Journal of Structural Geology. Vol. 1. No. 4. 1979. pp. 283 to 297
0191-8141/79/1201-0283 $02.00/0

Fabric development in shear zones: theoretical controls and observed phenomena

G. S. LISTER and P. F. WILLIAMS

Department of Tectonics, Geological Institute, University of Leiden, Leiden, The Netherlands
Department of Structural and Applied Geology, Institute of Earth Sciences, University of Utrecht, Utrecht, The Netherlands

(*Received* 19 *May* 1979; *accepted in revised form* 18 *December* 1979)

Abstract—It is suggested that the kinematic framework controls the orientation of crystallographic fabrics developed in plastically deformed quartzites. Important directions in this framework are those of the instantaneous stretching axes, and the flow plane and flow direction if these can be uniquely defined. Rotation of the crystal axes takes place at any instant of time dependent on the orientation of the grain relative to the stretching axes. Because of this dependence the skeletal outline* of a pattern of preferred orientation is sensitive to the closing stages of deformation. Thus fabrics measured in major movement zones cannot be related to early thrust or shear displacements without considering the effects of the geological history subsequent to those events.

Nevertheless, asymmetric fabrics in movement zones may allow determination of the shear direction and sense of shear. Asymmetry in the intensity distribution is less susceptible to modification than asymmetry in the fabric skeleton, and may remain as a persistent measure of the sense of shear in mylonites subjected to coaxial deformation after non-coaxial events. However, fabric asymmetry need not always be related to the deformation history, and effects related to the population of initial grain-orientations must be considered, as well as the influence of recrystallization and grain growth.

A problem of scale is involved in extrapolating the movement picture inferred from the behaviour of a few hundred crystal grains to larger dimensions. This question is also encountered when trying to specify deformation paths in mesoscopic shear zones. It is difficult to obtain simple shear experimentally because of the role discontinuities play in deformation. In certain cases in natural shear zones the quartz grains may be subjected to a coaxial deformation path while the bulk deformation is progressive simple shear. Caution must therefore be exercised when attempting to use quartz fabrics to infer characteristics of the bulk kinematics or movement picture applicable during deformation.

INTRODUCTION

THIS PAPER reviews data concerning the development of crystallographic fabrics in quartzites that have been plastically deformed in shear zones. The topic is one which has recently returned as a focus of interest because of the possibility that quartz fabrics can be used to solve problems such as determining the sense of shear in movement zones, or in ascribing kinematical significance to lineations. For example one might attempt to decide whether a lineation developed parallel to an extension direction, and whether the deformation was predominantly coaxial or non-coaxial.

It has been suggested by a number of authors (Nicolas *et al.* 1971, 1972, 1973, 1976, 1977, Bouchez 1978) that in a polycrystalline aggregate subjected to progressive simple shear, when one slip system is clearly dominant, the glide plane tends to become aligned parallel to the flow plane, and the slip direction parallel to the flow direction. In the case of quartzite, where the basal <**a**> glide systems seem to be an important deformation mechanism under many circumstances, this could mean that **c**-axes should preferentially align normal to the flow plane and that **a**-axes should preferentially align parallel to the flow direction. If the foliation is taken to be exactly parallel to the axes of finite strain, as assumed by the above authors, and therefore not parallel to the flow plane, then asymmetry of fabric relative to the foliation can be interpreted: (a) as an indicator of non-coaxial deformation; and (b) as a measure of the sense of shear.

Considerable work has been carried out investigating the relation between symmetry of fabrics and symmetry of the deformation path; see for example Berthé *et al.* (1979), Bossière & Vauchez (1978), Bouchez *et al.* (1976, 1977, 1978, 1979), Burg & Laurent (1978), Christie (1963), Eisbacher (1970), Laurent & Etchecopar (1976), Lister & Price (1978), Lister *et al.* (1978, 1979), Lunardi & Baker (1975), Paterson & Weiss (1961), Riekels & Baker (1977), Sylvester & Christie (1968), and Tullis (1977). Of particular importance is the Curie symmetry principle discussed by Paterson & Weiss (1961).

The Curie symmetry principle can be stated formally as follows:

$$G_{\text{effect}} \supseteq \{G_1 \cap G_2 \cap \ldots \cap G_n\}$$

where G_{effect} is the point symmetry group of an effect associated with causes 1, 2, . . . *n*.

The symbols denote:

$\supseteq$, contains or is identical with;
{ }, the group generated by; and
$\cap$, the intersection operator

and G_1, G_2, . . . G_n are the point symmetry groups of the causes 1, 2, . . . *n*. It is thus indicated that the point symmetry group of an effect associated with a particular set of causes must contain at least all of those symmetry elements which are common to all of the causes. However, irrelevant items can be added to the list of causes without invalidating the principle and this reduces the practical value of symmetry arguments. It is useful to note that if a symmetry element is missing from the symmetry group

---

* Defined on page 284

associated with a particular effect, then that symmetry element must be absent in at least one of the symmetry groups associated with the causes of that effect. The factors which influence the development of deformation fabrics include: (a) the initial orientation distribution; (b) the deformation path; and (c) the metamorphic conditions. Therefore there is no reason to automatically relate asymmetric fabrics to simple shear deformations. The effects of the population of initial grain orientations and of deformation paths where the deformation increments were not always the same must also be considered. There is no need to limit discussion of the effects of the symmetry of the deformation path to deformations that were constant in their kinematic description throughout.

In this paper we discuss characteristics of fabric patterns relating to: (a) *properties of the intensity distribution*, for example the angular distribution of the basal (0001) trace in the *XZ* plane of the finite strain ellipsoid (Bouchez 1977) or the **c**-axis distribution projected onto the *XZ* plane (Lister & Hobbs, in press); and (b) *properties of the skeletal outline*, obtained from a contoured pole figure by considering the loci of points of maximum curvature across the contour lines. The fabric skeleton is analogous to the outline of the peaks, crests and ridges which can be traced on any topographic map if sufficient density is available in the contour pattern. The skeletal outline is thus more meaningful when 'local' topographic variations are smoothed, and if the overall intensity variation is large. It is difficult to delineate the skeleton if too few grains are measured, or if there are not enough contour lines present. The method of obtaining a fabric skeleton is subjective in that only those traces should be selected which allow the best description of the topological variation.

THEORETICAL PREDICTIONS

Models for the development of crystallographic fabrics during plastic deformation are rather inadequate, and there are only two models allowing predictions for simple shear.

Etchecopar (1974, 1977) was interested in the problem of how a 2-dimensional polycrystal would deform with only one slip system allowed. He obtained preferred orientation because rotation of the 'grain' shapes was allowed to minimize overlap between adjacent polygons (Fig. 1). This model takes an interesting step towards considering interactions between adjacent crystal grains. The other model is the Taylor–Bishop–Hill analysis extended to general deformation paths (Lister *et al.* 1978, in press). This has been applied to the problem of predicting fabric development during plastic deformation of quartzite but it was necessary to assume homogeneous strain, rigid-plastic behaviour, and operation of glide systems with the <**c**+**a**> Burgers vector. It should be noted that in the Taylor–Bishop–Hill analysis no bulk rotation of grains takes place, so the reorientation mechanism is fundamentally different to that used by Etchecopar.

Etchecopar's model predicts for plane strain that a bimodal preferred orientation develops, with slip directions concentrating in two maxima symmetrically disposed about the extension axis. For simple shear a distinct asymmetry develops (Fig. 1c) and the patterns have the following characteristics:

(a) the strongest and most sharply defined maximum disposes the slip direction within 5° of the shear direction;

(b) the second weaker maximum is a broad concentration of slip directions at high angles to the axis of instantaneous shortening (for progressive simple shear);

(c) the two maxima are more or less symmetrically related to the finite strain axes;

(d) the angle between the maxima decreases with increasing finite strain.

Lister & Hobbs (in press) applied the Taylor–Bishop–Hill model to the problem of simulating the effect of deformation path on fabric development. Out of a wide range of possibilities they chose three hypothetical model quartzites (involving different CRSS values on different glide systems) and subjected them to a sequence of coaxial strain paths, and non-coaxial deformations including progressive simple shear. The results allow the following statements concerning simple shear:

(a) The **c**-axis fabrics formed by coaxial plane strain and progressive simple shear are rather alike at low strains and the pattern elements such as girdles or maxima are symmetrically disposed about the *XY*-plane of the finite strain ellipsoid. However in some model

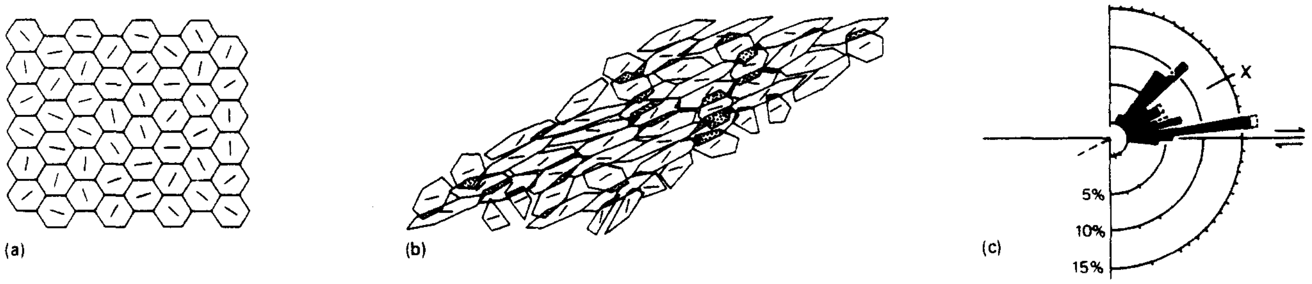

Fig. 1 (After Etchecopar 1977, Fig. 13 and 1974, Fig. A14). Etchecopar considers deformation of polygons with one slip direction. Preferred orientation results because of 'bulk' rotations of grain shapes to minimize overlaps and holes. Initial state (a) is related to deformed state (b) by a simple shear with $\gamma = 1.43$ and shear angle 55°. The overall shape is shortened 48.6% in consequence, and the axis of shortening lies 27.2° from the bulk shear plane. The rose diagram (c) shows a definite asymmetry in the angular distribution of the slip direction. The most sharply defined maximum lies near the shear direction, but not parallel to it.

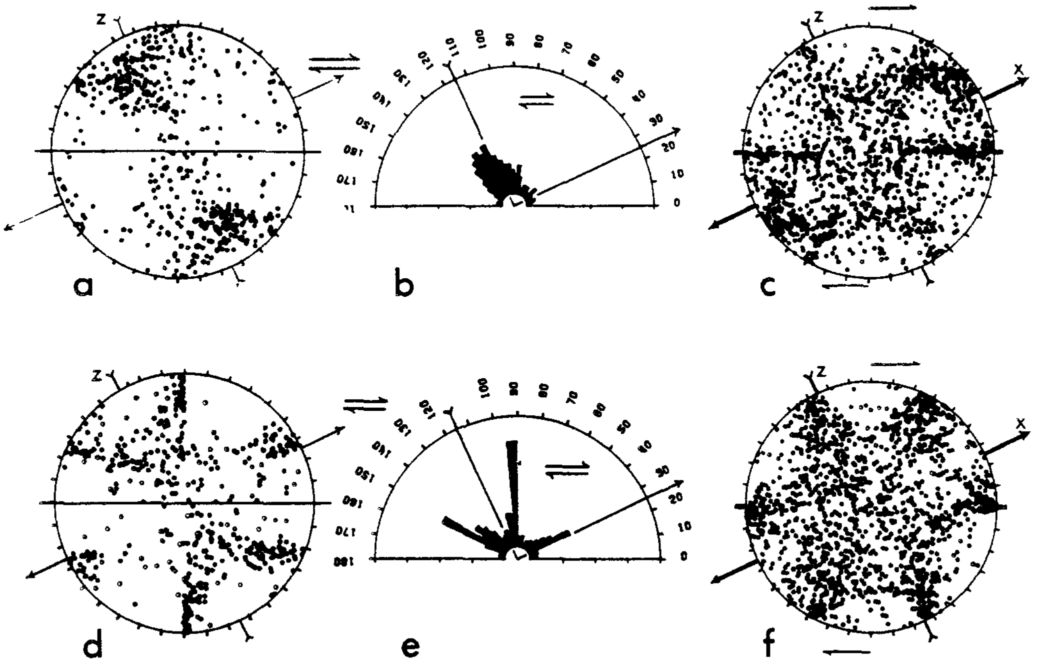

Fig. 2. Two model quartzites consisting of 500 randomly oriented grains are subjected to progressive simple shear involving 15 increments, shear tangent 1.5, shortening 50% using the Taylor–Bishop–Hill analysis. Model B (a, b, c) and Model C (d, e, f) (after Lister & Hobbs, in press) are shown with: (a) c-axis pole figures (a, d); (b) trend of c-axes projected on the *XZ* plane of the finite strain ellipsoid (b, e); and (c) a-axis pole figures (c, f). Model C produces fabrics in which many grains align with the basal plane parallel to the flow plane and with the a-direction parallel to the flow direction. If kinking on the basal plane was included in the simulation the strong maximum at *X* would disappear. In this case compare these predictions with those of Etchecopar. Note base scale (b, e) graduated in increments of 5% of the orientation population.

quartzites (e.g. model C, Fig. 2) an asymmetry in intensity distribution develops that consistently reflects the sense of shear. A girdle of c-axes forms precisely orthogonal to the direction of shear. This girdle contains most c-axes, and is more sharply defined than the other girdle.

(b) At high strains asymmetry in fabrics becomes quite marked, both in respect to the finite strain axes and in respect to the skeletal outline of the fabric pattern.

(c) The a-axis fabrics have an asymmetry that can be consistently related to the sense of shear. The strongest maximum in the a-axis fabric disposes one a-axis precisely parallel to the flow direction. This is interesting because <a> is the easiest slip direction in the three model quartzites.

(d) Once the elements of a fabric pattern form, the maxima and girdles remain fixed in their angular relationships with the kinematic frame, i.e. constant angles are maintained between the pattern elements and specific directions in a reference framework stationary with respect to the instantaneous stretching axes, for example in relation to the flow plane and flow direction (see Lister & Hobbs, in press) for examples.

FIELD STUDIES

Fabric development in relation to the kinematic framework

The best way to test these theoretical predictions would seem to be by studying the fabrics developed in shear zones conforming to the characteristics described by Ramsay & Graham (1970) as necessary for simple shear.

The data provided by Carreras *et al.* (1977) is of particular interest and will be discussed again later in this paper. These authors examined narrow mylonite zones from the Hercynian belt exposed in the axial zone of the Pyrenees. Veins in the country rock have been deformed to form mylonitic lenses, and in one outcrop veins parallel to an earlier foliation curve progressively into near parallelism with the trend of the mylonitic layering (Fig. 3) from the outside to the inside of the shear zone.

Fabric development can be interpreted as follows. Initially the quartz c-axis fabrics are related to host-grain orientations. As strain increases however, the quartz suffers extensive dynamic recrystallization, and after sufficient strain the patterns do not show effects that can be related to the small population of crystal orientations present in the coarse-grained veins before deformation. Eventually it is likely that a balance is achieved between lattice reorienting effects related to intrinsic details of the deformation process (such as the conservative components of dislocation movements) and in this case scattering effects due to heterogeneous strain, recrystallization and grain growth. This would give rise to the 'steady-state' fabric reported by Carreras *et al.* (1977) as shear strain increases.

As can be observed from Fig. 3, the skeletal outline of the fabric patterns appears to rotate as the quartz layers rotate, a situation which compares to that shown schematically in Fig. 4(a). If the shear zone is such that at every point the deformation is progressive simple shear, this example appears to contradict the hypothesis that fabric development occurs in relation to the kinematic framework. The fabric pattern appears to track the orientation of the axes of finite strain, which themselves

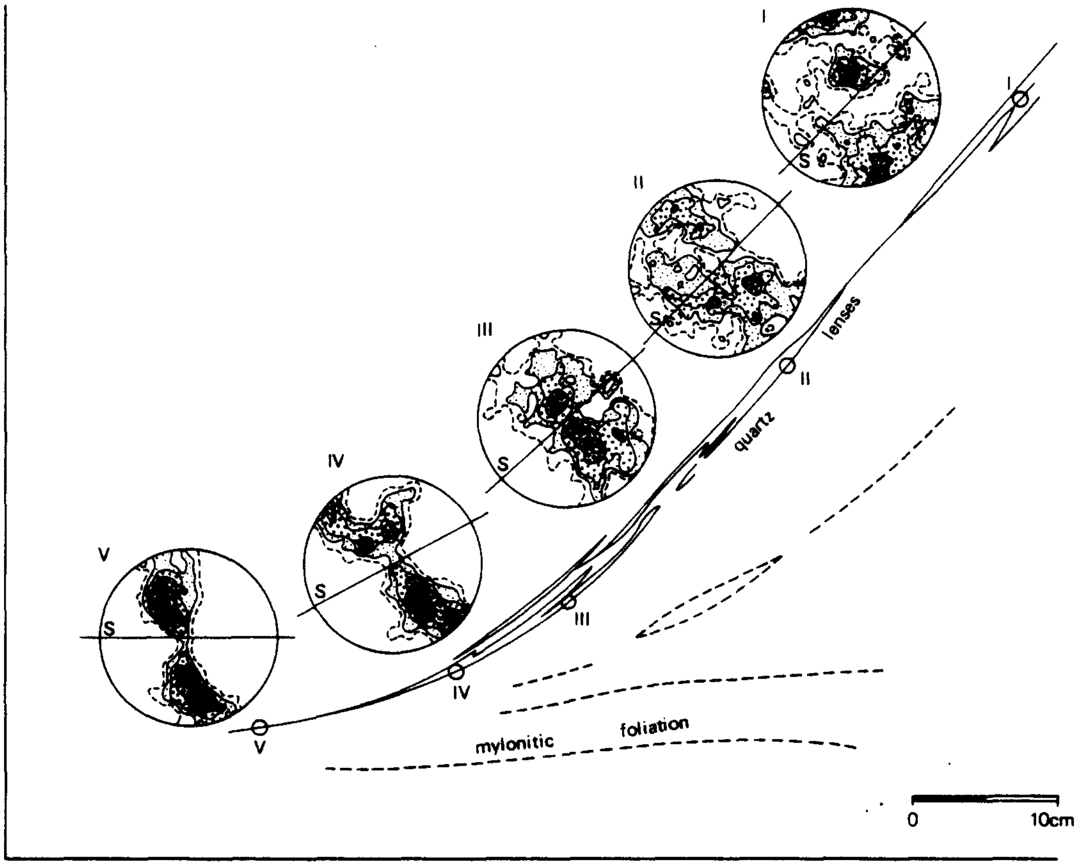

Fig. 3 (After Carreras *et al.* 1977). A quartz lens sequence is caught up in a narrow mylonite zone. Quartz c-axis fabrics develop progressively into the zone and the final c-axis fabric is distinctly asymmetric. Bouchez & Pecher (1976) used the distribution of the basal trace in the *XZ* section of the finite strain ellipsoid to predict the sense of shear. This method applied to the illustrated fabrics gives correct answers only for fabrics produced by low shear strains (I, II, III). The basal trace method fails in the high shear strain situations (IV, V).

progressively rotate as the boundary of the mylonite zone is approached.

However, the question of scale of approximation has been omitted from discussion, and we must return later in the paper to examine this point. In the mylonite zone itself the skeletal outline of the c-axis pattern becomes asymmetric (Fig. 5) and is consistent with the predictions of the Taylor–Bishop–Hill analysis for fabric development during progressive simple shear (Fig. 4b).

The data provided by Hara *et al.* (1973) for fabric development in narrow shear zones in a granite has been referenced as indicating orthorhombic fabric patterns developed during simple shear (e.g. as in Fig. 4a). However these fabrics are decidedly asymmetric, as can be seen by accentuating the zero level contour and delineating the pole-free areas on the pole figure (Fig. 6) (as noted by Bell & Etheridge 1976). The fabric skeleton is most clearly asymmetric (in relation to the foliation) at low shear strains (Figs. 6a & b) a situation which is to be compared with that illustrated in Fig. 4(b).

Three studies have specifically addressed the question as to whether the orientation of quartz fabrics developed in narrow shear zones is related to the orientation of the kinematic framework (Berthé *et al.* 1979, Burg & Laurent 1978, Van Roermund *et al.* 1979). Interpretation is made difficult by variation from fabric pattern to fabric pattern, but the data suggest that the flow plane and flow direction are important in determining the orientation of the deformation fabrics developed. The data provided by Burg & Laurent (1978) has been used to construct a synoptic plot of maximum orientations (Fig. 7a) and this can be compared with the synoptic plot of maximum orientations and pole free areas from Van Roermund *et al.* (1979) (Fig. 7b). In both cases a girdle orthogonal to the shear direction is clearly defined, and a maximum free area around all possible positions for the axis of extension. In Fig. 7(a) there is a second girdle that disposes the basal plane at high angles to the axis of shortening. This second girdle is not clearly defined in Fig. 7(b).

These data are consistent with the situation shown in Fig. 4(b). It is worthwhile noting how asymmetry with respect to the foliation changes from low shear strains to high shear strains (extend the situation depicted in Fig. 4b). Note also that the variation in fabric in the above studies can be attributed to different populations of pre-deformation grain orientations.

Hudleston (1978) reports a study from the Barnes Ice Cap where the overriding action of the main glacier has produced shear zones on the scale of a few centimetres. Ice is an interesting analogue for quartz since it is a hexagonal material that readily recrystallizes, and at high homologous temperatures deforms by slip on the basal plane. In the shear zone studied in detail (Fig. 8) Hudleston found that c-axis fabrics developed from a fairly uniform distribution outside the shear zone, to a

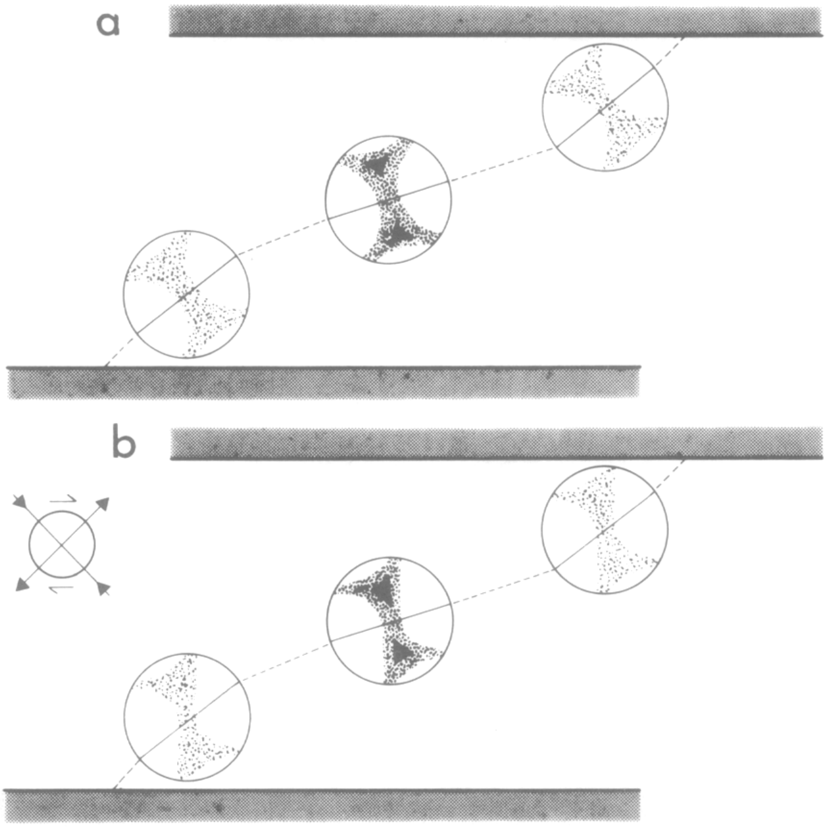

Fig. 4. A narrow ductile shear zone in which the bulk deformation path is progressive simple shear. Fabrics in quartzites seem to follow either of two trends: (a) the maxima and girdles rotate as the foliation rotates, tracking the finite strain axes; or (b) the fabric stays fixed in its relationship to the flow plane. Diagrams show schematic c-axis fabrics. Diagram (b) summarizes the predictions of the Taylor–Bishop–Hill analysis for strict heterogeneous simple shear throughout the shear zone. It will be noted that at low shear strains the asymmetry of the c-axis distribution with respect to the foliation is consistent with the asymmetry argued by Bouchez & Pecher (1976). At high shear strains this asymmetry will eventually undergo an apparent reversal. Note that a girdle orthogonal to the shear direction is always defined.

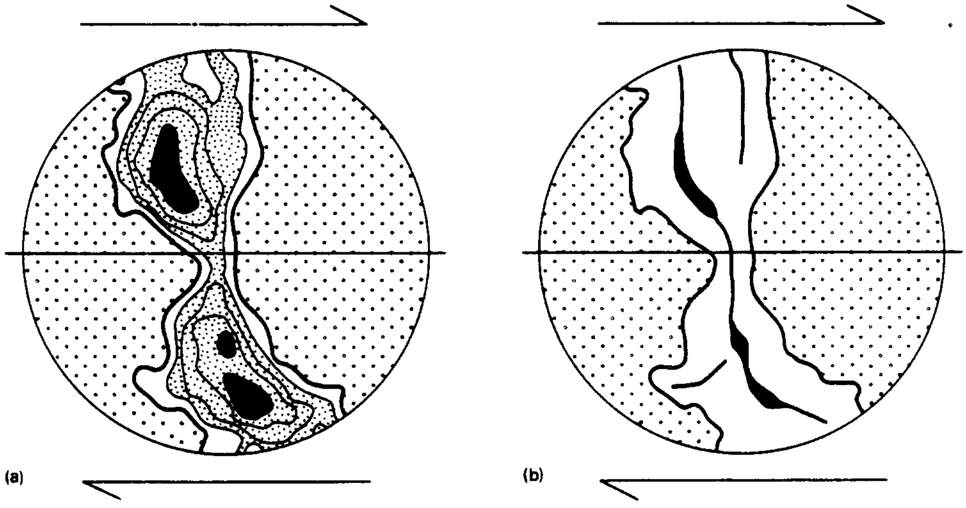

Fig. 5. The most deformed part of the quartz lens sequence shown in Fig. 3 (after Carreras *et. al.* 1977) develops the illustrated e-axis fabric. Note the asymmetry in relation to the shear sense in (a) and note how the fabric skeleton (b) picks out the most essential topological characteristics of the fabric. This is specimen V from Fig. 3. In this case whereas the asymmetry in the fabric skeleton allows prediction of the correct sense of shear, the basal trace method as applied by Bouchez & Pecher (1976) will give an incorrect answer.

double maximum fabric within the zone. One maximum is much stronger than the other and this maximum disposes the basal plane parallel to the flow plane. In the central part of the zone, where the strongest fabric is developed, the weaker maximum disappears. These data are consistent with the results obtained in experiments with ice (Kamb 1972) except that Kamb did not report the connection across the axis of intermediate strain, as measured by Hudleston (Fig. 9). In both cases fabric development has taken place with pattern elements forming in specific directions relative to kinematic axes, and no change takes place in these angular relations with increasing shear strain (cf. Fig. 4b). Further the strongest and most sharply defined maximum (and associated girdle) forms with its leading edge perpendicular to the shear direction.

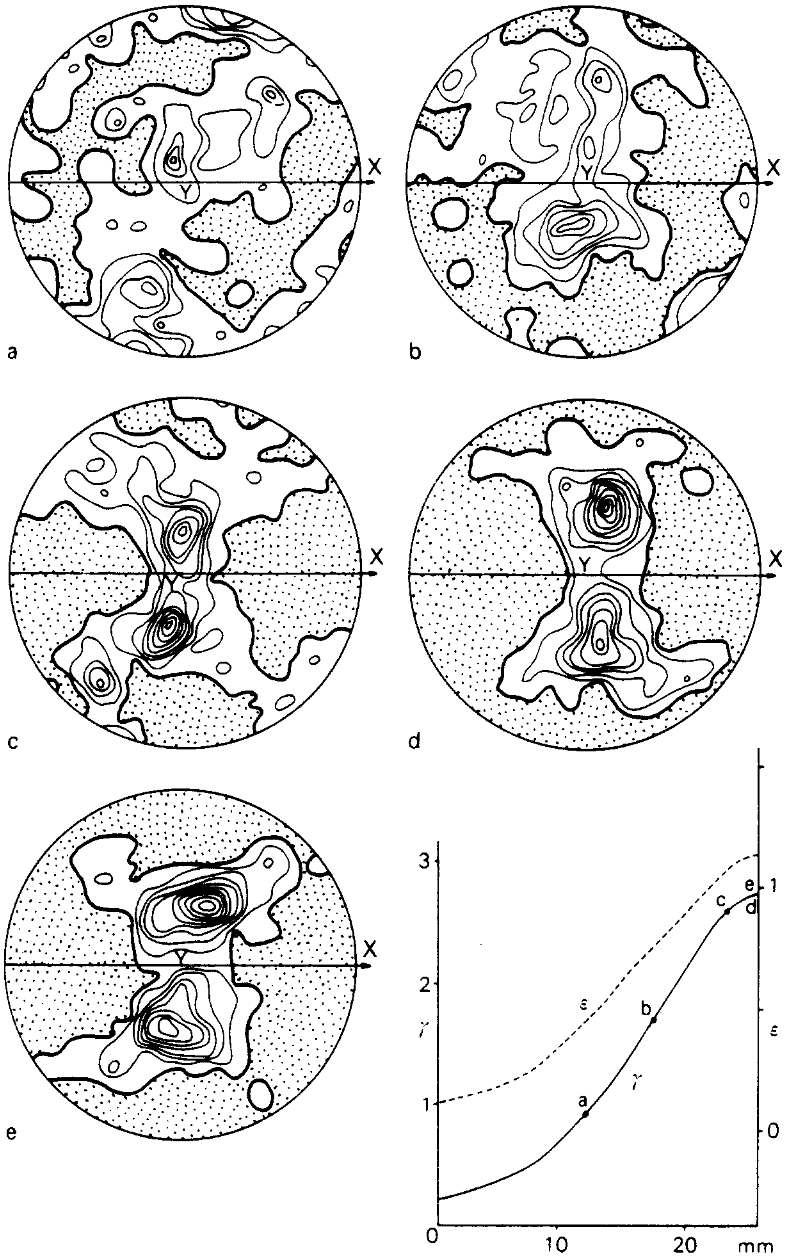

Fig. 6 (After Hara *et al.* 1973). Progressive development of c-axis fabrics in a narrow ductile shear zone within the Teshima granite, Sambagawa terrain, Japan. The shear strains γ and the strain ε_{XZ} are graphically displayed for each fabric. Pole free areas are stippled. X denotes the axis of extension.

Asymmetry in intensity distribution

We turn now to the question of whether or not there is a consistent asymmetry in intensity distribution related to the sense of shear for quartz fabrics developed in shear zones. Three studies support such a conclusion.

Christie (1963) reported orthorhombic c-axis fabrics (Fig. 10a) from part of the Moine thrust zone in Scotland. Riekels & Baker (1977) examined one of these rocks and determined preferred orientation using an X-ray fabric goniometer. The patterns obtained are markedly monoclinic (Figs. 10b & c) and this asymmetry can be related to the sense of shear. It should be noted that the X-ray determined c-axis pattern is not orthorhombic, and the X-rays detected a significant proportion of c-axes parallel to the axis of extension (Fig. 10c). These differences can be related to the fabric in the fine-grained recrystallized ground mass of the quartz mylonite, which need not be the same as the optically determined pattern of the porphyroclasts.

Bouchez (1977) examined a Hercynian shear zone in which quartz porphyroclasts deformed differently according to their orientation in relation to the strain-axes. Ribbon grains in the 'most deformed at highest temperature' specimens display a *Y*-axis maximum c-axis fabric. These are type II crossed-girdle patterns and they have an asymmetry (Fig. 11) that can be related to the sense of shear independently determined using *cornu*-shaped grains. Bouchez plotted the orientation distribution of the trace of the basal (0001) plane (in the *XZ* section of the finite strain ellipsoid) for several megacrysts and noted the similarity of these diagrams with the distributions predicted by Etchecopar (Fig. 1).

Bouchez & Pecher (1976) measured c-axis fabrics in

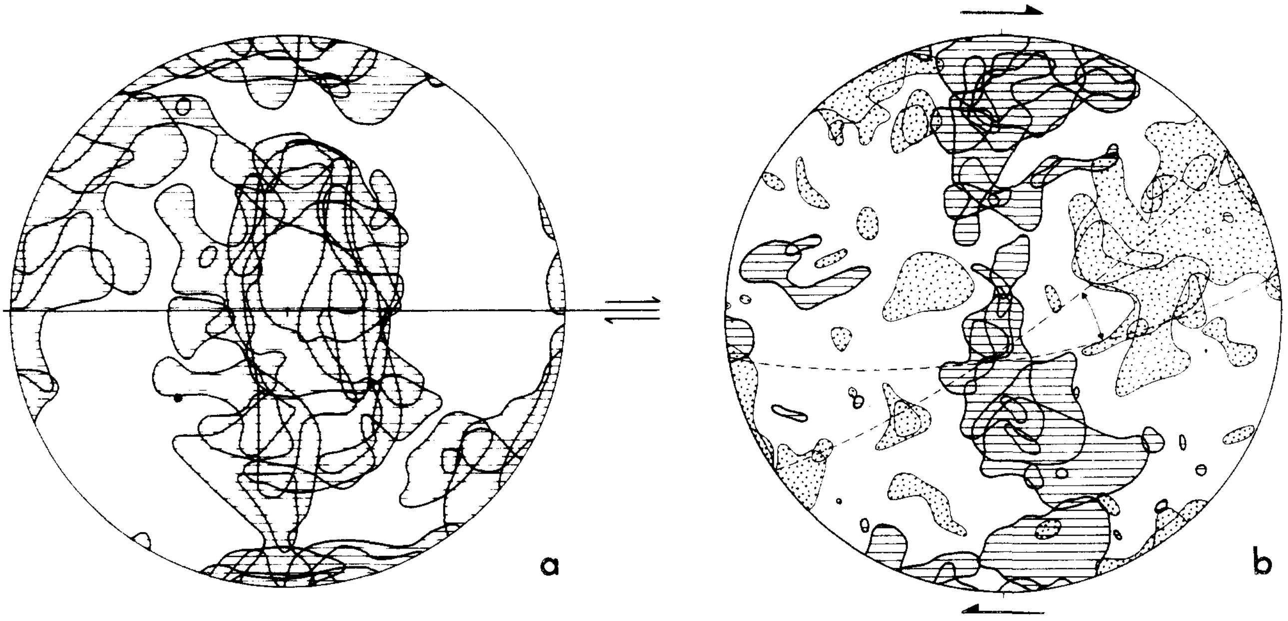

Fig. 7. Synoptic maximum plots from two discrete shear zones support the idea that fabrics are related to the kinematic framework, and do not track the finite strain axes. Diagram (a) was assembled from the data published by Burg & Laurent (1978) and shows a crossed-girdle with one girdle orthogonal with the shear direction. Diagram (b) after Van Roermund *et al.* (1979) shows again one girdle orthogonal to the shear direction. Pole free areas are shown stippled. Note that maximum free areas surround the axis of extension.

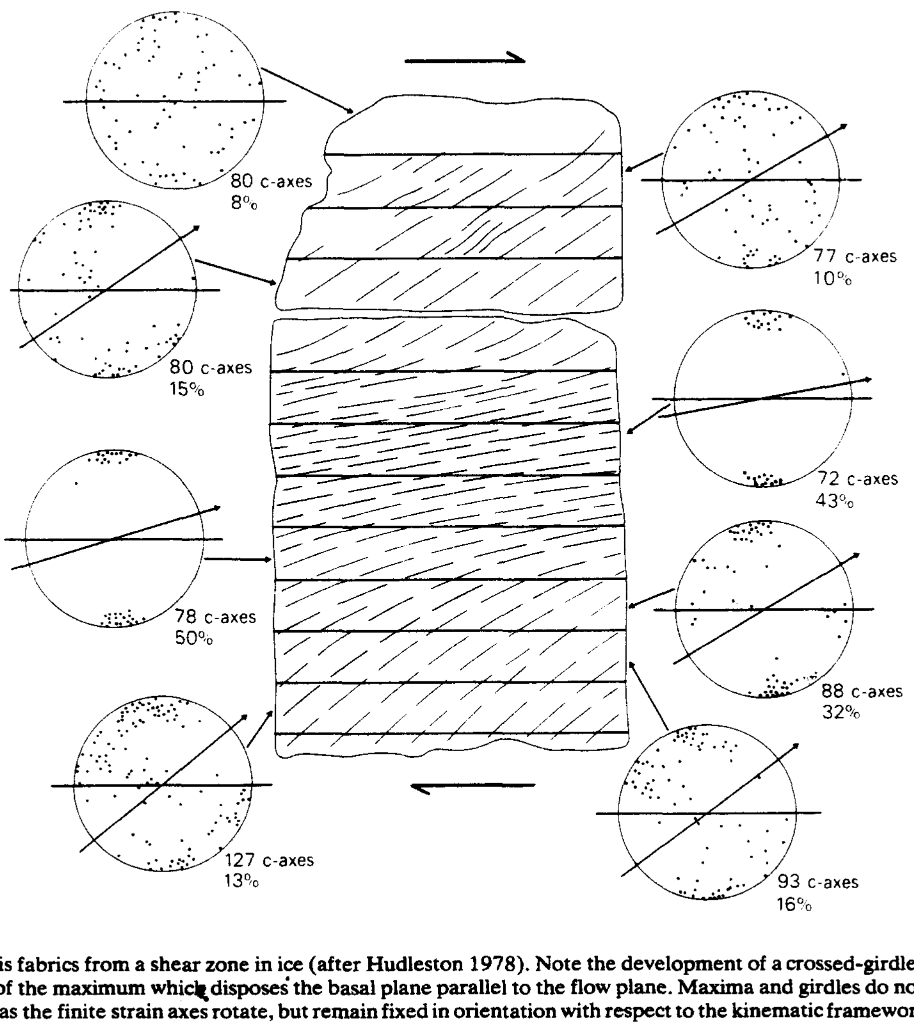

Fig. 8. C-axis fabrics from a shear zone in ice (after Hudleston 1978). Note the development of a crossed-girdle fabric, and the growth of the maximum which disposes the basal plane parallel to the flow plane. Maxima and girdles do not change in orientation as the finite strain axes rotate, but remain fixed in orientation with respect to the kinematic framework. Note the leading edge of the main maximum is approximately orthogonal to the shear direction.

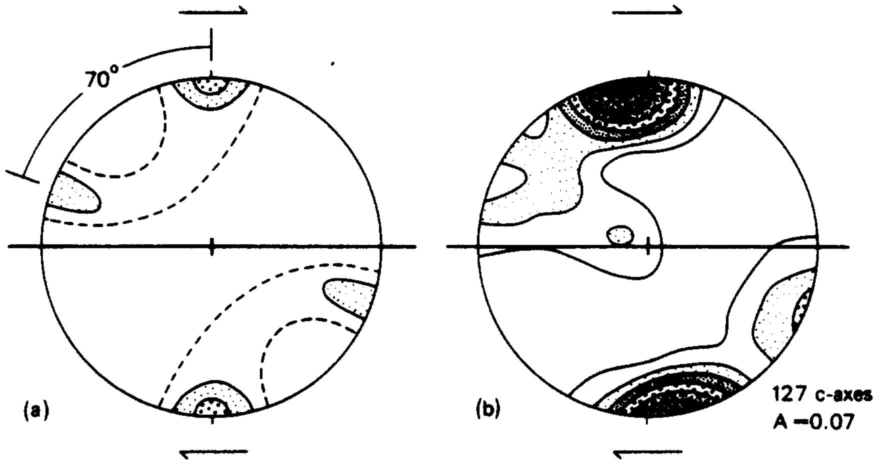

Fig. 9 (after Hudleston 1977). This figure illustrates c-axis fabrics in deformed ice. Diagram (a) after Kamb (1972) illustrates fabrics formed in simple shear experiments. Using the same contouring techniques Hudleston (1977) prepared one of his diagrams (b) for comparison. The results are similar, except Kamb did not discover a connection across the intermediate strain axis.

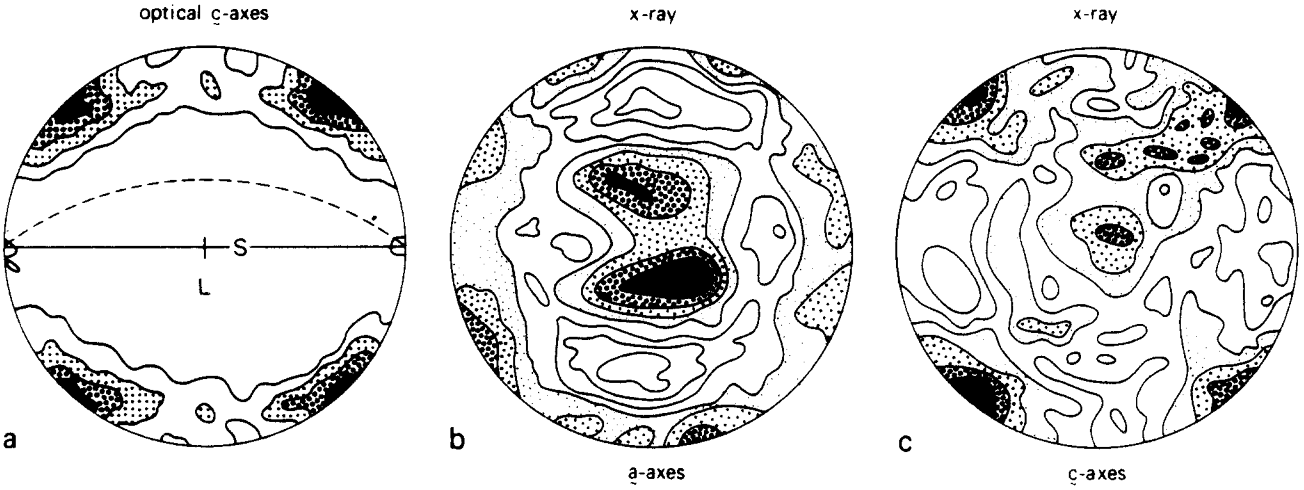

Fig. 10. Quartz fabrics from the Moine thrust (after Riekels & Baker 1978). Diagram (a) after Christie (1963) shows the optically determined c-axis fabric of the megacrysts and should be compared with (c) showing the X-ray determined pattern of c-axis distribution. The a-axis fabric (b) is asymmetric and this asymmetry is related to the sense of shear. These are type I fabrics.

strongly deformed quartzites collected from the Main Central Thrust of Nepal. The orientation distribution of the basal trace in the assumed *XZ* section of the finite strain ellipsoid was determined. This distribution was markedly asymmetric in many cases, and the shear sense inferred from most of these specimens agreed with that argued from large-scale tectonic considerations. Bouchez *et al.* (1979) used neutron diffraction to study the orientation distribution more thoroughly in some of these rocks. This technique has the advantage that there is little background scatter, and that large specimens are transparent to the neutron beam. The pole figures that result are markedly monoclinic in symmetry, and are asymmetrically inclined to the foliation (Fig. 12).

Shear sense inferred from fabric asymmetry

If it is assumed that fabric asymmetry is related to simple shear deformation, there are three ways to proceed in an attempt to determine shear sense:

(a) Use asymmetry in the a-axis fabric, assuming that the greatest concentration of a-axes marks the flow direction, and that the foliation marks the *XY* plane of the finite strain ellipsoid (Bouchez 1978);

(b) If enough c-axes can be measured to allow adequate delineation of the fabric skeleton, use asymmetry in the skeletal outline in relation to the foliation, for example assuming that the sharpest girdle is orthogonal to the shear direction;

(c) Determine the angular distribution of the basal (0001) trace in the *XZ* plane of the finite strain ellipsoid, and assume the strongest most sharply defined maximum marks the shear direction (Bouchez 1977, Bouchez & Pecher 1976).

These techniques need to be checked for several different types of fabrics in situations where shear sense is independently obtainable for each fabric. For example it should not be assumed that the behaviour of type II crossed-girdles (Bouchez 1977) is the same as the behaviour of type I crossed-girdles (Carreras *et al.* 1977). In the case of specimen V (Fig. 6 after Carreras *et al.* 1977) whereas asymmetry in the fabric skeleton seems to indicate the correct sense of shear, the basal trace method gives the wrong answer.

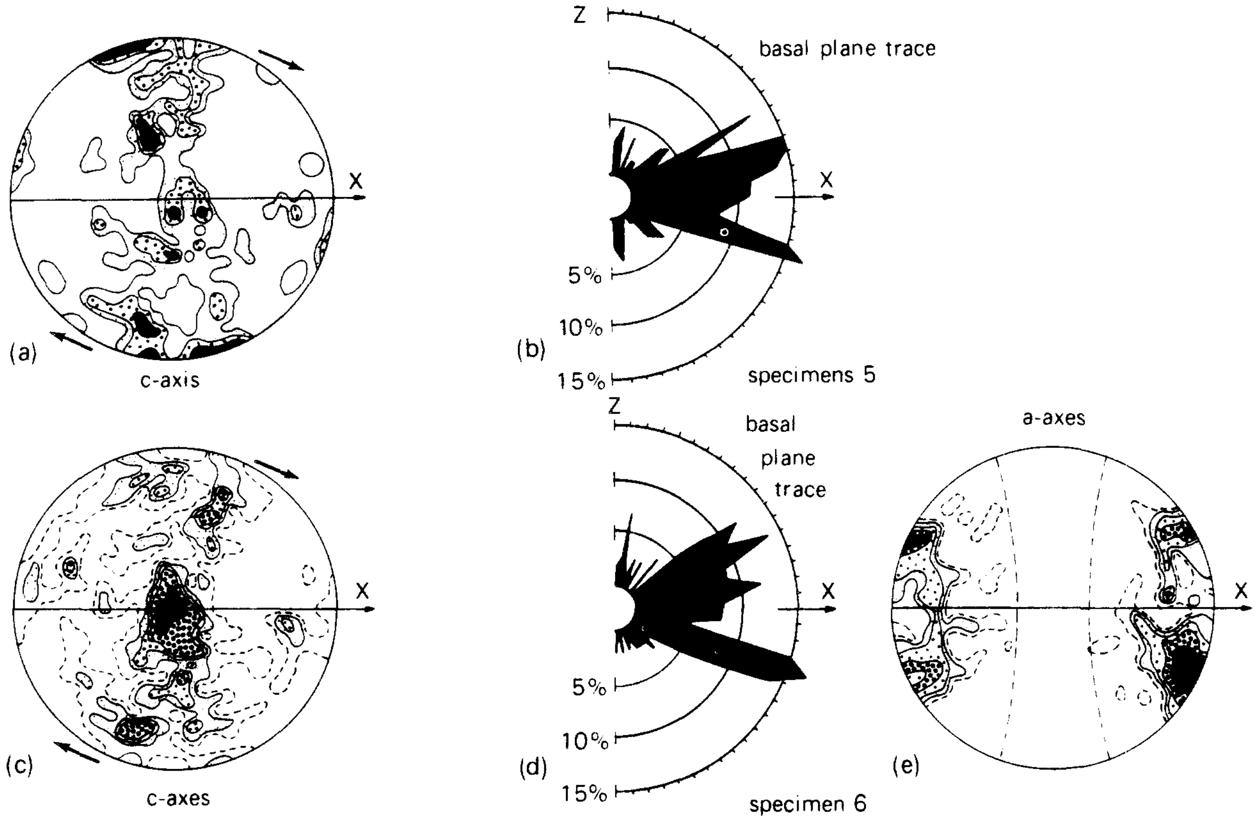

Fig. 11. The Angers quartzite (after Bouchez 1977) is highly deformed in places and exhibits asymmetric type II crossed girdle c-axis fabrics (a, c). Bouchez plots the distribution of the trace of the basal (0001) plane in the *XZ* section of the finite strain ellipsoid and notes a strong asymmetry related to the sense of shear. The rose diagrams (b, d) show that one arm of the crossed girdle is more sharply defined than the other and this is assumed to be sub-parallel to the flow plane. Thus the sense of shear can be determined. Diagram (e) after Bouchez (1978) shows the a-axis fabric for (c) and in this fabric one of the maxima is much stronger than the others. Bouchez (1978) assumes this maximum is an indicator of the flow direction and proposes a-axis fabric asymmetry as an alternative way of determining sense of shear.

If: (a) simple shear is assumed; (b) the strongest a-axis concentration does mark the flow direction; and (c) the foliation marks the *XY* plane of the finite strain ellipsoid; then we have a method of estimating shear strain. If such a method is valid the strain estimates are independent of the percentage of strain accomplished by crystal plasticity. However, shear strains obtained by this means are generally rather low (e.g. for Fig. 12, after Bouchez *et al.* 1979 we estimate shear strain between 2 and 3 and aspect ratios not higher than 1:3:10). This may be because of changes that result when a fabric is modified continuously during the waning stages of deformation if the kinematic description of deformation begins to change.

Questions surrounding the assumption that the foliation is exactly parallel to the *XY* plane of the finite strain ellipsoid have been reviewed by Williams (1976, 1977). There are difficulties and arbitrary decisions should be avoided. *A priori* assertions concerning the location of the finite strain axes will almost certainly lead to controversy analogous to that which occurred concerning labelling of the *a*, *b* and *c* kinematic axes.

Pole free areas defining the axis of extension

In many c-axis fabrics the location of the *YZ* plane of the finite strain ellipsoid appears to be marked by maxima, girdle intersections or by girdles that connect maxima or other girdles. In addition *Y*-axis maximum fabrics are reasonably common (e.g. Sylvester & Christie 1968). Often pole free areas surround the axis of extension. Such observations may be of practical use, especially in ascribing kinematic significance to lineations.

However care is needed. If an optical determination of fabric results in a pole free area normal to the plane of the thin section, it may be that grains with c-axes at high angles to the section have been excluded by accident from the sample population. For example, Ramsay & Graham (1970) recorded maxima in the *ZX* plane of the finite strain ellipsoid, and a pole free area normal to the axis of shearing, in quartz fabrics from a narrow shear zone in a boudinaged and folded sheet of metagabbro. Starkey & Sutherland (1978) suggest that these fabrics are random, and the sampling accidentally excluded c-axes at high angles to the plane of the thin section.

If it is possible, pole free areas normal to the plane of the thin section should be checked with another thin section at right angles, and where convenient thin-sections should be stained so as to avoid problems with feldspar.

Asymmetry related to the initial orientation distribution

Many c-axis fabrics do not develop from random initial orientation distributions, and any study of fabric asymmetry is incomplete if some attempt is not made to ascertain characteristics of the starting grain population before deformation. Frequently large quartz grains are

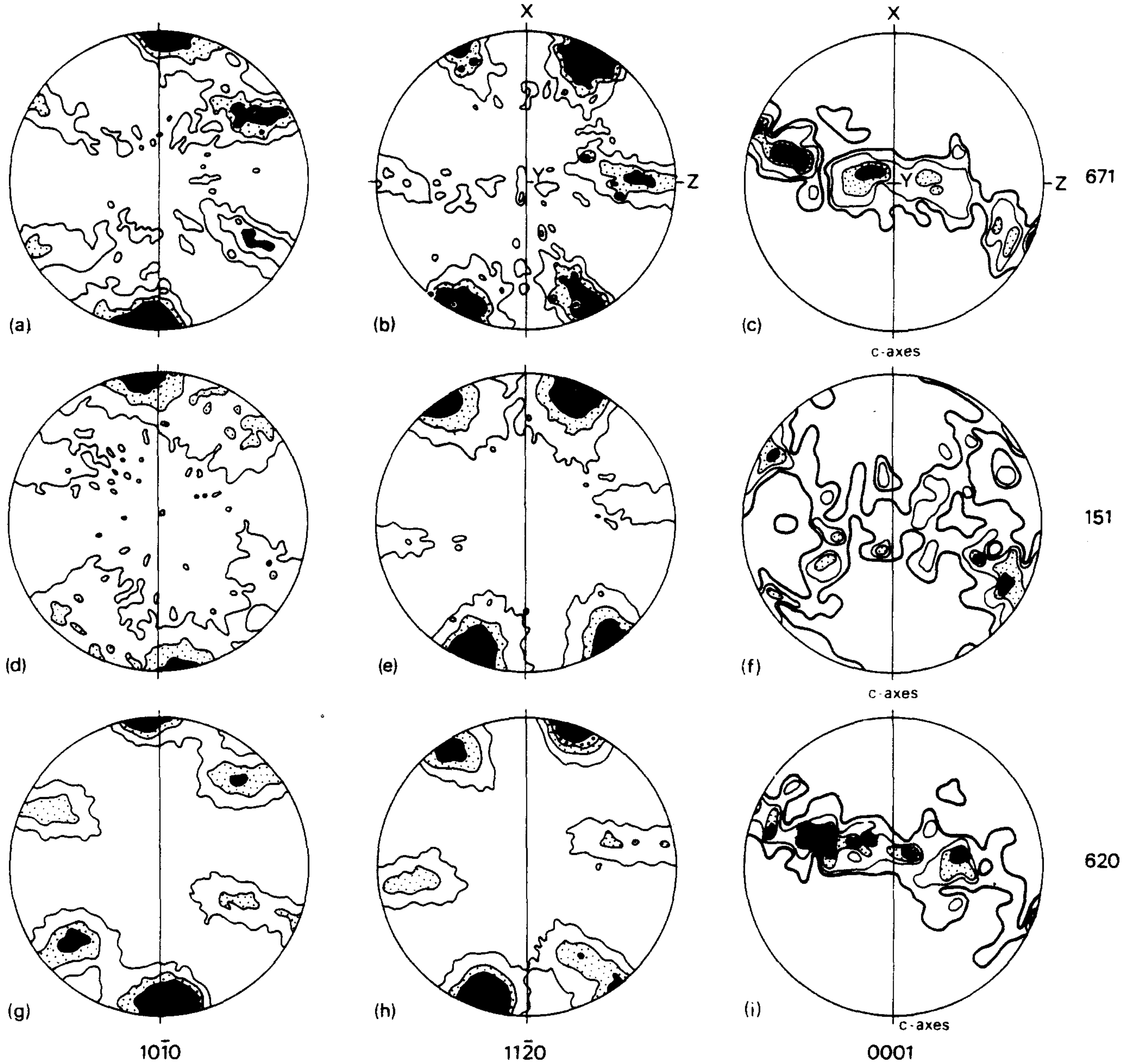

Fig. 12 (After Bouchez *et al.* 1979). Quartz c-axis fabrics from the Himalayan Main Central Thrust (Bouchez & Pecher 1976) exhibit asymmetry which they relate to the macrotectonic sense of shear. These are type I crossed-girdle fabrics except that one arm appears ill defined (compare specimen 151 with 671 or 620). These authors used neutron diffraction to determine other fabric patterns and the a-axis and {10$\bar{1}$0} pole figures are shown. Again these patterns are asymmetric, and they lie asymmetrically inclined to the foliation. Skeletal analysis and the basal trace method give the same answer for the sense of shear when applied to the c-axis fabric of specimen 151.

deformed and recrystallized to produce the volume of quartzite finally examined. Recrystallization and heterogeneous deformation may not succeed in producing a scatter of orientation, sufficient to obliterate the effect of the small starting population. Such a situation seems to have applied in the mylonite studied by Eisbacher (1970). The c-axis fabrics vary from aggregate to aggregate in the specific configuration and orientation of maxima. Combination of these areas by random traversing of thin sections reveals standard crossed-girdle patterns. Asymmetry in these patterns cannot therefore be related directly to the effects of deformation path. Without the detailed microstructural evaluation made by Eisbacher these qualifications would not be recognized.

THE EFFECT OF THE CLOSING STAGES OF DEFORMATION

In major movement zones such as the Moine Thrust Belt in Scotland (Johnson 1957, 1960) or the Seve–Koli thrust–slice complex in Sweden (Williams & Zwart 1977) a substantial deformation history follows the early thrusting events. We therefore turn to the question of what happens to a quartz fabric in a movement zone if the kinematic description of deformation changes during the closing stages of deformation. A simple and interesting case to study is set-up by assuming: (a) constant metamorphic conditions; (b) the same crystal-plastic mechanisms continue to operate throughout deformation; and (c) the rock is subjected to coaxial

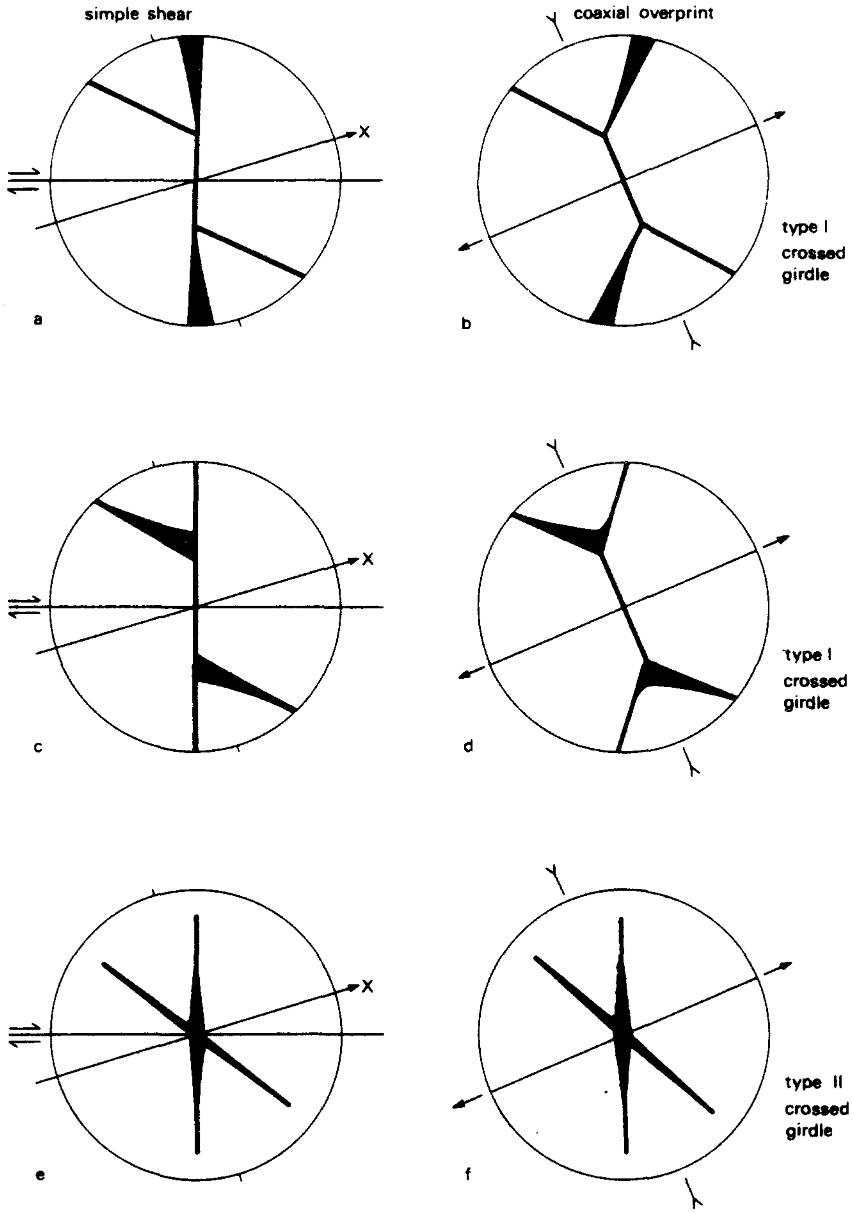

Fig. 13. The effect of coaxial deformation after progressive simple shear will modify the fabric skeleton rapidly, but any overall asymmetry in the orientation distribution may be preserved. Fabric skeletons for two type I crossed-girdle patterns and one type II crossed-girdle are shown (a, c, e) as they would emerge from the simple shear history, and (b, d, f) as they would appear after being modified by a later coaxial overprint, with the strain axes shown. The effect of the closing stages of deformation is an important factor in any fabric analysis.

deformation after early non-coaxial deformation. This compares with the history supposed by Christie (1963) in the Moine Thrust Belt. The late coaxial shortening is envisaged as taking place with the kinematic shortening axis approximately normal to the foliation, and the kinematic extension axis approximately parallel to the stretching lineation formed in the early stages.

Simulations with the Taylor–Bishop–Hill analysis lead to the conclusions:

(a) that asymmetry in the intensity distribution can be preserved and can survive later coaxial deformation to remain as a reasonably persistent indicator that there were early shear movements; but

(b) the fabric skeleton is sensitive to any change in the kinematic description of deformation and pattern elements migrate to reflect the new orientation of the instantaneous stretching axes (Fig. 13). The imposed coaxial deformation results in orthorhombic skeletal outlines (pseudo-orthorhombic symmetry) although the intensity distribution over the fabric skeleton may remain asymmetric.

Clearly any such sensitivity of deformation fabrics to changes in the kinematic description during the waning stages of deformation is a factor which complicates the use of fabric analysis as a practical tool for structural geologists.

THE NATURE OF DEFORMATION IN SHEAR ZONES

There is widespread acceptance of the idea (Ramsay & Graham 1970) that simple shear is prevalent in shear zones. On a larger scale simple shear has been suggested as applying to whole mountain belts, e.g. the Western

Alps (Laurent & Etchecopar 1976). It is interesting to discuss this point.

Experimental attempts to obtain simple shear

Predictions that result from experimental studies are useful because it is difficult to obtain precise information from natural shear zones. However it is difficult to obtain simple shear experimentally.

Rutter & Rusbridge (1977) attempted to study the effect of simple shear on fabric development. Several methods were tried: (a) direct shear tests by introducing a narrow shear zone in the specimen via a specially cut steel jacket; (b) punching an annular shear zone. In both cases the shear zone was only a few grains wide and Rutter & Rusbridge suspected bulk rotation of many grains and found little to suggest any significant component of progressive simple shear in these tests.

Rutter & Rusbridge went on to two-stage tests and found that whereas grain-shape orientation reflected finite strain, the crystallographic fabric responded rapidly to variations in orientation of the incremental strain axes. This study supports the theoretical predictions that fabric asymmetry in nature could result from: (a) a non-random initial fabric; (b) a polyphase deformation history of a variable deformation path; or (c) a non-coaxial deformation history constant in its kinematic description throughout. Only for this last case can fabric asymmetry be related directly to details of the movement picture.

Tullis (1977) performed experiments in which the upper piston punched through the deforming quartzite below. Material was warped up and sheared past the piston as it punched into the specimen. These difficult experiments allowed an approximation to simple shear, but the deformation path was more complicated than progressive simple shear. The c-axis fabrics shown by Tullis are only for a few grains, but it is apparent that the fabric maxima rotate with and track the apparent orientation of the axes of finite strain. No obvious asymmetry exists in the patterns.

Coaxial deformation in shear zones

The preceding results suggest that although the bulk deformation may approximate to simple shear, smaller volumes of the movement zones (such as individual mineral grains, or parts of thrust slices, depending on the scale) are not always automatically subject to the same deformation. There may be a tendency for these smaller volumes to follow coaxial deformation paths, and any such tendency will favour sliding on existing discontinuities. Similarly, sliding on discontinuities will influence the deformation path in the adjacent rock.

Figure 14 illustrates an idealized shear zone in which any increment of deformation is a simple shear, as long

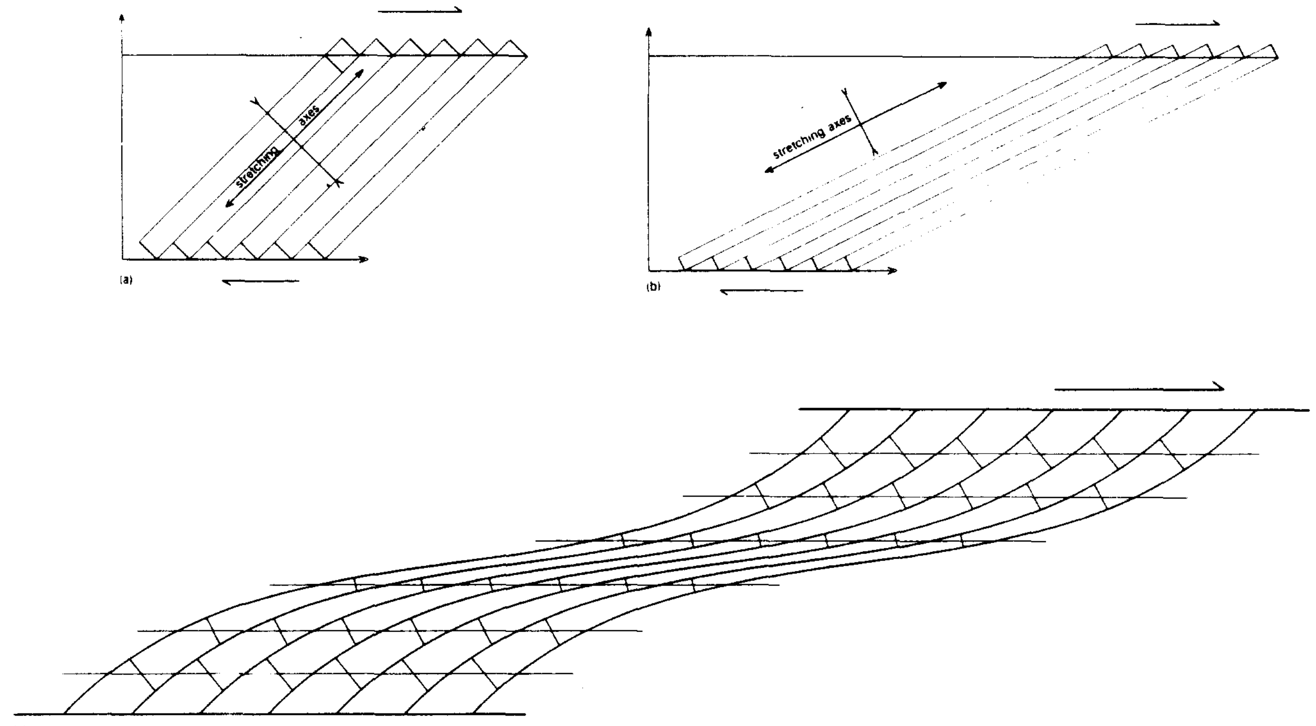

Fig. 14. An idealized shear zone in which any increment of deformation is simple shear as long as a bulk approximation is used. However the role of the discontinuities must be considered. The rock between the discontinuities is not behaving in a passive way, consequently sliding on the discontinuities becomes an important element of deformation. The microlithons between these discontinuities suffer a coaxial deformation history with the extension axis parallel to the foliation plane. In the microlithons the instantaneous stretching axes rotate as the foliation rotates, maintaining parallelism with the finite strain axes. No small element undergoes progressive simple shear at all. Precise description of the scale of consideration is vital when discussing deformation paths undergone by geological bodies. Quartz fabrics developed in such a shear zone would rotate as finite strain increased, apparently tracking the changing attitude of the trajectories of the finite strain axes. Quartz fabrics however only reflect the intracrystalline part of deformation, and cannot be so easily used to infer characteristics of the bulk kinematics.

as a bulk approximation is used. The rock between the discontinuities, however, suffers a coaxial deformation history with the extension axis parallel to the foliation plane. The instantaneous stretching axes rotate as the foliation rotates, maintaining parallelism with the finite strain axes. Sliding becomes less important as deformation goes on, but movement on the foliation planes is nevertheless the factor that allows the overall deformation path to remain rotational.

The idealized model shown in Fig. 14 suggests an explanation for the seemingly contradictory situations represented in Figs. 4(a) and (b). Quartz fabrics formed in the material between the discontinuities will be such that the pattern elements will appear to rotate with increasing finite strain and to track the orientation of the finite strain axes. If the stretching axes are calculated as for a simple shear increment, using the bulk approximation, the fabrics would then appear to ignore the orientation of the kinematic framework. Since the instantaneous stretching axes in the quartz grains are parallel to the finite strain axes, such a conclusion would be erroneous.

Sliding on foliation planes and other discontinuities can be an important part of deformation under certain conditions and under these circumstances the role of discontinuities cannot be ignored. For example, in the zone studied by Carreras *et al.* (1977) although the bulk deformation may have been progressive simple shear, the deformation of the quartz lenses themselves may have remained coaxial, with such non-passive behaviour being made possible by heterogeneous deformation and sliding on discontinuities at the edges of the lenses.

Quartz fabrics reflect only the local deformation, so they cannot be easily used to ascribe characteristics to the bulk movement picture. The question of scale must always be considered.

The argument that simple shear takes place in shear zones

Central to many published studies concerned with quartz fabrics in shear zones are assumptions that progressive simple shear has taken place. These assumptions are based on strain compatibility arguments.

When a ductile fault develops between two bodies of relatively undeformed rock, taking the scale of consideration so as to average out local heterogeneities, there are problems if the overall or bulk deformation does not approximate simple shear. If deformation was in the flattening field for example, material would be extruded from the zone, and a strain accommodating mechanism would be necessary in the surrounding rocks to preserve strain compatibility.

Ramsay & Graham (1970) set out boundary conditions which must apply if every small volume within a shear zone is to undergo progressive simple shear. For macroscopic shear zones there are poor limits to be placed on boundary conditions from geological ebservations. Thus it is difficult to apply precise arguments to qualify the deformation path for any particular hand specimen. For mesoscopic shear zones there is a better chance of being able to qualify boundary conditions during deformation, and in addition progressive changes can often be observed. In consequence much work has been concentrated on narrow ductile shear zones (e.g. Berthé *et al.* 1979, Burg & Laurent 1978, Carreras *et al.* 1977, Van Roermund *et al.* 1979).

It is difficult to model the deformation path convincingly for a small volume within a mesoscopic shear zone (e.g. for an individual quartz grain or a quartz lens). The strain compatibility arguments used by Ramsay & Graham (1970) can be used in ideal cases to argue that small volumes of rock within a shear zone (for which the bulk strain path is progressive simple shear) also suffer progressive simple shear. However for this model to apply the following conditions must be strictly fulfilled:

(1) *The material should behave as a continuum* — however in rocks, discontinuities are the rule not the exception;

(2) *The zone should have perfectly planar walls, and should have infinite areal extent* — deviations from this condition allow deviations of similar magnitude from strict progressive simple shear (e.g. Coward 1977);

(3) *The wall rocks must be undeformed* — this is generally difficult to check, since wall rocks generally lack strain markers that are sufficiently sensitive to record low strains;

(4) *No variation in strain is allowed in any direction parallel to the walls of the zone* — this includes tension gashes or any other regularly repeated variation. Regular variations relax the compatibility requirement substantially. For example, tension gashes are dilation fissures probably formed initially with poles near normal to the maximum compressive stress. Continued deformation is involved between the dilating 'tension gash' and the surrounding material. Overall volume change can remain zero. The existence of these periodic discontinuities allows a great deal of freedom in the deformation path for any volume of rock. A schematic solution to the deformation path in a zone involving gashes (Fig. 15) shows that although deformation is rotational there can be minimum non-coaxiality. No part of the rock need undergo progressive simple shear except on a bulk scale.

(5) *No variation in volume is allowed at any point in the zone* — deformation tends to lead toward dilatancy in several circumstances especially in the presence of pore fluid. Shear zones are expected to provide permeable pathways for the migration of fluid and thus favour solution processes involving volume change.

The scale problem

When attempting to envisage the overall or 'bulk' movement picture for a large body of deformed rock local complications are commonly overlooked. However as pointed out by Sander, the large scale movement

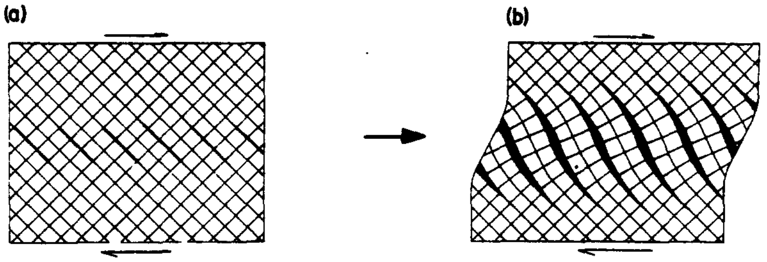

Fig. 15. An idealized sequence showing the development of *en echelon* tension gashes in a shear zone. Although the deformation on the scale of the block is heterogeneous simple shear the existence of periodic discontinuities relaxes the strain compatibility conditions. Small volumes between the gashes do not deform by progressive simple shear. They tend in this example to minimize the degree of non-coaxiality. It is difficult to infer the movement picture for a small volume of rock from the 'bulk' pattern, and vice versa.

picture is the result of relative movements of the component parts of a deforming body, and if discontinuities are present their role cannot be neglected. The point is that while the bulk-strain path may be, for example, a progressive simple shear (as in Fig. 15) the strain path followed by component elements may differ substantially. In Fig. 15 this is made possible by the presence of discontinuities. This problem is generally passed over by modern quartz fabric literature. For example, Laurent & Etchecopar (1976) extrapolated the movement picture inferred from the behaviour of collections of a few hundred crystal grains on the scale of centimetres to the scale of an entire mountain belt. This is the same as assuming no significant complexities in time or space exist for the complete kinematic description of about 100 million years of deformation, for the Western European Alps.

In large scale thrust slice complexes such as the Seve–Koli or the Moine it is possible that the overall or 'bulk' deformation is simple shear. However, the movement picture on a smaller scale may be considerably more complex. For example, thrust slices slide over each other as well as themselves being strongly deformed. Williams & Zwart (1978) likened the situation to overall laminar flow with zones of much higher differential displacement. Although the bulk deformation may add up to simple shear, because the movement picture is internally complex, no hand-specimen sized piece of rock need ever to have undergone progressive simple shear.

CONCLUSIONS

(1) There are fabrics in shear zones with asymmetry that can be related to the deformation undergone. These fabrics may be used to determine the direction of shear, the sense of shear, and in ascribing kinematical significance to lineations. However there are complicating factors because asymmetry can be also related to the existence of a prior fabric (e.g. if a few 'old' grains deformed and recrystallized to produce the volume of quartzite examined), or asymmetry can be related to a deformation history not constant through time in its kinematic description.

(2) Small volumes of rock are only expected to have experienced simple deformation histories (e.g. progressive simple shear at all stages) in rare circumstances. Statements concerning the deformation path must always be cautiously qualified. On the bulk scale deformation may be simple shear, but strain discontinuities offered by discrete movement surfaces in the zone mean that the intracrystalline part of deformation can deviate significantly.

(3) The skeletal outline of a fabric is readily modified by a change in deformation path, because reorientation of the crystal axes takes place in response to the movement picture or kinematic framework at any particular instant. Therefore fabrics measured in major movement zones cannot be directly related to early shear or thrust displacements, as early formed fabrics can be changed during the subsequent deformation history.

(4) Three aspects of the fabrics developed in plastically deformed quartzites seem to be important in the question of the relation between fabric asymmetry and shear sense. These are: (a) the skeletal outline of the fabric pattern; (b) the c-axis fabric projected onto the *XZ* plane of the finite strain ellipsoid; and (c) the a-axis fabric. Several workers have plotted the trace of the basal plane in the *XZ* section of the finite strain ellipsoid, and this is essentially the same as (b). However individual fabric types seem to behave differently in shear zones, and the basal trace method should not be applied indiscriminately.

Acknowledgements —The authors benefited from helpful discussions with Tim Bell, Jean-Luc Bouchez, Anne-Marie Boullier, John Platt, and Ernie Rutter.

REFERENCES

Bell, T. H. & Etheridge, M. A. 1976. The deformation and recrystallisation of quartz in a mylonite zone, Central Australia. *Tectonophysics* **32**, 235–267.

Berthé, D., Choukroune, P. & Jegouzo, P. 1979. Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the South Armorican Shear Zone. *J. Struct. Geol.* **1**, 31–42.

Bossière, G. & Vauchez, A. 1978. Deformation by ductile shear of a granite in the Western Great Kabylia, Algeria. *Tectonophysics* **51**, 57–81.

Bouchez, J.-L. 1977. Plastic deformation of quartzites at low temperature in an area of natural strain gradient (Angers, France). *Tectonophysics* **39**, 25–50.

Bouchez, J.-L. 1978. Preferred orientations of quartz a-axes in some tectonites; kinematic inferences. *Tectonophysics* **49**, T25–T30.

Bouchez, J.-L. & Pecher, A. 1976. Plasticité du quartz et sens de cisaillement dans les quartzites du Grand Chevauchement Central Himalayen. *Bull. Soc. géol. Fr.* **6**, 1375–1384.

Bouchez, J.-L., Dervin, P., Mardon, J. P. & Englander, M. 1979. La diffraction neutronique appliquée à l'étude de l'orientation préfèrentielle de reseau dans les quartzites. *Bull. minéral.* **102**, 225-231.

Burg, J. P. & Laurent, P. 1978. Strain analysis of a shear zone in a granodiorite. *Tectonophysics* **47**, 15–42.

Carreras, J., Estrada, A. & White, S. 1977. The effects of folding on the *c*-axis fabrics of a quartz mylonite. *Tectonophysics* **39**, 3–24.

Christie, J. M. 1963. The Moine thrust zone in the Assynt region, Northwest Scotland. *Univ. Calif. Pubs. geol. Sci.* **40**, 345–440.

Coward, M. P. 1977. Strain within ductile shear zones. *Tectonophysics* **34**, 181-197.

Eisbacher, G. H. 1970. Deformation mechanics of mylonite rocks and fractured granites in Colequid mountains, Nova Scotia, Canada. *Bull. geol. Soc. Am.* **81**, 2009–2020.

Etchecopar, A. 1974. Simulation par ordinateur de la déformation progressive d'un aggrégat polycristallin. Etude du développement de structures orientées par écrasement et cisaillement. Thèse 3ème cycle, Nantes.

Etchecopar, A. 1977. A plane kinematic model of progressive deformation in a polycrystalline aggregate. *Tectonophysics* **39**, 121-139.

Hara, I., Takeda, K. & Kimura, T. 1973. Preferred lattice orientation of quartz in shear deformation. *J. Sci. Hiroshima Univ., ser. C*, **7**, 1-10.

Hudleston, P. J. 1978. Progressive deformation and development of fabric across zones of shear in glacial ice. In: *Energetics of Geological Processes* (edited by S. Saxena & S. Bhattacharji) Springer, Berlin, 121-150.

Johnson, M. R. W. 1957. The structural geology of the Moine thrust zone in Coulin Forest, Wester Ross. *Q.Jl Geol. Soc. Lond.* **113**, 241-270.

Johnson, M. R. W. 1960. The structural history of the Moine thrust zone at Lochcarron, Wester Ross. *Trans. R. Soc. Edinb.* **64**, 139–168.

Kamb, B. 1972. Experimental recrystallization of ice under stress. In: *Flow and Fracture of Rocks* (edited by H. C. Heard, I. Y. Borg, N. L. Carter & C. B. Raleigh) *Amer. Geophys. Union, Geophys. Monogr.* **16**, 211-241.

Laurent, P. & Etchecopar, A. 1976. Mise en évidence à l'aide de la fabrique du quartz d'un cisaillement simple à deversement ouest dans le Massif de Dora Maira (Alpes Occidentales). *Bull. Soc. géol. Fr.* **18**, 1387-1393.

Lister, G. S. & Hobbs, B. E. in press. The simulation of fabric development during plastic deformation and its application to quartzite; the effect of deformation path. *J. Struct. Geol.*

Lister, G. S., Paterson, M. S. & Hobbs, B. E. 1978. The simulation of fabric development in plastic deformation and its application to quartzites; the model. *Tectonophysics* **45**, 107-158.

Lister, G. S. & Price, G. P. 1978. Fabric development in a quartz feldspar mylonite. *Tectonophysics* **49**, 37-78.

Lunardi, L. F. & Baker, D. W. 1975. Determination of movement direction and shear sense in deep-seated thrust zones from mylonites. *Eos. (Trans. Am. Geophys. Union)* **56**, 602.

Nicolas, A. 1976. Flow in upper mantle rocks: some geophysical and geodynamic consequences. *Tectonophysics* **32**, 93–106.

Nicolas, A., Bouchez, J. L., Boudier, F. & Mercier, J. C. 1971. Textures, structures and fabrics due to solid state flow in some European lherzolites. *Tectonophysics* **12**, 55–85.

Nicolas, A., Bouchez, J. L. & Boudier, F. 1972. Interpretation cinématique des déformations plastiques dans le Massif de lherzolites de Lanzo (Alpes piémontaises). *Tectonophysics* **14**, 143–171.

Nicolas, A., Boudier, F. & Bouillier, A. M. 1973. Mechanism of flow in naturally and experimentally deformed peridotites. *Am. J. Sci.* **273**, 853–876.

Nicolas, A., Bouchez, J. L., Blaise, J. & Poirier, J. P. 1977. Geological aspects of deformation in continental shear zones. *Tectonophysics* **42**, 55–73.

Paterson, M. S. & Weiss, L. E. 1961. Symmetry concepts in the structural analysis of deformed rocks. *Bull. geol. Soc. Am.* **72**, 841–882.

Ramsay, J. G. & Graham, R. H. 1970. Strain variation in shear belts. *Can. J. Earth Sci.* **7**, 786–813.

Riekels, L. M. & Baker, D. W. 1977. The origin of the double maximum pattern of optic axes in quartzite mylonite. *J. Geol.* **85**, 1–14.

Rutter, E. H. & Rusbridge, M. 1977. The effect of non-coaxial strain paths on crystallographic preferred orientation development in the experimental deformation of a marble. *Tectonophysics* **39**, 73–86.

Starkey, J. & Sutherland, I. 1978. A reinvestigation of the orientation of quartz in a shear zone from Castell Odair, Scotland. *Can. J. Earth Sci.* **15**, 664–667.

Sylvester, A. G. & Christie, J. M. 1968. The origin of crossed girdle orientations of optic axes in deformed quartzites. *J. Geol.* **76**, 571–580.

Tullis, J. 1977. Preferred orientation of quartz produced by slip during plane strain. *Tectonophysics* **39**, 87–102.

Williams, P. F. 1976. Relationships between axial-plane foliations and strain. *Tectonophysics* **30**, 181-197.

Williams, P. F. 1977. Foliation; a review and discussion. *Tectonophysics* **39**, 305–328.

Williams, P. F. & Zwart, H. J. 1978. A model for the development of the Seve-Koli Caledonian Nappe Complex. In: *Energetics of Geological Processes* (edited by S. K. Saxena & S. Bhattacharji) Springer, Berlin, 169–187.

Van Roermund, H., Lister, G. S. & Williams, P. F. 1979. Progressive development of quartz fabrics in a shear-zone from Monte Mucrone, Sesia-Lanzo zone, Italian Alps. *J. Struct. Geol.* **1**, 43–52.