Journal of Structural Geology, Vol. 15, No. 8, pp. 1055 to 1060, 1993
Printed in Great Britain

0191–8141/93 $06.00+0.00

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SHORT NOTE

Quartz *c*-axis fabrics in deformed conglomerates: some support for a skeletal approach to fabric analysis

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(*Received* 7 *April* 1992; *accepted in revised form* 12 *December* 1992)

Abstract—Preferred orientation patterns of *c*-axes in deformed quartzite rocks are conveniently characterized by (1) their skeletal outline and (2) by the way this skeleton is populated by *c*-axes. It has been recognized that the fabric skeleton principally reflects the kinematics of the flow during at least the later part of the deformation history, whilst the distribution of *c*-axes over the fabric skeleton is less reliable in this respect, because the *c*-axis orientation distribution may be dominated by the effect of an uneven and non-random distribution of *c*-axes prior to deformation. Little evidence has been presented, however, to confirm this interpretation. Quartz *c*-axis fabrics in quartzite pebble conglomerates from southern Spain show variable and incomplete patterns in individual pebbles which, however, all have a similar fabric skeleton, and link to form more complete patterns when *c*-axes from several pebbles are plotted together. In view of the common deformation history of the pebbles within a given sample, the variable and incomplete fabrics in single pebbles can only be explained by the effect of initial non-randomness of *c*-axes prior to deformation. It follows that the *c*-axis orientation distribution in this case bears little relationship with the inferred kinematics of the flow whilst the fabric skeleton shows a consistent relationship with the kinematic framework.

INTRODUCTION

CRYSTALLOGRAPHIC preferred orientation patterns principally develop as the result of reorientation of crystal axes, during crystal-plastic flow, in response to the kinematic framework at any particular instant of the deformation (Lister *et al.* 1978). The resulting fabrics can best be characterized by their skeletal outline (Lister & Williams 1979, Lister & Hobbs 1980), and by the population of *c*-axes distributed over this fabric skeleton. The skeletal outline (Lister & Williams 1979), although mathematically poorly defined, has proven to be a useful concept in fabric studies (e.g. Behrmann & Platt 1982, Law *et al.* 1984, Platt & Behrmann 1986, Schmid & Casey 1986, Vissers 1989), and is described as the set of lines, in a contoured fabric, which delineate the crests and ridges of the contour pattern. This skeleton has geometrical characteristics which are believed to be principally related to the kinematic framework and therefore highly sensitive to changes of the flow path. Lister & Williams (1979) have suggested that irregular, uneven or asymmetric *c*-axis populations of the fabric skeleton may result from an inherited lattice preferred orientation, brought about by major changes of the kinematic framework during deformation, or by other reasons such as when only a few old grains deformed and recrystallized to produce the volume of rock in which the fabric is sampled. There is common agreement about this interpretation, but little evidence exists as yet to demonstrate its validity. Here I analyse quartz *c*-axis fabrics in quartzite pebbles from two samples of an intensely deformed conglomerate. The structural setting, finite strain and microstructures of the samples are considered first. I then proceed to evaluate the *c*-axis fabrics by comparing the *c*-axis distributions and skeletal outlines in single-pebble and cumulative fabric diagrams.

STRUCTURAL SETTING

The samples studied were collected in the Sierra de los Filabres, an E–W-trending mountain range in the Alpine Betic Zone of southern Spain. This mountain range is made up of a number of high-pressure greenschist facies thrust units, separated by a low-angle detachment from mostly low-grade quartzites, phyllites and carbonates (Platt *et al.* 1984, Platt & Vissers 1989). The quartzite pebble conglomerates occur amidst massive arenaceous and quartzitic beds from the basal parts of the Permo-Mesozoic cover sequence of the Nevado-Lubrín unit, one of the deepest tectonic units exposed in the Betic Zone. Structural analyses (Vissers 1981, Bakker *et al.* 1989) have shown that this unit went through a history of multiple folding, under metamorphic conditions changing from blueschist via high-pressure greenschist to low-greenschist facies.

The conglomerates are made up of white-weathering quartzite pebbles in a dark, phyllosilicate-dominated matrix. The quartzite pebbles contain variably small amounts of colourless mica and epidote group minerals. Some pebbles contain small detrital grains of rutile and zircon suggesting that these pebbles are deformed and metamorphosed fragments of quartz-rich sandstone.

Other pebbles with only accessory amounts of mica may have been derived from relatively pure quartz aggregates like vein quartzites. The conglomerates are intensely flattened, with the long axes of the pebbles parallel to a planar matrix schistosity defined by the parallel arrangement of colourless mica, epidote-group minerals and, to a lesser extent, actinolite and chlorite. This schistosity represents the earliest Alpine structure (S_1) recognized in the area. In adjacent micaschists, this schistosity is deformed by younger crenulations and associated crenulation foliations (S_2, S_3) parallel to the axial planes of tens to hundreds of metres scale, open to tight folds. The S_2 and S_3 foliations are oriented at distinct angles to the bedding and bedding-parallel schistosity. The conglomerates are virtually unaffected by these younger deformations, and in few outcrops only is there a weak microfolding of the matrix schistosity. In addition, post-kinematic porphyroblasts of garnet and albite have overgrown this schistosity in some of the samples, while in nearby micaschists these minerals clearly pre-date the S_2 and S_3 foliations, respectively. This observation, and the absence of younger foliations in the conglomerate matrix, suggest that the strains accumulated during these later deformations were mainly taken up by the surrounding micaschists with virtually no imprint on the conglomerates. It follows that the structures and fabrics in the conglomerates are essentially related to the early deformation reflected by the matrix schistosity. The ambient conditions during this deformation have been estimated at pressures in the range 8–11 kbar, at temperatures of 400–450°C, whilst the growth of post-kinematic garnet in the matrix reflects peak temperature conditions around 500°C at decreasing pressures (Vissers 1981, Bakker *et al.* 1989).

FINITE STRAIN

The use of conglomerate pebbles as strain markers involves a number of difficulties, of which inhomogeneity due to different mechanical properties of the pebbles and the matrix is probably the most important one (Ramsay 1967, p. 221). According to Lisle (1977), the harmonic mean of the axial ratios of deformed elliptical markers may reasonably approximate the strain ratio, provided that the following assumptions are valid: (1) the strain ratio is high; (2) the initial axial ratios of the pebbles prior to deformation were small; (3) the long axes of the undeformed pebbles had no preferred orientation; and (4) the strain is homogeneous.

The harmonic means of the pebble axial ratios in XZ sections in most cases exceed a value of 10, such that the requirement of a large strain seems satisfied. However, the initial shape of pebbles is poorly constrained. This may largely be overcome by the inferred high strain ratios. As an example, Lisle (1977) has shown that an initial axial ratio of the pebbles of 3, which is probably a good figure for most quartzite pebble conglomerates (Sneed & Folk 1958), would introduce an error of less than 10% at strain ratios of about 3.5. This error decreases with smaller initial ratios and with higher strains. A more serious problem may be posed by any preferred orientation of the pebbles prior to deformation. There is little constraint on this effect. In one sample, the long axes of the deformed pebbles show highly variable orientations in the XY plane over about 130° around a vague mineral lineation. This may be consistent with a very low initial preferred orientation of the pebbles. The finite strain in this sample according to the harmonic mean method closely approximates axial-symmetric shortening, while an R_f/ϕ_f analysis in the XY plane yields only a slightly higher value of the strain in that plane (Fig. 1). In the other samples, in which the harmonic means of pebble axial ratios suggest strains further away from axial-symmetric shortening, there are no constraints on initial preferred orientation of the pebbles. Finally, the requirement of homogeneity of the strain is probably poorly satisfied in view of the obvious contrast between the quartzite pebbles and the phyllosilicate-rich matrix, although the generally high pebble to matrix ratio exceeding 50 vol % in the samples studied may have led to pebble-dominated bulk rock properties (G. Lloyd personal communication 1992). In any case, inhomogeneity of the deformation principally affects strain estimates for the aggregate as a whole. For present purposes, aiming to constrain the flow of the quartzite pebbles, harmonic means may yield an appropriate estimate of the strain taken up by the pebbles. Strain estimates using harmonic means of pebble axial ratios are shown in Fig. 1 for seven samples, including those of which c-axes fabrics are discussed below (samples V 416 and V 737), and consistently indicate strains in the flattening field.

MICROSTRUCTURES

The microstructures of the pebbles are characterized by equant to slightly inequant quartz grains, with irregular grain boundaries and a rather inhomogeneous grain size distribution (Figs. 2a & b). In most pebbles, variable small amounts of oriented colourless mica define a faint schistosity subparallel to the foliation in the matrix and

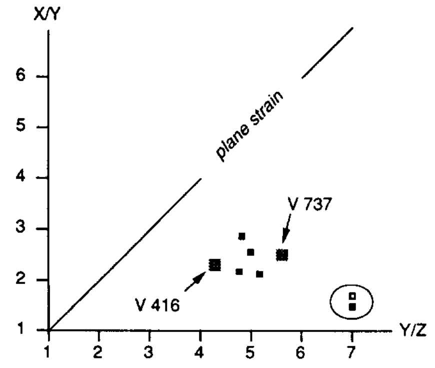


Fig. 1. Flinn diagram representation of strain estimates in the conglomerates using harmonic means. Grey squares, samples of which c-axes fabrics are shown in Fig. 3 (V 416 and V 737). Encircled open and black squares, strain estimate using R_f/ϕ_f method (open), almost identical with estimate using harmonic means (black).

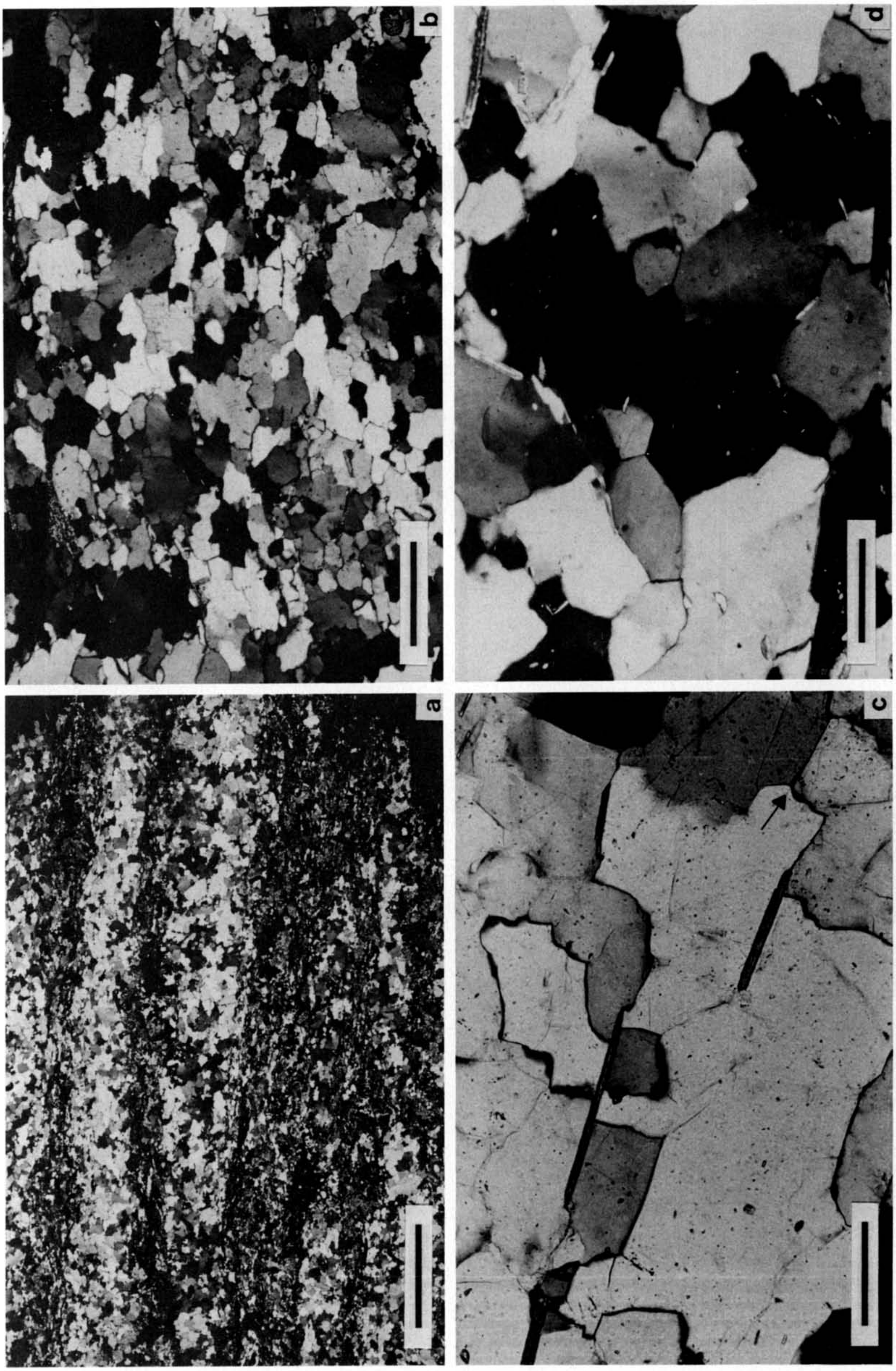
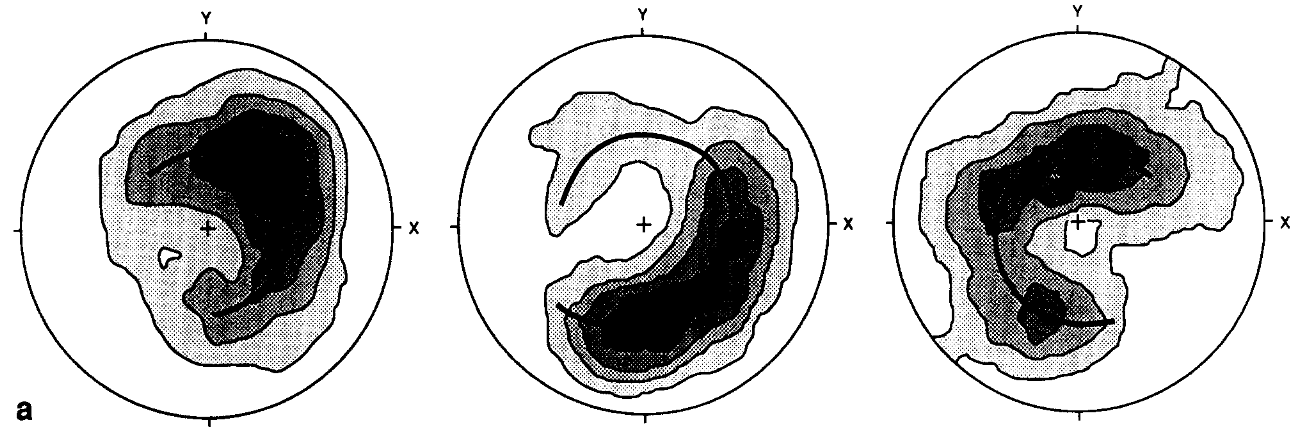


Fig. 2. Microstructure of conglomerates. (a) Microstructure of sample V 737, scale bar = 2.5 mm. (b) Microstructure of sample V 416, pebble 1, scale bar = 500 μm. (c) Detail of microstructure in a quartzite pebble of sample 737, showing quartz grain with curved boundaries concave away from the grain suggesting migration recrystallization towards the centres of curvature; arrow indicates developing triple junction, scale bar = 125 μm. (d) Detail of quartz microstructure in pebble from sample V 416 showing triple junctions as well as intracrystalline deformation features in several of the grains, scale bar = 125 μm.



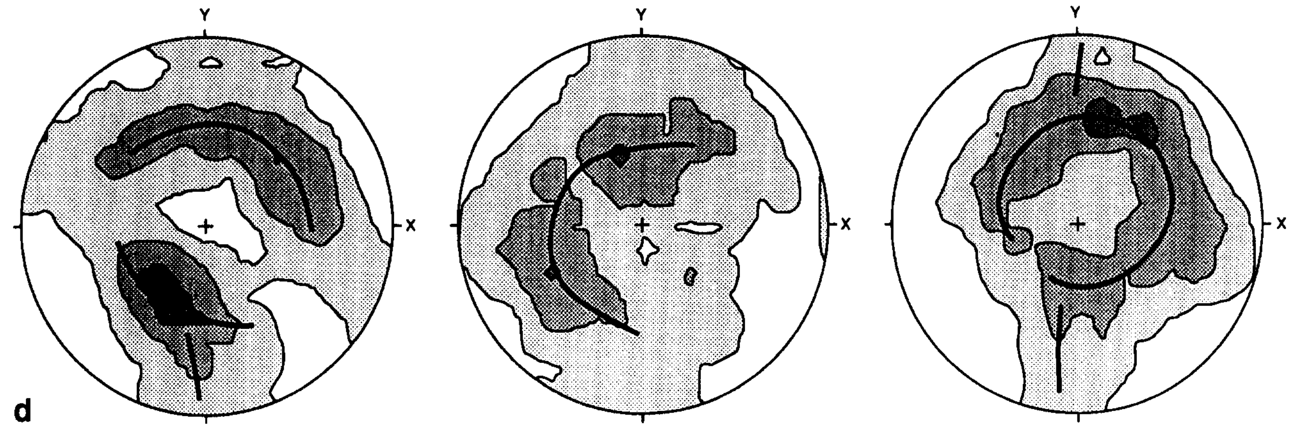
V 737 pebble 1 - 100 c axes

V 737 pebble 2 - 100 c axes

V 737 pebble 3 - 100 c axes

cumulative diagram - 300 c axes in 3 pebbles

synopsis of skeletal outlines



V 416 pebble 1 - 100 c axes

V 416 pebble 2 - 100 c axes

V 416 pebble 3 - 100 c axes

cumulative diagram - 300 c axes in 3 pebbles

synopsis of skeletal outlines

Fig. 3.

surrounding rocks. The mica grains have an obvious effect on the microstructure, in that a tendency exists towards smaller and more homogeneous grain sizes of the quartz at higher contents of colourless mica. The mica grains lie either along quartz grain boundaries or are partially or completely included in quartz (Fig. 2c). Quartz–quartz interfaces commonly are perpendicular to (001) mica interfaces, or are pinned at the ends of mica grains. Quartz grains may meet at triple junctions (Figs. 2c & d), but there is no foam texture of polygonal grains developed. The microstructures clearly indicate a significant contribution of migration recrystallization and grain growth, presumably in response to peak temperature conditions inferred from the growth of post-kinematic garnets in the conglomerate matrix. However, many quartz grains show intracrystalline strain features such as undulatory extinction and broad deformation bands (Fig. 2d), also in grains with curved boundaries suggesting grain boundary mobility. Quartz grains that enclose several mica grains commonly show low-angle kink-type subgrain boundaries separating broad deformation bands. Such low-angle boundaries are often pinned by the included particles, as well as at grain boundary edges. Deformation lamellae rarely occur in grains that also show optically visible subgrains. These grains may represent relic portions of strongly deformed and partially recrystallized original grains, although it remains difficult to exclude that the lamellae formed during weak later deformation. Likewise, the undulose extinction and broad deformation bands reflect slight intracrystalline strains during the waning stages of flattening, or result from weak later imprints: e.g. related to the deformations producing the S_2 and S_3 foliations in the nearby schists.

c-AXIS FABRICS

Quartz *c*-axis fabrics were measured optically with a universal stage, in sections parallel to a weak lineation and perpendicular to the dominant schistosity. For clarity, the fabrics have been rotated such that the pole to the foliation (*Z*) is perpendicular to the plane of the paper, with the weak lineation (*X*) oriented E–W (Fig. 3).

The pebbles show three kinds of *c*-axis distributions: partial small-circle girdle patterns (Fig. 3a, pebbles 1 and 2; Fig. 3d, pebble 2); multiple maximum patterns (Fig. 3a, pebble 3; Fig. 3d, pebble 1); and symmetric small-circle girdle patterns (Fig. 3d, pebble 3). A relatively pole-free area around *Z* is obvious in most single pebble patterns, but the small-circle girdle may be poorly developed. In addition, all fabrics of sample V 416 (Figs. 3d & e) tend to show a weak connecting girdle across *Y*.

From inspection of these fabric diagrams it is clear that the orientation distributions tend to be asymmetric with respect to *X*, *Y* and *Z*, and that the locations of the *c*-axis maxima vary from pebble to pebble, in particular in the case of Fig. 3(a). However, the *c* axes tend to form partial small-circle girdle patterns with skeletal outlines oriented symmetrically with respect to the axes of finite strain. Notably, the only almost complete small-circle girdle distribution occurs in a pebble (Fig. 3d, pebble 3) which contains large amounts of fine-grained mica, rutile, opaques and rounded zircons suggesting derivation from a siliciclastic sandstone. With this exception, however, the cumulative diagrams (Figs. 3b & e) show a much better defined small-circle girdle than the single-pebble diagrams, and the *c*-axes orientation distributions in these cumulative diagrams have a much more pronounced symmetry with respect to the finite strain. The cumulative diagrams more clearly show two well-known fabric patterns, namely a small-circle distribution around *Z* and a weak cross-girdle distribution (Figs. 3b & e, respectively).

DISCUSSION AND CONCLUSIONS

Two types of processes may produce lattice-preferred orientation patterns in a deforming rock mass: processes involving lattice reorientation during crystal-plastic deformation; and processes associated with syntectonic and annealing recrystallization (Tullis 1977). The characteristics of the cumulative *c*-axis patterns and the obviously high strains of the pebbles justify interpretation in terms of crystal plasticity. However, the ample evidence for migration recrystallization and grain growth requires re-evaluation of the effect of these processes on fabric. In this context it is emphasized that even the highly asymmetric orientation distributions show a distinct tendency to form small-circle girdle outlines. In addition, the variably oriented *c*-axis patterns of single pebbles combine in the cumulative diagrams to more complete small-circle girdles symmetrically related to the axes of finite strain. This is even more obvious when inspecting the skeletal outlines of the fabrics which, though incomplete, all approach a same small circle centred around *Z* (Fig. 3c) and, in sample 416, a connecting girdle normal to *X* (Fig. 3f). It is difficult to conceive how recrystallization alone could exert an orienting control leading to these characteristics.

Fig. 3. Quartz *c*-axis fabrics from the two conglomerate samples, with skeletal outlines. (a) *c*-axis fabrics of three pebbles in sample V 737. (b) Cumulative *c*-axis pattern of sample V 737. (c) Synoptic diagram showing fabric skeletons of individual pebbles (black) and cumulative fabric (grey) in sample V 737. (d) *c*-axis fabrics of three pebbles in sample V 416. (e) Cumulative *c*-axis pattern of sample V 416. (f) Synoptic diagram showing fabric skeletons of individual pebbles (black) and cumulative fabric (grey) in sample V 416. All fabrics contoured according to Kamb (1959) at 2, 4, 6 and 8 times standard deviation of number of points (E) expected to fall within counting circle (A). $E = 8.3$ and $A = 8.3\%$ for single-pebble diagrams (a & d); $E = 8.7$ and $A = 2.9\%$ for cumulative fabric diagrams (c & e).

The *c*-axis distributions in the cumulative fabric diagrams and the skeletal outlines of all of the fabric patterns are consistent with Taylor–Bishop–Hill simulations of fabric development in coaxial flattening (Lister *et al.* 1978, Lister & Hobbs 1980), though *a*-axis fabrics and an analysis of slip systems are needed to confirm this fully. The symmetry of the *c*-axis orientation distributions and skeletal outlines in the cumulative diagrams, and the coincident orientations, in both samples, of the fabric symmetry axes with the axes of finite flattening suggest largely coaxial deformation during at least the later stages of the deformation history (Lister & Hobbs 1980). Whether the deformation was also coaxial during earlier parts of the deformation history is principally unknown. However, alternative two-stage histories involving, for example, two mutually perpendicular plane deformations to account for the finite flattening strain cannot explain the variable oblique orientations of the *c*-axis maxima. Provided that the deformation histories of the quartzite pebbles within a conglomerate sample were essentially similar, such changes of the kinematic framework would necessarily lead to identical single-pebble patterns. Therefore, irrespective of the uncertainties regarding the flow path during these earlier stages, it seems unlikely that the variably oriented maxima result from major changes of the kinematic framework only. A more plausible interpretation, therefore, is that the pebble already had non-random *c*-axis orientation distributions before deformation of the conglomerates, either as a result of deformation in the source rock, or due to an initially small population of large oriented grains which during deformation recrystallized to produce the sampled grain population; for example in the case of pebbles representing detrital fragments of vein quartzite.

The above analysis suggests that the variable orientations of the *c*-axis maxima in the different pebbles was primarily caused by non-randomness of the *c*-axis populations before deformation. The cumulative fabric patterns are less ambiguous, in that they show more even and complete orientation distributions, presumably because the allied population of initial orientations better approached randomness. Nevertheless, the skeletal outlines of the single-pebble fabrics are virtually coincident and all suggest coaxial deformation in the flattening field consistent with the estimated finite strain. This justifies the conclusion that kinematic interpretations of *c*-axis orientation distributions may be ambiguous, and that the skeletal outline is a much more reliable tool to infer the kinematics of the flow than the *c*-axis distribution and orientation of *c*-axis maxima.

Acknowledgements—John Platt and Gordon Lister are kindly thanked for discussion at a very early stage of this study. I also thank Gordon Lister and Geoff Lloyd for helpful reviews.

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