The reliability of asymmetric c-axis fabrics of quartz to determine sense of vorticity

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ABSTRACT


Asymmetric c-axis fabrics of quartz are commonly used to determine sense of vorticity in ductile shear zones. This method seems to work if the fabric pattern resembles a model fabric proposed by Lister and Hobbs (1980). Usually, however, c-axis fabrics are rather vague. The reliability of such vague fabrics was tested in a major shear zone with known sense of vorticity. Only 62% of the c-axis fabrics predict the correct sense. Great care should therefore be taken in applying this method to determine sense of vorticity.

INTRODUCTION

In the study of ductile shear zones one of the major aims is a reconstruction of the local deformation pattern and history. Important aspects of progressive deformation are the sense and degree of non-coaxiality and the orientation of the flow plane and the flow direction. In many ductile shear zones a foliation and lineation have developed due to flattening and rotation of minerals and mineral aggregates. In the absence of major volume changes and shifts in the orientation of the kinematic frame, the foliation is thought to be subparallel to the long and intermediate axes of the finite strain ellipsoid of local non-coaxial flow (Ramsay and Graham, 1970; Williams, 1977; Ramsay, 1980). The lineation is thought to approach parallelism with the direction of maximum finite elongation (Ramsay, 1980; Tullis et al., 1982).

Sense of vorticity (Lister and Williams, 1983; Means et al., 1980) can be detected in narrow homogeneous ductile shear zones by the displacement of markers, the orientation of the foliation in the zone with respect to the zone boundaries (Ramsay and Graham, 1970) and the asymmetry of microstructures (Passchier, 1982a, 1982b; Simpson, 1982). In wide zones with indefinite boundaries these criteria can rarely be used and asymmetry of crystallographic fabrics is sometimes applied to detect sense of vorticity.
Crystallographic preferred orientation patterns of quartz-c-axes (further referred to as c-axis fabrics) are commonly asymmetric in overall shape and with respect to the foliation and lineation in ductile shear zones (e.g., Berthé et al., 1979; Brunel, 1980; Van Roermund et al., 1979; Simpson, 1980). Lister (1977) and Lister and Hobbs (1980) produced asymmetric c-axis fabrics by computer simulations using the Taylor–Bishop–Hill theory and gave a theoretical background for the mechanisms by which they are formed. They suggest that the sense of vorticity of the bulk flow in a quartzite deforming by progressive simple shear and dominant basal slip can be detected from the sense of asymmetry of the c-axis fabric produced. This holds even in the absence of other markers. There are, however, some drawbacks:

- the model only applies under severe restrictions on complexity of deformation conditions, rheological behaviour of quartz and rock homogeneity;
- changes in the orientation of the kinematic frame during deformation and a non-random initial orientation population of grains can produce asymmetric fabrics which bear no relationship to sense of vorticity of the bulk flow (Lister and Williams, 1979);
- the overall shape of the c-axis fabric should be as predicted by Lister and Hobbs (1980); a main girdle with characteristic minor girdles branching off, giving the fabric an internal asymmetry. The main girdle is orthogonal to the flow plane of the kinematic frame of deformation, and is therefore inclined to the direction of maximum finite elongation, giving the fabric an external asymmetry as well (Fig. 1B).

Unfortunately, the restrictions mentioned can rarely all be met. Asymmetric c-axis fabrics of this kind are seldom found in nature (e.g., Boullier and Bouchez, 1978; Behrmann and Platt, 1982; Shelley, 1982). Commonly rather vague or single girdle c-axis fabrics, which lack a distinct internal asymmetry, are used to determine sense of vorticity (e.g., Laurent and Etchecopar, 1976; Burg and Laurent, 1978; Berthé et al., 1979; Brunel,

![Fig. 1. Schematic diagram of the geometric relationship of the foliation (S) and lineation (L) developed in a ductile shear zone, and the shape of asymmetric quartz c-axis fabrics from the zone. A. Model of the shear zone. FD = flow direction; FP = flow plane. B. Model c-axis fabric of Lister and Hobbs (1980) possessing internal asymmetry. X and Y represent long and intermediate axes of the finite strain ellipsoid. α = main girdle; β = minor girdles. C. c-axis fabric as usually described from ductile shear zones, with a righthanded external asymmetry with respect to S and L.](image-url)
Since data on the orientation of the kinematic frame of progressive deformation are usually lacking, the external asymmetry of the c-axis fabric with respect to the foliation in the rock is used to detect sense of vorticity in such cases. This external asymmetry is thought to correspond with that of the model fabric of Lister and Hobbs (1980) with respect to the finite strain axes; a dextral sense of vorticity should give a right-handed fabric (Fig. 1B, C). Since vague or single girdle c-axis fabrics are commonly the only data on the sense of vorticity, it is important to investigate their reliability. This is done by measuring c-axis fabric asymmetry in a major mylonite zone with good control on the sense of vorticity.

**SETTING OF THE C-AXIS FABRICS**

C-axis fabrics were measured in a mylonitic gneiss complex in the Saint Barthelemy Massif, French Pyrenees (Passchier, 1982b). The gneiss was formed from Variscan granodiorite by intense ductile flow in a major mylonite zone. The mineral composition is quartz, oligoclase—andesine, orthoclase, biotite and minor muscovite, sillimanite, almandine and cordierite. The microstructure is characterized by an alternation of the following elements: (1) porphyroclasts of feldspar cut by intracrystalline micro-shear zones and mantled by fine-grained recrystallized feldspar, forming lens or rod-shaped aggregates; (2) lens or rod-shaped domains of partially recrystallized quartz, commonly as monocristalline quartz ribbons; (3) fragments of coarse biotite and muscovite crystals, commonly lozenge-shaped and surrounded by fine-grained recrystallized biotite. The different domains define a mylonitic foliation ($S_g$) and a stretching lineation ($L_g$). Stable coexistence of almandine with the minerals mentioned above, partial breakdown of sillimanite, abundant recrystallization of both feldspars and absence of chlorite and epidote indicate upper greenschist facies conditions of deformation.

The intensity of deformation varies over the studied area, causing an alternation of mylonitized gneiss and more strongly deformed mylonites in shear zones up to a few metres wide. Ultramylonite bands (Sibson, 1977) up to 1 cm wide with a strong biotite preferred orientation cut the gneiss and the mylonites and represent the last stage in the mylonitic deformation event (Passchier, 1981, 1982a, 1982b). Maximum finite strain values were reached in these bands (Passchier, 1982b).

There is no indication for important volume change during the mylonitic event (Passchier, 1982b). Deformation seems to have been strongly non-coaxial with approximately the same flow direction and sense of vorticity throughout the area and during the entire mylonitic event (Passchier, 1982a, 1982b). This follows from the invariable orientation of stretching lineations throughout the area, the sense of displacement of major lithologic units by the major mylonite zone and from the invariable sense of asymmetry of the following structures on sections parallel to the stretching lineation $L_g$ (Fig. 2); (1) vergence of sheath folds in $S_g$ and in the compositional layering in ultra-
mylonite; (2) trails of recrystallized grains around porphyroclasts of feldspar and quartz; (3) orientation of different generations of shear band cleavage in gneiss, mylonite and ultramylonite (White, 1979; Platt and Vissers, 1980), and (4) fragments of porphyroclasts displaced along microfaults and microshear zones. For ultramylonite bands the same sense of vorticity is indicated additionally by (5) deflection of $S_g$ in the gneiss along the bands; (6) the sense of misorientation of biotite preferred orientation and a compositional layering; and (7) the sense of displacement of markers such as deformed xenoliths, which are cut by the bands.

C-AXIS FABRICS

A number of c-axis fabrics were measured in monomineralic quartz domains in the gneiss, mylonite and ultramylonite. Their dimensions vary from 100 $\mu$m wide and 2 mm long to 1 cm wide and several centimetres long. Measurements were made in dynamically and statically recrystallized new grains. Dynamic recrystallization was mainly by subgrain rotation (Passchier, 1982b). Most c-axis fabrics are incomplete type I cross-girdles of Lister (1977) (Fig. 3). Only fabric G has an internal asymmetry corresponding to the model fabric of Lister and Hobbs (1980). The others are vague and single girdle fabrics of inconsistent or no external asymmetry.
Fig. 3. Quartz c-axis fabrics measured in the Saint Barthélemy Massif in mylonitized gneiss (G), mylonite (M) and ultramylonite (U). L = stretching lineation; S = foliation in gneiss and mylonite; compositional layering in ultramylonite. Arrows indicate sense of vorticity (w). Equal area projection, lower hemisphere.

DETERMINATION OF SENSE OF VORTICITY

The reliability of vague and single girdle c-axis fabrics which lack an internal asymmetry for the determination of sense of vorticity can be checked in the Saint-Barthélemy Massif, since the flow pattern in the major mylonite zone seems to have changed little with time. Sense of vorticity is known to be constant throughout the area. Therefore, a different relative age
in the mylonitic deformation event and different finite strain values are thought to have no influence on the sense of asymmetry of a c-axis fabric in the major mylonite zone (Lister and Williams, 1979). This means that all c-axis fabrics measured may be compared in one analysis. In order to obtain enough data, all thin sections of gneiss, mylonite and ultramylonite, including the ones which yielded complete c-axis fabrics, were investigated for external c-axis fabric asymmetry. This was done by keeping the foliation trace E–W on the microscope stage, determining with the gypsum plate which interference colour dominated in the quartz domains. In the thin sections which yielded complete c-axis fabrics, this method gives a reliable sense of external asymmetry. The results are illustrated in Fig. 4; 62% of the specimens yield a righthanded asymmetry and 14% are lefthanded; 24% of the specimens yield symmetric patterns or contain quartz domains with conflicting sense of asymmetry. Only c-axis fabrics with righthanded external asymmetry would yield a correct sense of vorticity.

DISCUSSION

The asymmetric c-axis fabric predicted by Lister and Hobbs (1980) increases in sharpness with progressive deformation and does not rotate with respect to the kinematic frame axes (Fig. 5). It is interesting to follow the development of this fabric if its overall shape is vague for whatever reason, e.g., inhomogeneous deformation, activity of slip systems and
Fig. 5. Schematic representation of two ways in which a model asymmetric c-axis fabric of Lister and Hobbs (1980) can deteriorate into a vague, single girdle fabric, and the development of these fabrics with increasing strain. Large stereograms have fixed orientation of the flow plane (FP) and flow direction (FD). Small stereograms have fixed orientation of foliation (S) and lineation (L); (a) single girdle, formed by merging of girdles α and β of the model fabric; (b) single girdle, composed of a broadened girdle α only. (a) results in a single girdle which changes from righthanded (RH) through symmetric (SM) to left-handed (LH) external asymmetry with increasing strain; (b) remains righthanded up to very high strains, when it approaches symmetry. ω = sense of vorticity. X and Y represent long and intermediate axes of the finite strain ellipsoid.
deformation mechanisms not incorporated in the model and the presence of minerals other than quartz. Considering only the external asymmetry of the c-axis fabric with respect to the foliation and lineation for a dextral sense of vorticity, two possible situations may arise:

(a) A vague, single girdle is composed of the merged predicted girdles α and β of Lister and Hobbs (1980) (Fig. 5a); in that case the observed c-axis fabric will have righthanded asymmetry at the start of deformation and become lefthanded when shear strain exceeds 1.0 (based on figs. 12, 13, 14 of Lister and Hobbs, 1980).

(b) A vague, single girdle contains only girdle α; in that case the girdle will retain righthanded asymmetry until very high strain values, when it becomes symmetrical (Fig. 5b).

Situation (b) is most likely to be observed since girdle β may not be observed in small measurement populations (G.S. Lister, pers. commun., 1981) and girdle α is always the most prominent one (Lister and Williams, 1979; Lister and Hobbs, 1980). Moreover, several authors reported disappearance of girdle β at high strain in the shear zones investigated by them (Bouchez and Pecher, 1976; Laurent and Etchecopar, 1976; Burg and Laurent, 1978).

In the Saint-Barthélemy Massif a tendency exists for righthanded fabrics to become relatively more abundant with increasing finite strain in the sequence mylonitized gneiss—mylonite—ultramylonite (Fig. 4). Therefore, situation (b) of Fig. 5 seems to apply here as well, which means that girdle β of Lister and Hobbs (1980) was not clearly developed in most of the c-axis fabrics measured. In this case, all c-axis fabrics would be expected to have righthanded asymmetry with the possible exception of some symmetric fabrics in ultramylonite bands in which very high finite strain values were reached. The actual data in Fig. 4 suggest that a large scatter in fabric asymmetry exists, especially at low finite strain values. Only 62% righthanded fabrics occur and symmetric, inconclusive and lefthanded fabrics are relatively common in gneiss and mylonite. Thus, the occurrence of lefthanded and symmetric c-axis fabrics may be explained by the fact that the fabrics were not measured in a homogeneous quartzite but in small quartz lenses in polymineralic inhomogeneous rocks where aberrations in the flow pattern must have been common. In addition, many of the other restrictions laid out by Lister and Hobbs (1980) for the theoretical model are not met.

CONCLUSIONS

Although vague and single girdle c-axis fabrics with an external asymmetry with respect to the foliation and lineation seem to indicate the correct sense of vorticity in many cases, they cannot be used as an independent, infallible criterion. Only where reliable criteria exist to distinguish elements of the kinematic frame, or where the fabric has a distinct internal asymmetry as predicted by Lister and Hobbs (1980) can a c-axis fabric be used to detect sense of vorticity in shear zones with accuracy.
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