal rotation (Rosenfeld, 1970). There is a tendency for a closer spacing of pre-existing foliation planes on the upper left-hand and lower right-hand side of all of the clockwise rotating grains (position A in Figures 4B, 4D, 4E, and 4F). A comparison with Figure 26 of Gosh and Ramberg (1976) shows that the same microfold criterion can be applied to their experimental model (see Fig. 4G, here reproduced in mirror-image form for ease of comparison), although the spacing of their marker lines remains more or less constant on either side of the rotating rigid inclusion. The second diagnostic feature occurs at the site of the most recent deposition of material in the pressure shadow, where the junction of the pressure-shadow area and the crystal has a shape that is concave toward the adjacent more widely spaced foliation planes (position B in Figs. 4D, 4E, and 4F), whereas at the opposite side of the pressure-shadow area, this junction more commonly has a straight or only very gently curved form.

Using the two criteria outlined above, the correct sense of shear can be elucidated in each of the examples cited. In general, however, it may be necessary to examine several pressure-shadow regions before the sense of shear can be determined with confidence.

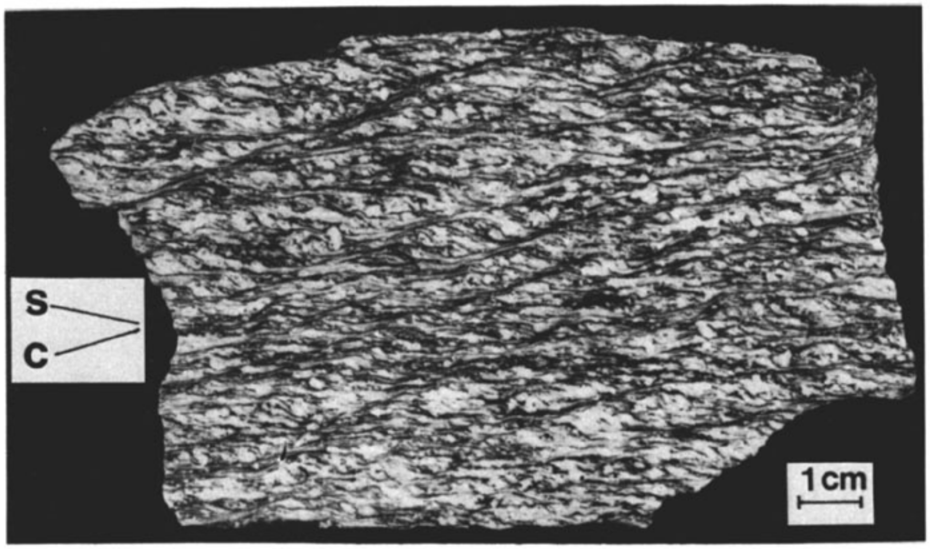

Figure 5. Polished surface of a sheared granodiorite (Palm Canyon, California) with c- and s-surfaces (see text) indicating sinistral shear.

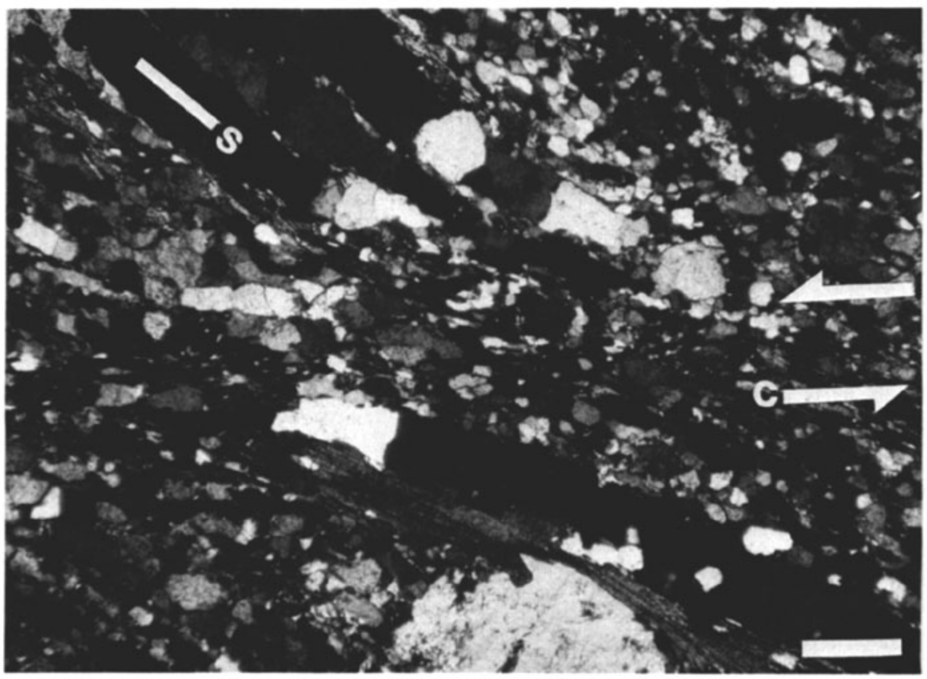

Figure 6. Thin section of c- and s-surfaces illustrating how the s-surfaces, defined by quartz and feldspar ribbon aggregates, are deflected into the c-surfaces (sheared granodiorite, Palm Canyon, California). Scale bar = 0.5 mm, crossed nicols.

COMPOSITE PLANAR FABRICS

Berthé and others (1979a, 1979b) studied the progressive development of planar fabrics within granitic rocks into a large-scale ductile wrench fault. They observed two sets of planar anisotropies that they described as c- and s-surfaces, referring to "cisaillement" (shear) and "schistosité" (schistosity, foliation), respectively.

The c-surfaces (Fig. 5) are initiated and remain aligned parallel to the main shear zone boundary with progressive deformation, and they are considered to be spaced slip surfaces with a sense of shear the same as that of the over-all shear zone. Microstructurally, the c-surfaces appear as thin layers of a recrystallized, polymineralic aggregate with a reduced grain size.

The s-surfaces, on the other hand, are initially oriented at an angle of 45° to the c-surfaces and curve into the c-surfaces so that the angular relationships between the two surfaces define the sense of shear in the rock (Fig. 5). Microstructurally, the s-surfaces are defined by the mineral-shape preferred orientation of the old grains between the c-surfaces. In terms of the old rock fabric between the c-surfaces, the s-surfaces are perpendicular to the short axis of the finite strain ellipsoid and, hence, they mark the planes of finite flattening (Ramsay and Graham, 1970). However, it is doubtful that the s-surfaces match the planes of finite flattening of the *bulk* rock, as proposed by Berthé and others (1979a, 1979b), in view of the later discrete shearing along the c-surfaces.

With progressive deformation, the angle between the c- and s-surfaces decreases and the s-surfaces curve into near parallelism with the shear zone boundary, conforming to the model of Ramsay and Graham (1970). Figure 6 illustrates an s-surface, defined by a fine-grained quartz-feldspathic aggregate, asymptotically curving into a c-surface. In an advanced stage of deformation, c- and s-surfaces coincide and a few isolated feldspar (Fig. 7) and/or quartz intraclasts or augen with sigmoidal pressure-shadow tails define a geometry identical to that already described (compare Fig. 2 and Fig. 7). The genesis of the tails, however, is different in the two cases (dynamic recrystallization within one original mineral grain in Fig. 2 versus pressure shadows in Fig. 7).

At high strains in rather homogeneously foliated mylonitic rocks, a late, weakly penetrative foliation (shear bands) may develop at a low angle to the mylonitic foliation (Berthé and others, 1979a; Gapais, 1979; White and others, 1980). The sense of shear along these late shear bands is the same as that of the main shear zone and can be used to deduce the over-all sense of shear (Fig. 8). Similar structures, known as extensional crenulation, can also develop as a consequence of coaxial flattening oblique to a pre-existing foliation (Platt and Vissers, 1980). However, in the case of extensional crenulation, a weakly developed conjugate set of shear bands is expected to form.

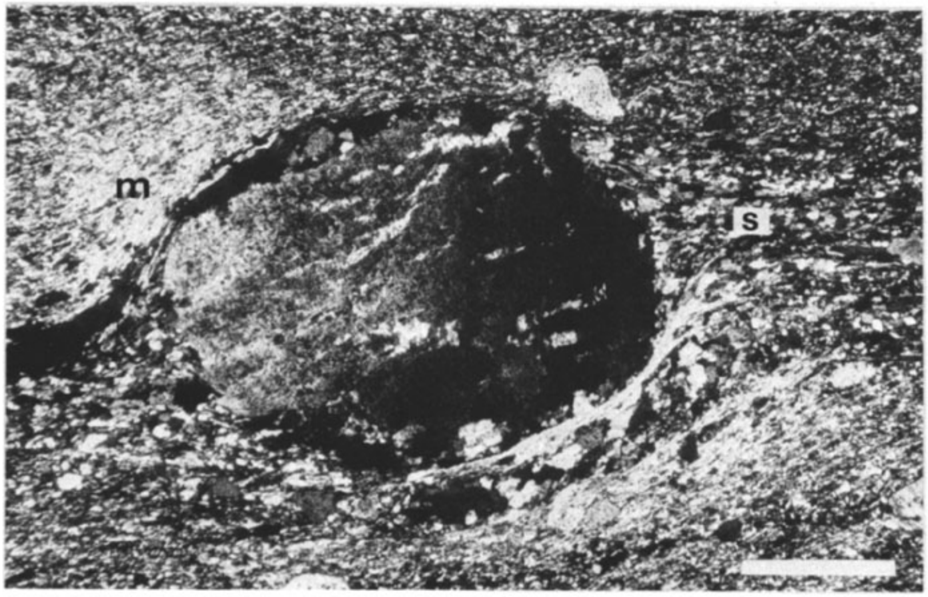

Figure 7. Isolated feldspar porphyroclast in a zone where c- and s-surfaces coincide in orientation. Pressure shadows at the ends of the porphyroclast (marked s) indicate dextral shear. Note the enrichment in micaceous material (marked m) at those sides of the porphyroclast facing the supposed direction of maximum compression (mylonitic granite from the Armorican shear zone, Brittany, France). Scale bar = 0.5 mm, crossed nicols.

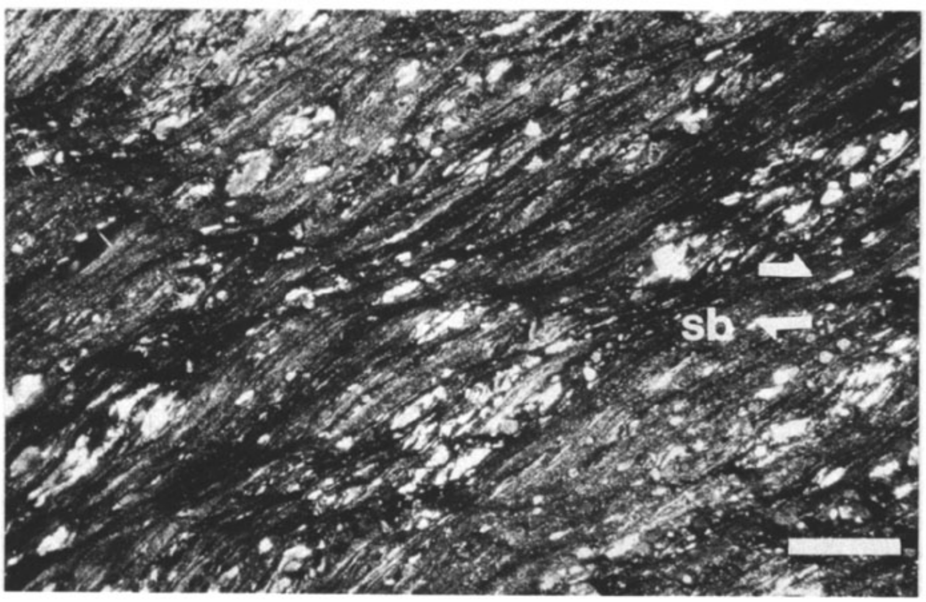

Figure 8. Shear bands (sb) in a mica-rich mylonite (Insubric line, Val Loana, Italy). Note that the shear bands are slightly curved and laterally not persistent. They indicate dextral shear of the bulk rock at a late stage during mylonitization. Scale bar = 1 mm, crossed nicols.

DISPLACED BROKEN GRAINS

Displaced broken grains, such as mica flakes, feldspars, or pyroxenes in a ductile matrix, occur frequently in sheared and mylonitic rocks and have been used to determine the over-all shear sense in the rocks (Choukroune and Lagarde, 1977). It should be emphasized, however, that the sense of displacement along microfractures oriented oblique to the foliation planes is, in many cases, *opposite* the over-all sense of shear in the rock (Fig. 9). This phenomenon is well illustrated by analogy with a sheared stack of books or cards (Etchecopar, 1974, 1977).

THE OBLIQUITY OF ELONGATE RECRYSTALLIZED GRAINS AND SUBGRAINS

In deformed limestones, Schmid and others (1981a) found the long axes of dynamically recrystallized grains to be oblique to the macroscopic foliation. Brunel (1980) and Simpson (1981) made similar observations for grains and/or subgrains within quartz aggregates of mylonitic gneisses and mylonites (Fig. 10). This obliquity of elongate grain shapes to the foliation plane may be explained by the fact that the observed dynamically recrystallized grains and subgrains form relatively late during progressive shearing deformation and, thus, record only the final stages. In a shearing environment, this leads to an orientation of the flattening plane of these new grains approximately perpendicular to the maximum compression direction of the last increment of deformation and, thus, at an acute angle to the plane of finite flattening in the bulk rock, that is, the macroscopically visible foliation (Fig. 10).

PREDICTION OF SHEAR SENSE FROM CRYSTALLOGRAPHIC FABRIC ASYMMETRY

Crystallographic fabrics developing along a rotational strain path are markedly asymmetric in respect to the macroscopic fabric axes (foliation and stretching lineation) and their symmetry departs from an orthorhombic character. Evidence for such asymmetries, reflecting the sense of shear, is found in many naturally deformed rocks. Numerical models have been developed that predict such asymmetries.

Etchecopar (1974, 1977) used a simple two-dimensional model by considering one slip system only, and he found in the special case of simple shear that there is a tendency for that single glide plane to align at a small angle to the shear plane, somewhere between the plane of finite flattening (the foliation plane) and the shear plane or shear zone boundary. Toward higher strains, the glide planes rotate into near parallelism with the shear plane in the bulk rock.

Lister and Hobbs (1980) used a three-dimensional model for quartz. This model

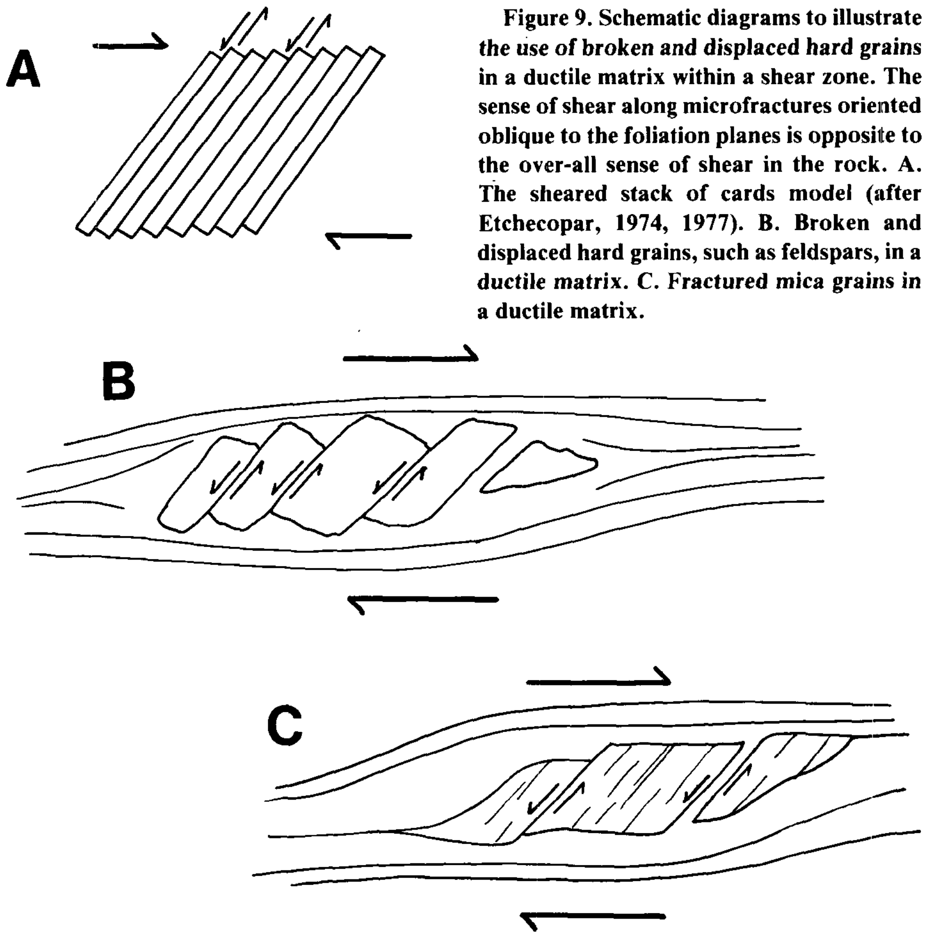

Figure 9. Schematic diagrams to illustrate the use of broken and displaced hard grains in a ductile matrix within a shear zone. The sense of shear along microfractures oriented oblique to the foliation planes is opposite to the over-all sense of shear in the rock. A. The sheared stack of cards model (after Etchecopar, 1974, 1977). B. Broken and displaced hard grains, such as feldspars, in a ductile matrix. C. Fractured mica grains in a ductile matrix.

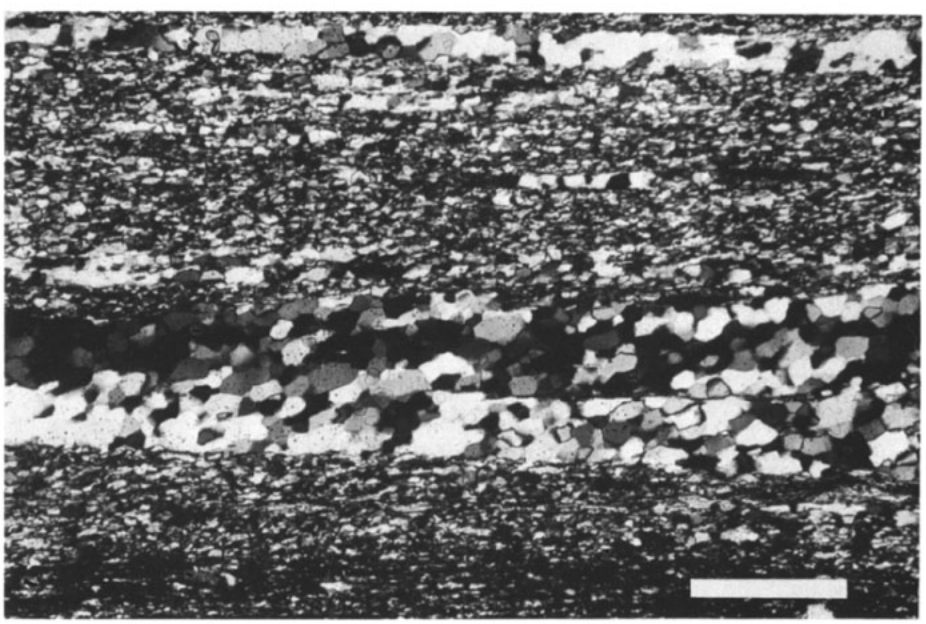

Figure 10. Subgrains and recrystallized grains with their flattening plane oblique to the macroscopically visible foliation plane (parallel to the long axis of the micrograph) indicating dextral shear (mylonitized Corvatsch granite, Engadine, Switzerland). Scale bar = 0.5 mm, crossed nicols.

assumed homogeneous strain and, as a consequence, at least five independent slip systems must operate (von Mises' criterion). The mechanism of fabric development in this model is fundamentally different from that of the two-dimensional model (for a discussion, see Lister, 1982). Lister and Hobbs (1980) obtained complex c-axis crossed-girdle patterns with the two girdles meeting at some angular distance from the intermediate strain axis (type 1 crossed girdles, Fig. 11D). They observed a sharply defined girdle orthogonal to the shear plane and a second girdle branching off at some distance from the intermediate strain axis. Concerning the crystallographic *a*-direction ($11\bar{2}0$) in quartz, Lister and Hobbs (1980) predicted a rather ill-defined maximum of *a*-axes parallel to the shear direction and at an acute angle to the lineation in the rock.

Based partly on these two models and partly on observations in naturally deformed rocks with a known sense of shear, three criteria for inferring the sense of shear have been proposed for quartz fabrics:

Criterion 1. The *a*-direction ($11\bar{2}0$) is a very important glide direction for glide on the basal planes (0001), the rhombs ($10\bar{1}1$, $01\bar{1}1$) and the first-order prisms ($10\bar{1}0$) (White and others, 1978). Very often, a predominant *a*-maximum can be observed at an angle of about 30° from the lineation and in the X-Z plane of the pole figure (Fig. 11B). Assuming the crystallographic slip direction to align with the shear direction in the rock (Etchecopar, 1977) the sense of shear can be deduced. Nicolas and others (1972) found the same principle to hold for olivine [100] slip directions. Bouchez (1978), Bouchez and others (1979), and Schmid and others (1981b) found such asymmetries on the basis of neutron and X-ray diffraction measurements on quartz aggregates.

Criterion 2. The basal plane in quartz is a particularly important glide system, especially at low temperatures (Tullis and others, 1973). The model of Etchecopar (1977) thus would predict a c-axis maximum normal to the shear plane and oblique to the foliation. If other glide systems such as glide on the rhombs or first-order prisms operate as well, c-axis submaxima along a single asymmetric c-axis girdle are to be expected on the basis of this model (Fig. 11A). Bouchez and Pecher (1981) found such submaxima for some of their samples, although in others the c-axes are diffusely distributed within a single girdle. This is in agreement with criterion 1 because of the orthogonality between *a*-axes and c-axes. In view of the

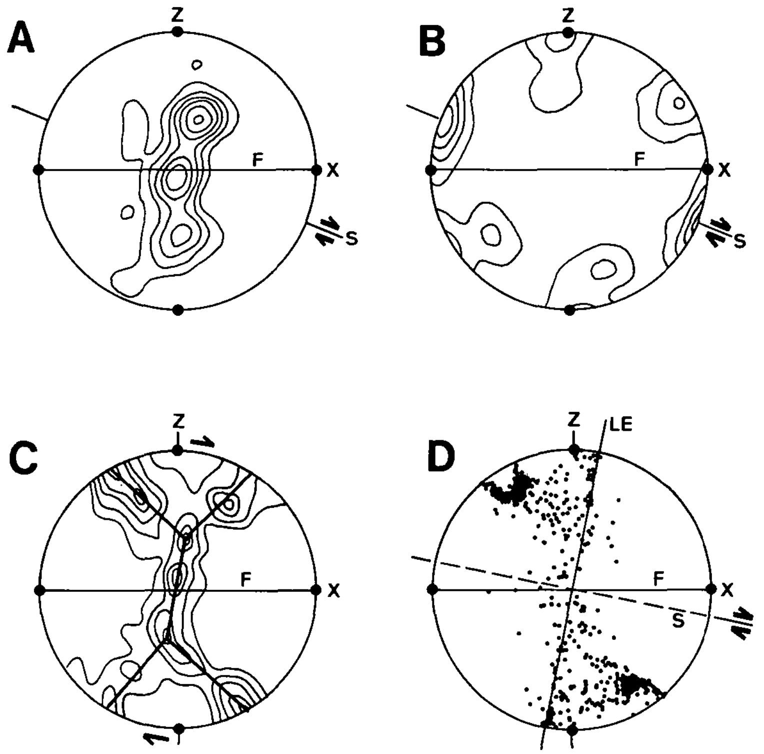

Figure 11. Examples of crystallographic fabrics indicating dextral shear. All pole figures are plotted in the X-Z plane, where Z is the foliation normal and X the stretching lineation. Contours are given in 1, 3, 5, 7, 9 times uniform (for 11A and 11B) and in 1, 2, 3, 4, 6 times uniform (for 11C). A. Quartz c-axis pole figure, calculated from the orientation distribution function based on pole figures for nine crystallographic directions (quartz-ribbon in "Plattengneis," Koralpe, eastern Alps, Austria). Note that the single girdle is oblique to the foliation plane F and normal to the dominant *a*-axis maximum of Figure 11B. Three distinct maxima along the girdle suggest the alignment of first-order prisms and rhombs, respectively, with the shear plane marked S. B. Quartz *a*-axis pole figure for the specimen of Figure 11A suggesting strong alignment of *a*-glide directions at an angle to the lineation X within the X-Z plane. C. Optically measured c-axis fabric (type 1 crossed girdle) with the skeletal outline superimposed. Note the asymmetry of the central part of the girdle with respect to the foliation and, additionally, the unequal angles between the central part of the girdle and the peripheral legs. Quartzite sample from the Betic Zone, southern Spain (from Behrmann and Platt, in press). D. c-axis pole figure resulting from the fabric simulation in progressive simple shear ($\gamma = 4$) on model quartzite A (Lister and Hobbs, 1980). S marks the shear plane, LE denotes the leading edge of a sharp girdle orthogonal to the shear plane, and F indicates the flattening plane.

fact that c-axes can be readily measured on a U-stage, this criterion has been widely used (Laurent and Etchecopar, 1976; Brunel and Geyssant, 1978; Bouchez, 1977; Bouchez and Pecher, 1976a, 1976b; Simpson, 1980), but it is not predicted by the simulations of Lister and Hobbs (1980).

Criterion 3. With asymmetric crossed-girdle patterns, the use of the first two criteria is problematic. The transition from single into crossed-girdle fabrics may be gradational (Bouchez and Pecher, 1981). It is possible that crossed-girdle patterns indicate additional flattening perpendicular to the shear-zone boundary (Bouchez and Pecher, 1981). On the other hand, Lister and Hobbs (1980) predicted crossed-girdle patterns for strictly simple shear deformation. On the basis of computer simulations, Lister and Williams (1979) and Lister and Hobbs (1980) proposed that certain characteristics of the "skeletal outline" can be used to derive the sense of shear (see Fig. 11C). This "skeletal outline" can be extracted from contoured c-axis pole figures by connecting the loci of points of maximum curvature across the contour lines. Lister and Hobbs (1980) proposed the use of a subvariant of this criterion, namely, the "leading edge" principle, the leading edge being a sharply defined boundary into the pole-free area around the extension axis (Fig. 11D). This boundary is expected to be oriented perpendicular to the shear plane in the rock on the basis of their simulations. This third criterion has been applied in a regional study by Behrmann and Platt (in press).

Criterion 1 is probably the most reliable, but not all crystallographic fabrics exhibit a predominant *a*-maximum. Occasionally, criterion 2 has been found to indicate a sense of shear opposite to the over-all displacement sense of the shear zone (Bouchez and Pecher, 1976a, 1976b; Carreras and others, 1977; Schmid and others, 1981b). These inconsistencies may arise from over-simplified assumptions about the homogeneity of strain. For example, local reversals of the shear sense are possible in cases where rigid domains cause a highly inhomogeneous strain pattern (Garcia-Celma, 1982). Criterion 3 is useful for crossed-girdle patterns only. However, the difficulties in clearly defining "skeletal outlines" and "leading edges" make its use somewhat problematic.

These criteria cannot be used for all minerals. Schmid and others (1981a) showed that the obliquity of calcite c-axis maxima is in a sense opposite to that observed in quartz. This is explained by the different glide systems operative in calcite and the importance of twinning in the development of the crystallographic fabric (Casey and others, 1978).

CONCLUSIONS

The most reliable structures for the determination of the sense of shear in regions where no displaced marker horizons or margins of shear zones can be found are asymmetrical augen structures that show tails of fine-grained, dynamically recrystallized material of the same composition as the host porphyroclast, displaced broken grains, and shear bands in regions of high strain in mylonites.

Asymmetric pressure-shadow "wings" are also reliable, provided that a careful examination of the relationship between the grain and the surrounding foliation planes is made. It may be necessary to examine several pressure-shadow regions before unequivocal results are obtained. Similar care should be applied to the use of displaced broken grains within a ductile matrix.

The use of asymmetric quartz-crystallographic fabric patterns to deduce the sense of shear occasionally gives anomalous results. However, criteria 1 and 2 are reliable, provided that the strain within the over-all shear zone is homogeneous. In the absence of dependable field evidence, all of the available criteria should be used together. Only where all lines of evidence agree can the sense of shear be predicted with certainty.

ACKNOWLEDGMENTS

The authors are indebted to the participants of the Penrose Conference on Mylonites, held in San Diego, 1981, for lively discussion on many of the concepts presented in this paper. Special thanks are due to Win Means and Terry Tullis for particularly helpful discussion and to Nick Rast and Rolfe Stanley for their reviews of the manuscript. Constructive criticisms of earlier drafts of the manuscript by Geoff Milnes, Marc Parmentier, Terry Tullis, and Glen Stockmal are gratefully acknowledged.

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Manuscript Received by the Society May 17, 1982
Revised Manuscript Received November 11, 1982
Manuscript Accepted November 19, 1982