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Relationships between strain and quartz crystallographic fabrics in the Roche Maurice quartzites of Plougastel, western Brittany

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Abstract—An integrated microstructural and petrofabric study of the plastically deformed and partially recrystallized Roche Maurice quartzites of Plougastel, western Brittany, has revealed a clear correlation between the pattern of *c*-axis fabrics displayed by detrital quartz grains and the symmetry of the calculated strain ellipsoid. In specimens with flattening ($k = 0$) strains, *c* axes lie on a small circle girdle (opening angle 28–42°) centred about the principal finite shortening direction (Z). For specimens that exhibit approximate plane strain ($k = 1$), cross-girdle *c*-axis fabrics consisting of a small circle girdle centred about Z and connected through the intermediate principal extension direction (Y) were detected.

Within individual specimens *c*-axis fabrics of syntectonically recrystallized new quartz grains within the matrix are similar to those of detrital quartz grains. *c* axes of new grains located within the relatively undeformed sections of the host detrital grains are commonly orientated at angles between 10 and 40° to the host *c* axis and are, in addition, statistically orientated at a higher angle to Z than their host *c* axes. These relationships are interpreted as indicating that both host grain control and the local strain (and/or stress) field may have influenced the process of recrystallization; the relative influence of these factors is, however, unknown.

Microstructural and petrofabric studies indicate that the Roche Maurice quartzites have been subjected to essentially coaxial strain histories. The role of syntectonic recrystallization in facilitating continued plastic deformation in quartzites subjected to such strain histories is considered.

INTRODUCTION

IT HAS long been known that in tectonic belts where there is evidence for the rocks having been plastically deformed, quartzites exhibit many distinctly different types of preferred crystallographic orientation. Theoretical studies (e.g. Lister *et al.* 1978, Lister & Paterson 1979, Lister & Hobbs 1980) have indicated that the development of crystallographic fabrics in quartzites during plastic deformation involving intracrystalline glide is governed by three main factors: (1) the strain path or kinematic framework, (2) the magnitude and symmetry of finite strain and (3) the particular combination of crystallographic glide systems active during deformation.

The importance of these factors in controlling fabric development has been confirmed by experimental studies. For technical reasons the experimental deformation of quartzite has been almost exclusively confined to the study of coaxial strain paths, the majority of experiments (e.g. Green *et al.* 1970, Tullis *et al.* 1973) involving flattening ($k = 0$) deformation, whilst plane strain ($k = 1$) deformation has only been achieved (Tullis 1977) under unusual experimental conditions. An example of the theoretical relationships between strain symmetry and the development of quartz *c*- and *a*-axis fabrics for one particular combination of glide systems operating under coaxial deformation is illustrated in Fig. 1.

Direct correlation between experimentally produced fabrics and natural fabrics is made difficult by the many unknown quantities which may be involved in natural deformation. Prominent amongst these are strain path and the magnitude, symmetry and orientation of strain. Only in tectonites where strain markers, such as deformed detrital grains, have been preserved may an attempt be made (e.g. Marjoribanks 1977, Bouchez 1977, Miller & Christie 1981, Law *et al.* 1984, Price 1985) to correlate crystallographic fabrics with quantitatively determined strains. However, few such detailed studies have been attempted and, in particular, very few examples of *c*-axis fabrics from tectonites exhibiting flattening strains have been recorded. This is unfortunate because in order to make any meaningful comparison between quartz fabrics produced in experimental flattening deformation and those fabrics observed in natural tectonites it is essential that materials exhibiting similar strain symmetries be studied.

This paper reports the results of microstructural and petrofabric analysis of deformation features developed in the Roche Maurice quartzites of western Brittany. Within these plastically deformed L–S and S tectonites the preservation of detrital grain shapes has facilitated the quantitative analysis of bulk strain symmetry and magnitude. In addition, evidence will be presented which indicates that these tectonites have been subjected to approximately coaxial strain paths. The quartzites therefore provide an excellent opportunity to study the relationships between strain and crystallographic fabric development in naturally developed tectonites, and to compare these relationships with theoretical and experimental studies.

GEOLOGICAL SETTING

The specimens described in this paper have been collected from the Roche Maurice quartzites, which

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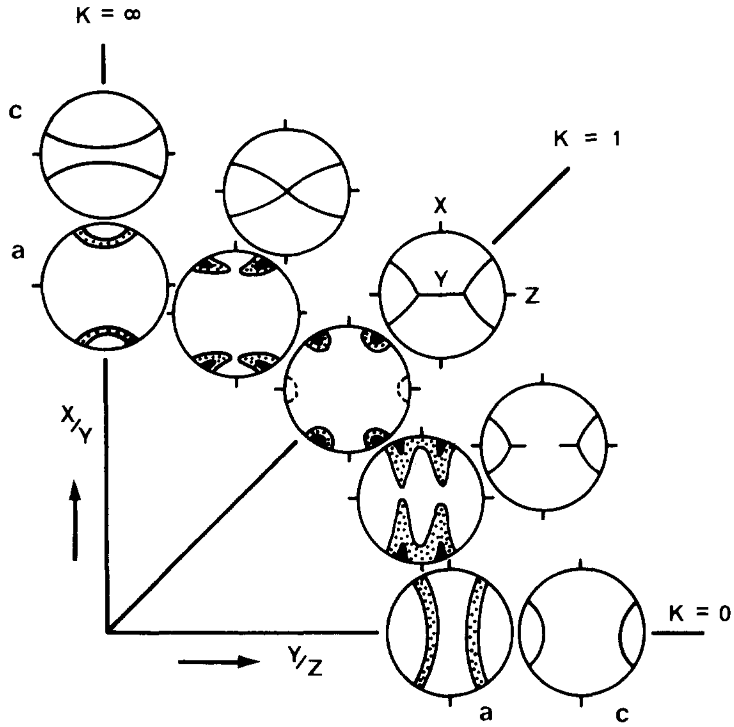


Fig. 1 Theoretical relationships for coaxial deformation, between strain symmetry and quartz *c*- and *a*-axis fabrics, represented by fabric skeletons, and contours, respectively. Adapted from Schmid & Casey (in press), and based on a Flinn Plot.

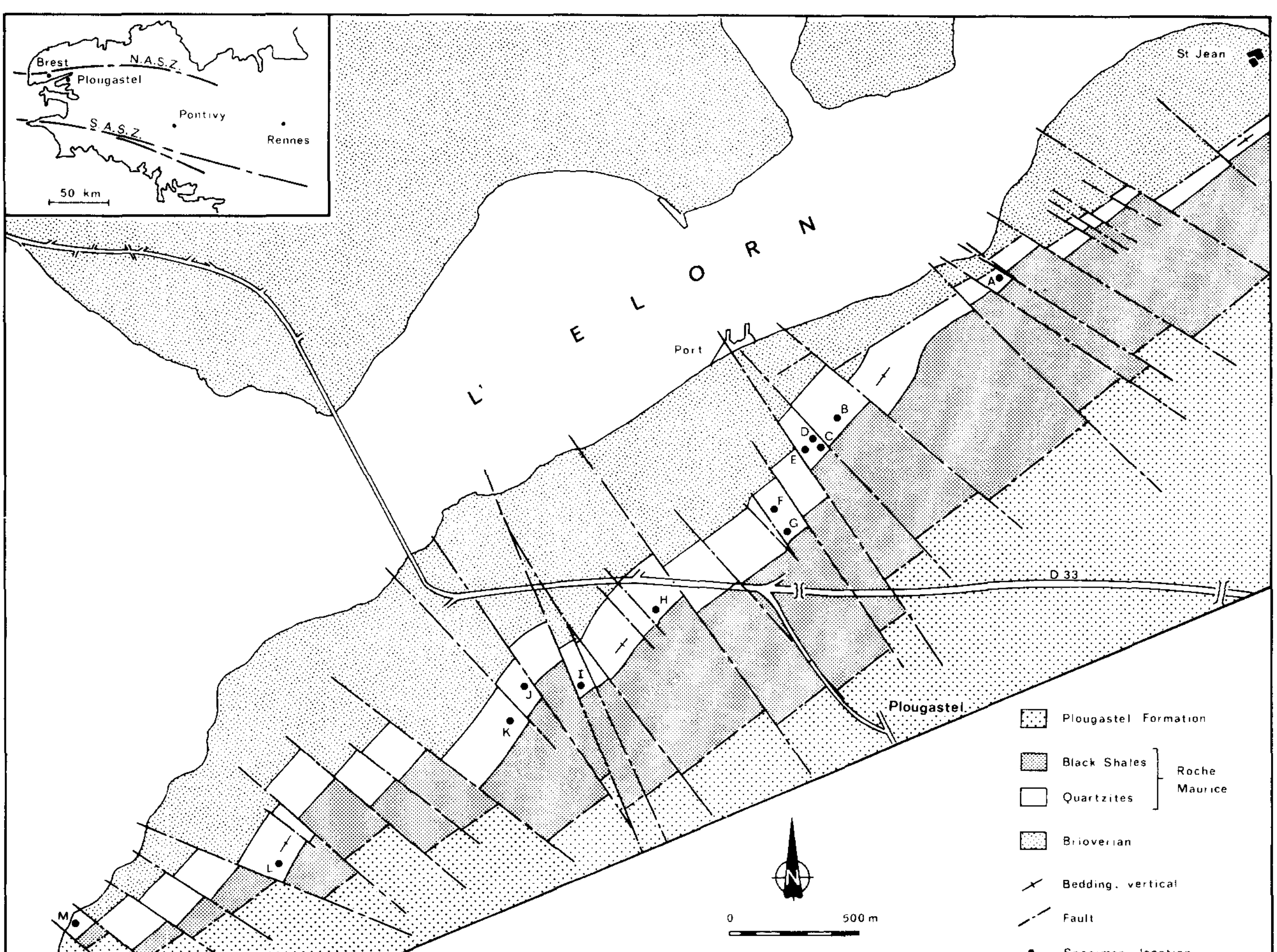


Fig. 2. Specimen locations within the Roche Maurice quartzites near Plougastel, western Brittany. Inset map shows the geographical location of the Plougastel region. N.A.S.Z., North Armorican Shear Zone; S.A.S.Z., South Armorican Shear Zone.

outcrop along the southern bank of the Elorn Estuary in the Plougastel region of western Brittany (Fig. 2). The quartzites are of Arenig age (Chauris & Hallégouët 1973) and are considered (Bishop *et al.* 1969) to be the lateral equivalent of the Gres Armoricain (lower Ordovician) quartzites which are extensively developed throughout the Armorican Massif to the southeast of the Plougastel area. Regionally the quartzites rest upon Brioverian (late Proterozoic) turbidites which crop out along the banks of the Elorn (Fig. 2). Both structurally and stratigraphically the Roche Maurice quartzites are the lowest member of a sequence of Palaeozoic shelf sediments which are exposed south east of the Elorn.

The quartzites are locally folded and exhibit a penetrative cleavage of variable intensity which fans, in a convergent pattern, about the hinge surfaces of minor folds. From studying the vergence of minor folds, bedding plane dips and younging directions in the quartzites, Renouf (1965) concluded the Roche Maurice is situated on the vertical, SE limb of an anticline arching over the Elorn to the NW (Fig. 2) and containing Brioverian rocks in its core. The fold, which has been mapped by Chauris & Hallégouët (1973) as closing to the ENE, 18 km to the ENE of Plougastel, was estimated to have an amplitude of at least 2000 m. This major fold, together with its associated minor structures which are described in this paper, is considered (Law 1981a) to have been formed during the early (Bretonic) stages of the Hercynian Orogeny.

Minor fold hinges within the Roche Maurice quartzites trend NE–SW, and are commonly either horizontal or plunge towards the NE at angles of up to 30° (Fig. 3). Bedding–cleavage intersection lineations (Fig. 3) are parallel to local fold hinges. Minor fold hinge planes in general strike ENE–WSW; whilst the majority dip at 30° NNW, dips as low as 14° and as high as 60° towards the NNW have been observed at some exposures. A considerable variation in minor fold interlimb angle was detected during mapping. In general, the thicker (1–2 m) quartzite units are deformed (e.g. loc. L, Fig. 2) into low amplitude folds of large (130–160°) interlimb angle whilst the thinly bedded (20–40 cm) quartzites are more tightly folded (e.g. Fig. 4) with interlimb angles varying from 60 to 90°. The most intensely developed penetrative cleavage was always observed in the more thickly bedded quartzites.

It has proved difficult to estimate the metamorphic grade of these essentially monomineralic rocks. From a study of chloritoid–illite and albite–chlorite–illite assemblages within the Ordovician and Devonian black shales of the Plougastel area, Paradis *et al.* (1983) have estimated palaeotemperatures of approximately 280°C. Within the phyllosilicate rich Brioverian turbidites located adjacent to the Roche Maurice quartzites (Fig. 2), syntectonic mineral assemblages are clearly indicative of greenschist facies metamorphism (Law 1981a). Recent whole rock K–Ar dating (Law unpublished data) has yielded an early Hercynian age (337 ± 12 Ma) for metamorphism of these late Proterozoic sediments.

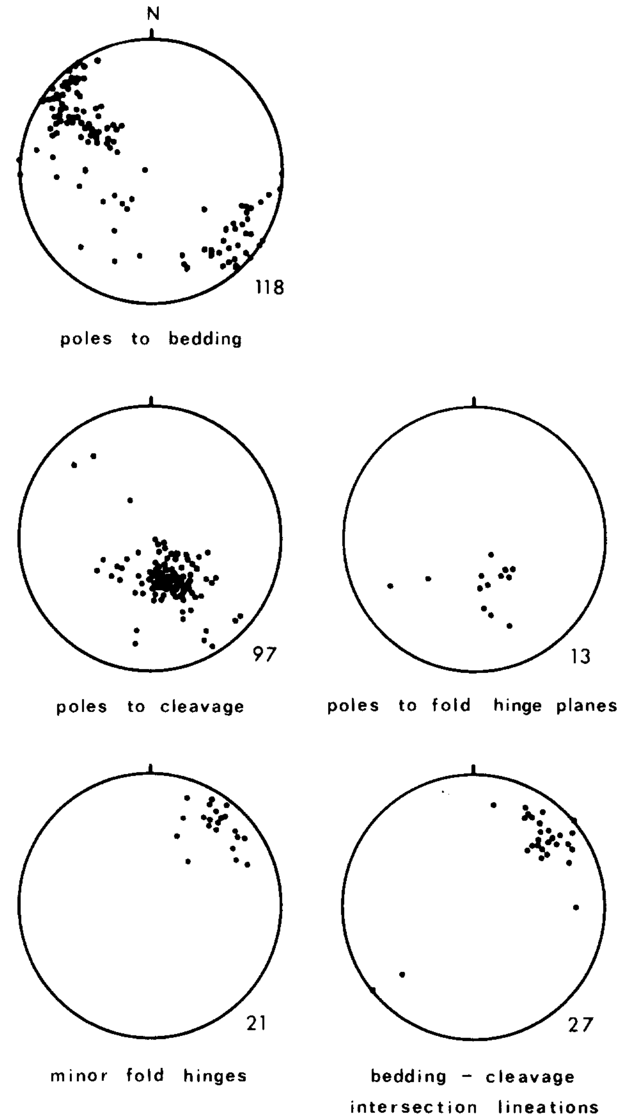


Fig. 3. Basic field data from the Roche Maurice quartzites.

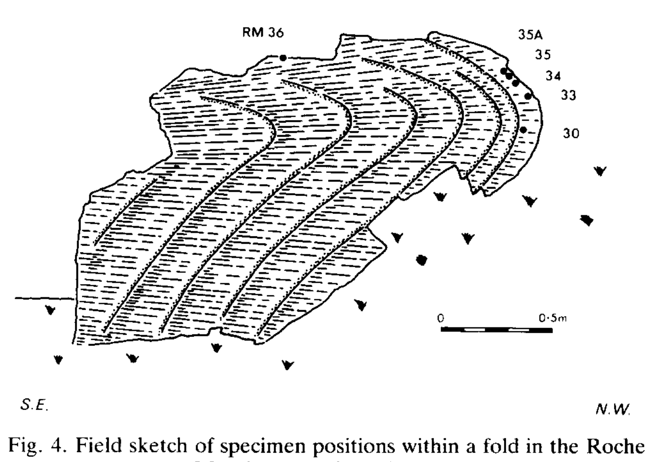


Fig. 4. Field sketch of specimen positions within a fold in the Roche Maurice quartzite at Loc. A.

SPECIMEN LOCATION

A marked variation (both from outcrop to outcrop and, to a lesser extent, from bed to bed) in intensity of penetrative cleavage is detected within the Roche Maurice quartzites. In addition, a considerable variation in macroscopic grain shape fabric is also observed, the quartzites ranging from L–S to S tectonites. A suite of oriented quartzite specimens spanning this deformation spectrum has been collected. With only one exception (specimen RM 36), the linear element of the grain shape fabric was always observed to be aligned parallel to the bedding–cleavage intersection lineation.

Sampling locations are indicated in Fig. 2, and individual specimens collected from these locations are listed in Table 1. At location A (Fig. 2) a series of weakly cleaved specimens has been collected from a single quartzite bed around a single minor fold (Fig. 4). Similarly at location C, a specimen (RM 37) of cleaved quartzite has been collected from the long limb of an asymmetric, NW verging minor fold. At the other sampling locations folds, when present, are generally developed on a scale larger than that of individual outcrops. The angles (α) between bedding and cleavage (measured in the calculated fold profile plane) are listed, for individual specimens, in Table 1.

MICROSTRUCTURE

In thin sections cut from specimens (RM 2 and 6) which exhibit no penetrative cleavage, the quartzites are seen to be composed of a compact aggregate of 0.15–0.3 mm detrital grains (Fig. 5a) whose aspect ratios range between 1:1 and 3:1. A statistical (Rf/ϕ) analysis of these grains (Law 1981a) failed to reveal any convincing preferred orientation of long axes in sections cut either parallel or perpendicular to bedding. Weak undulose extinction is displayed by some grains, and

Table 1. Angles (α) between bedding and cleavage measured in the calculated fold profile plane for individual quartzite specimens from localities indicated in Fig. 2

Location	Specimen	α
A	RM 30	90°
	33	63°
	34	50°
	35	45°
	35A	38°
	36	10°
B	27	50°
C	37	50°
D	26	86°
E	1	90°
F	20	?
G	19	90°
H	2	—
I	6	—
J	8	88°
K	10	90°
L	12	90°
M	14	?

grain boundaries of all orientations are commonly lobate (Fig. 5b). The random orientation of these lobate boundaries argues against a pressure solution origin for their formation. Alternatively they may be interpreted as indicating strain induced grain boundary migration (Hutchinson 1974). Such lobate boundaries between detrital grains are rarely observed in the more highly deformed Roche Maurice quartzites, possibly indicating that adjacent grains have acquired a similar dislocation density and that therefore there is no volume driving force (Nicolas & Poirier 1976, p. 167) for grain boundary migration.

In specimens with a weak penetrative cleavage, the detrital quartz grains are observed, in sections cut perpendicular to cleavage, to be elongate with a preferred alignment which defines the foliation in the rock (Figs. 6 and 7). Undulose extinction is commonly observed within these flattened detrital grains. Deformation bands, whose boundaries may be aligned either parallel or oblique to the foliation trace, are developed within some of the more elongate grains. At the margins of these grains patchy extinction suggesting the formation of subgrains is observed, whilst recrystallization at the detrital grain boundaries has led to the formation of small (50 μm), fairly equant new quartz grains (Fig. 8); this is the core and mantle structure of White (1976). Recrystallized grains are less commonly observed in the interior of the host detrital quartz grains. A small, but unquantified, element of pressure solution is indicated within these rocks by the presence of rare quartz – white mica beards aligned parallel to the foliation trace on the margins of a few of the smaller (<0.24 mm) detrital quartz grains.

In the more intensely cleaved quartzites an increase in the volume of new (recrystallized) quartz grains at the expense of old (detrital) grains is observed with increasing foliation intensity. In sections cut perpendicular to foliation the foliation trace is clearly defined by a preferred alignment of detrital quartz grain long axes. These grains (with aspect ratios commonly between 2:1 and 5:1) are often separated by a matrix of small (approximately 50μm), fairly equant recrystallized quartz grains (Fig. 8a). Recrystallized grains are also recorded within some of the detrital grains, being particularly common along deformation band boundaries aligned parallel to the foliation trace. Locally, continued recrystallization along these boundaries has resulted in the separation of moderately flattened detrital grains into highly elongate relic grains (ribbon grains with aspect ratios of commonly 10:1), separated by small new quartz grains. These particular ribbon grains clearly do not, necessarily, reflect high strains. Less commonly, ribbon-like relic quartz grains, which may reflect high strains, are observed to wrap around more equant detrital quartz grains (Fig. 8b).

Within all the deformed quartzites, a few detrital quartz grains are always observed in sections cut perpendicular to foliation, to display anomalously globular outlines (aspect ratios <2:1) in relation to their more elongate neighbouring grains (Figs. 5d and 8b). These

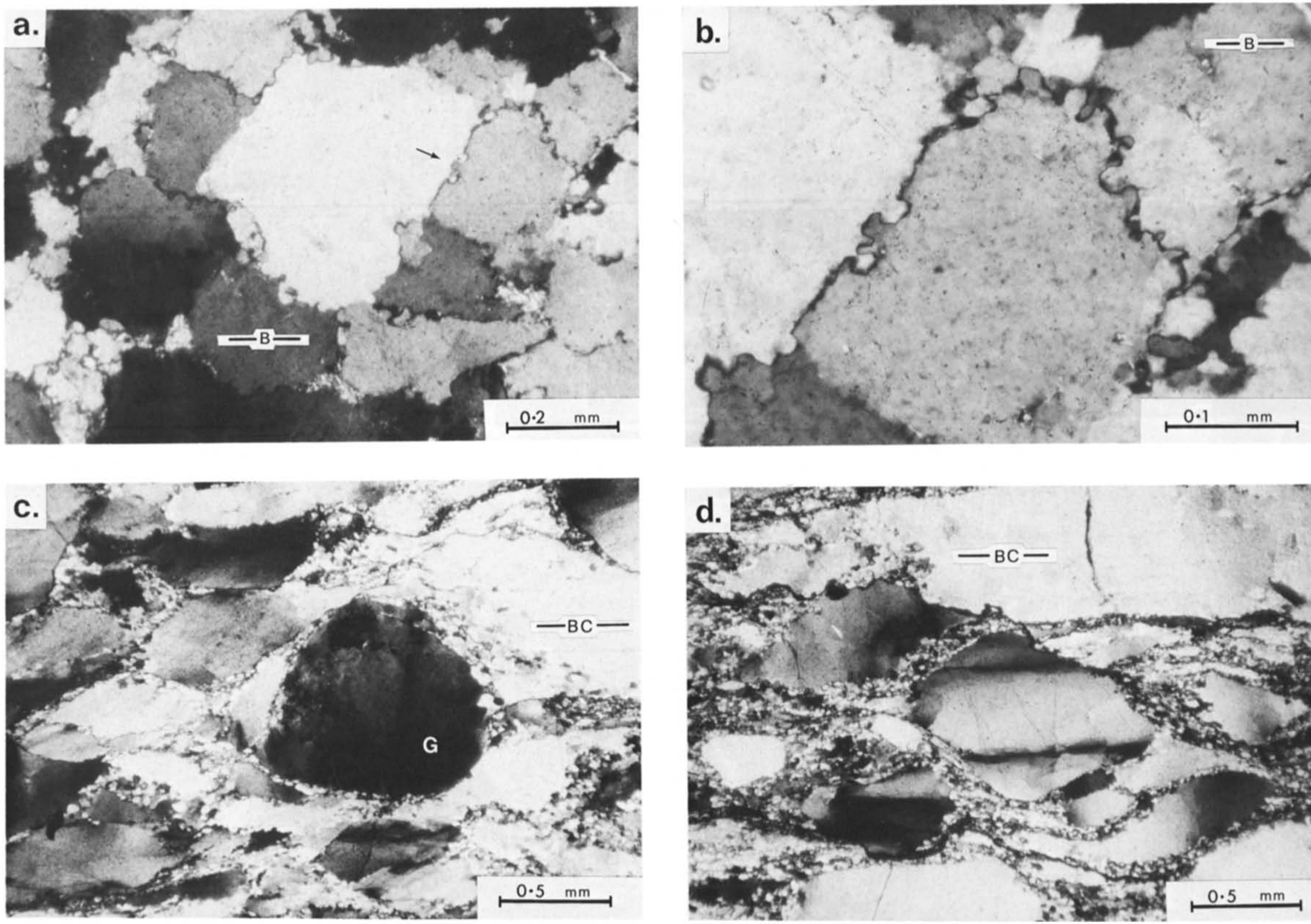


Fig. 5. Photomicrographs of Roche Maurice quartzite. (a and b) Uncleaved quartzite (specimen RM 2) cut perpendicular to bedding. Note the pronounced lobate boundaries of detrital grains. (c) Globular detrital quartz grain (G) surrounded by more highly deformed detrital grains (specimen RM 12); the *c* axis of the globular grain is orientated perpendicular to cleavage. Note recrystallization at detrital grain boundaries. (d) Globular detrital quartz grain with deformation bands aligned parallel to cleavage trace. B, bedding trace; BC, bedding cleavage intersection lineation.

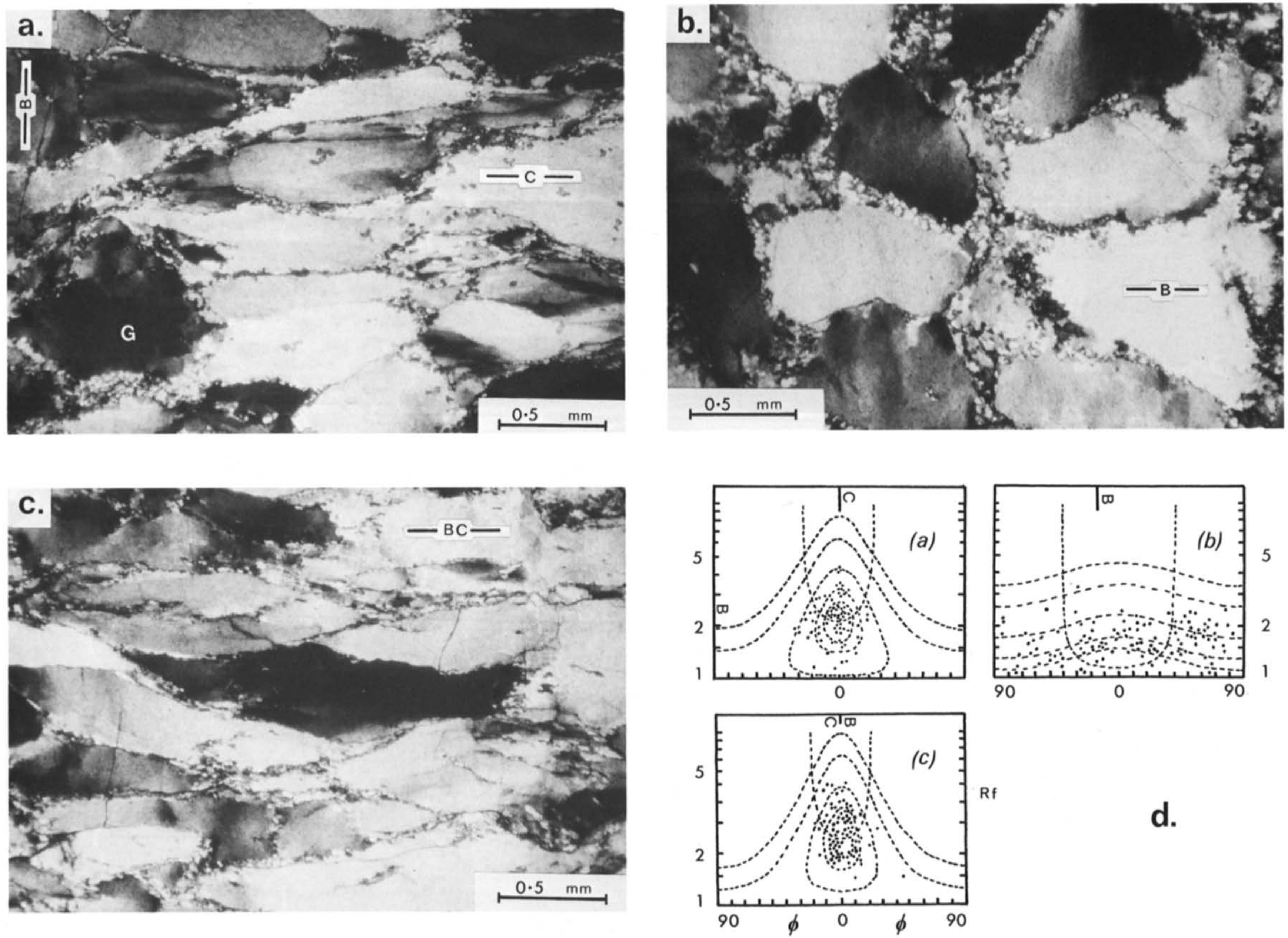


Fig. 6. Thin sections of an S tectonite (Specimen RM 12). (a) Perpendicular to cleavage and perpendicular to bedding – cleavage intersection. (b) Parallel to cleavage. (c) Perpendicular to cleavage and parallel to bedding – cleavage intersection. Aspect ratios (*Rf*) and orientations (ϕ, in degrees) of long axes of detrital quartz grains within these sections are illustrated in (d). B, bedding trace; C, cleavage trace; BC, bedding–cleavage intersection.

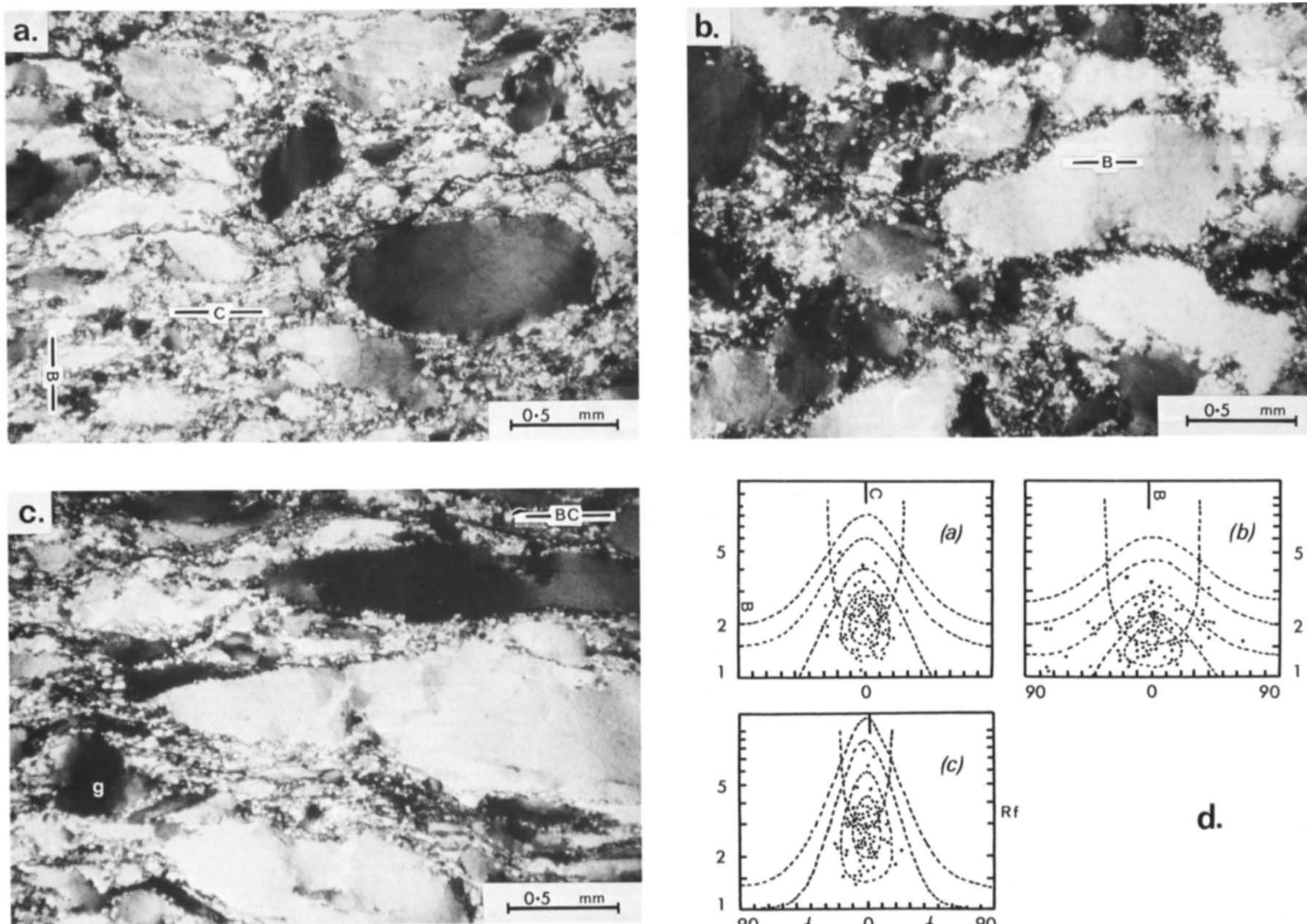


Fig. 7. Thin sections of an approximate L–S tectonite (specimen RM 1). (a) Perpendicular to cleavage and perpendicular to bedding – cleavage intersection. (b) Parallel to cleavage. (c) Perpendicular to cleavage and parallel to bedding–cleavage intersection. Rf/ϕ plots of deformed detrital quartz grains within these sections are illustrated in (d). B, bedding trace; C, cleavage trace; BC, bedding–cleavage intersection.

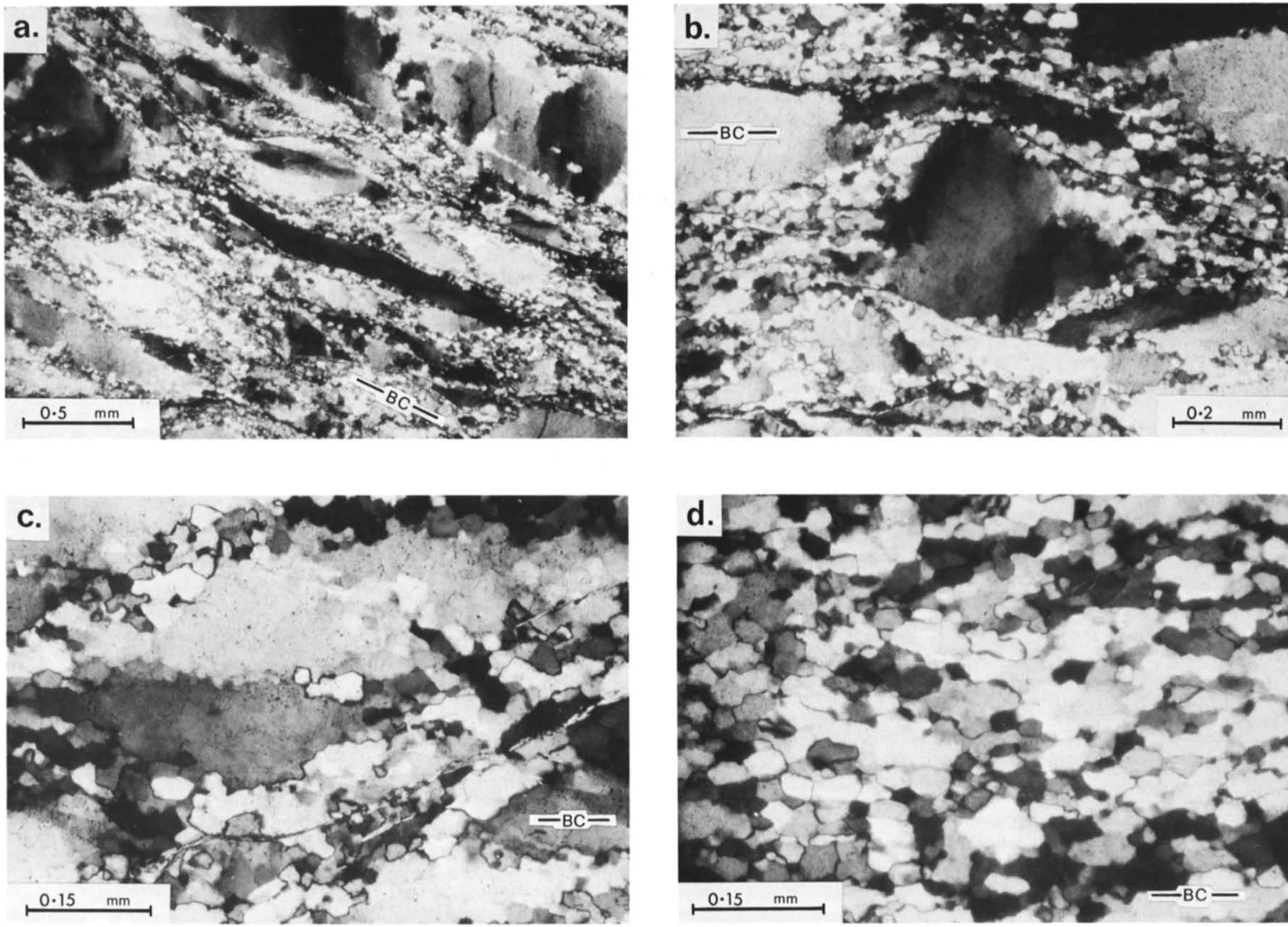


Fig. 8. (a) Ribbon grain aligned parallel to cleavage (BC) in specimen RM 1. Note deformation bands orientated oblique to cleavage trace in larger relic detrital grains. (b) Globular relic detrital grain (in specimen RM 1) with deformation bands orientated perpendicular to cleavage (BC). Ribbon grains wrap around these globular grains. (c) Widespread recrystallization (in specimen RM 37) at relic detrital grain margins and also along deformation band boundaries within the relic grains. (d) Complete recrystallization of quartz in specimen RM 20. Note preferred alignment of new grains parallel to cleavage trace (BC) in this section which is cut perpendicular to cleavage and parallel to bedding–cleavage intersection (BC).

'low strain' detrital grains represent less than 5% of the total number of detrital grains observed within any thin section. In the more deformed quartzites, highly strained detrital quartz grains often wrap around these globular grains (Fig. 8b).

Complete recrystallization of quartz has been noted within two specimens (RM 20 and 36) of cleaved quartzite, these specimens being composed of a fine grained (approximately 50 μm) aggregate of equant and inequant new quartz grains (Fig. 8d).

STRAIN ANALYSIS

The plastically deformed detrital quartz grains observed in these specimens have been used by Law (1981a,b) to quantify the bulk strain associated with penetrative cleavage development. Three mutually perpendicular thin sections were prepared from each specimen: (A) perpendicular to cleavage and perpendicular to bedding–cleavage intersection lineation, (B) parallel to cleavage and (C) perpendicular to cleavage and parallel to bedding – cleavage intersection lineation.

A simple two-dimensional strain analysis, using a modified version of the Rf/ϕ method of Dunnet (1969), was carried out on each thin section; the orientations and aspect ratios of a minimum of one hundred detrital quartz grains being measured in each section. Ribbon grains were not included in this analysis when it could be demonstrated that they were developed by kink band formation and recrystallization within more equant parent grains. Similarly strain analyses were not attempted on specimens in which recrystallization was considered to have significantly modified the aspect ratios of detrital grains. Representative two-dimensional strain data from deformed quartzites displaying S and L–S grain shape fabrics are presented in Figs. 6 and 7, respectively.

For each specimen the basic two-dimensional strain data were combined to estimate the bulk finite strain ellipsoid, making no assumptions concerning the possible relationships between cleavage, lineation and the finite strain ellipsoid. Within the limits of accuracy of the techniques employed, however, it was always found that the X axis and XY plane of the calculated finite strain ellipsoid were orientated parallel to the specimen lineation (i.e. local fold hinge) and foliation, respectively. Further strain analyses on four additional specimens (RM 33, 34, 35 and 35A), using mutually perpendicular thin sections cut oblique to cleavage, yielded results which are in close agreement with these findings.

Results of the strain analyses are shown in Fig. 9. Specimens exhibiting a pronounced cleavage plot well within the apparent flattening field (oblate ellipsoids), whilst specimens of comparable strain magnitude, but with less obvious cleavage, lie closer to the plane strain (at constant volume) line ($\nu = 0$) of the deformation plot. The percentage extensions (calculated assuming constant volume deformation) parallel to the principal

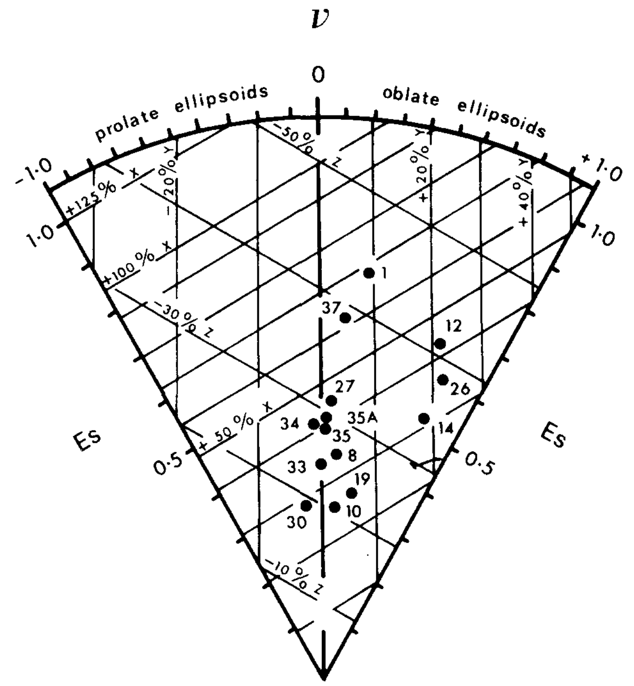


Fig. 9. Hsu natural strain plot of calculated strain states within the Roche Maurice quartzites. Elongation parallel to the principal axes of the finite strain ellipsoid are indicated. Es is natural logarithmic octahedral strain; Lode's ratio $\nu = (1 - k)/(1 + k)$.

axes of the bulk finite strain ellipsoid are also shown in Fig. 9. Shortening (Z) perpendicular to cleavage varies from 20 to 45%.

TECHNIQUES OF PETROFABRIC ANALYSIS

Petrofabric analysis of quartz c axes was carried out on one section from each specimen using an optical microscope and universal stage; a minimum of 600 c axes being measured in each thin section. Generally these thin sections were cut parallel to the XZ plane of the calculated strain ellipsoid. However, due to difficulties associated with specimen preparation, petrofabric analysis had to be carried out on sections cut oblique to cleavage in specimens RM 33, 34, 35 and 35A. During work on each specimen, a record was kept of each grain measured, by plotting the sites of individual c axis measurements on an enlarged photograph of the thin section. Several quartz grain types were distinguished in thin section; the c-axis orientations of the various grain types were recorded separately.

Quartz a-axis fabrics were measured, in collaboration with M. Casey, at E.T.H., Zürich, using an automatic X-ray texture goniometer operating in combined reflection and transmission modes (Siddans 1976). It should be noted that no information relating to individual grains can be obtained by X-ray texture goniometry.

The c- and a-axis data are displayed on equal area, lower hemisphere stereographic projections whose plane of projection is the XZ principal plane of the calculated strain ellipsoid. In specimens where recrystallization is too advanced for strain analysis to be attempted, c- and a-axis fabrics are displayed on equivalent

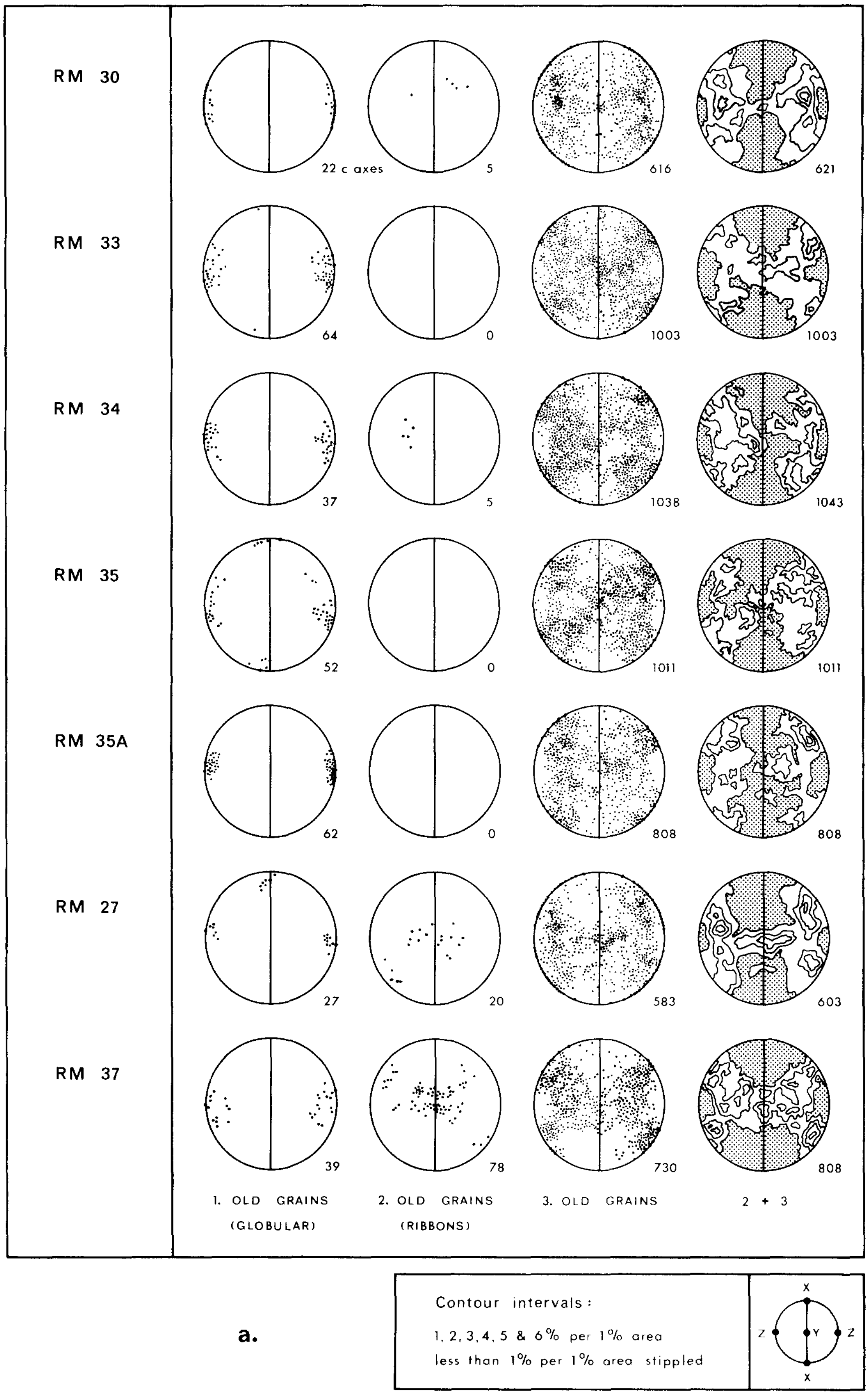
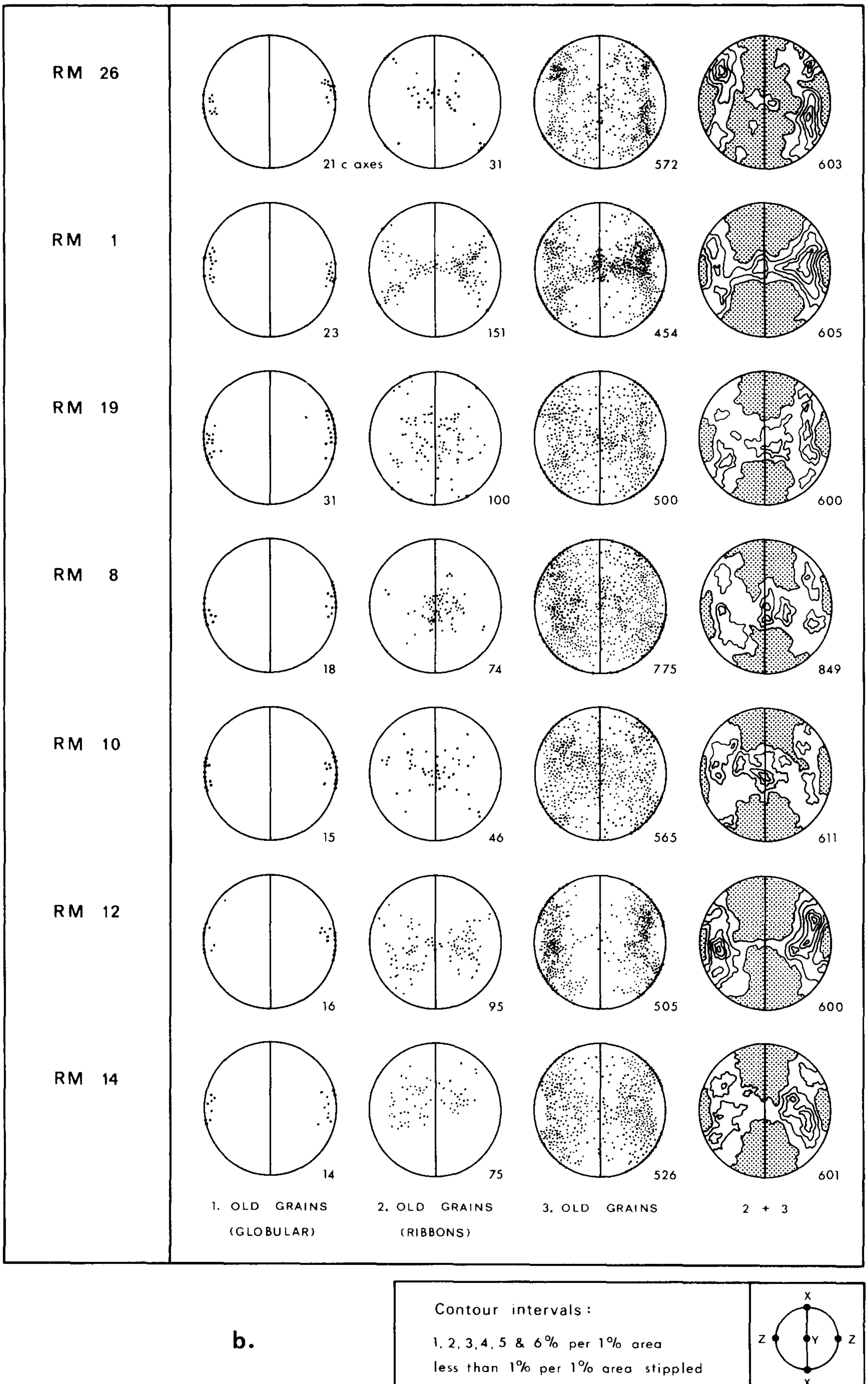


Fig. 10 (a and b) *c*-axis fabrics for detrital (old) grains within the Roche Maurice quartzites. Cleavage and bedding–cleavage intersection are orientated parallel to the *XY* plane and *X* axis of the calculated finite strain ellipsoid, respectively. See text for definition of the three grain types distinguished. Stereograms contoured using the method described by Kalsbeek (1963).


RM 26
21 c axes
31
572
603
RM 1
23
151
454
605
RM 19
31
100
500
600
RM 8
18
74
775
849
RM 10
15
46
565
611
RM 12
16
95
505
600
RM 14
14
75
526
601
1. OLD GRAINS (GLOBULAR)
2. OLD GRAINS (RIBBONS)
3. OLD GRAINS
2 + 3
Contour intervals:
1, 2, 3, 4, 5 & 6% per 1% area
less than 1% per 1% area stippled
X
Z
Y
Z
X

b.

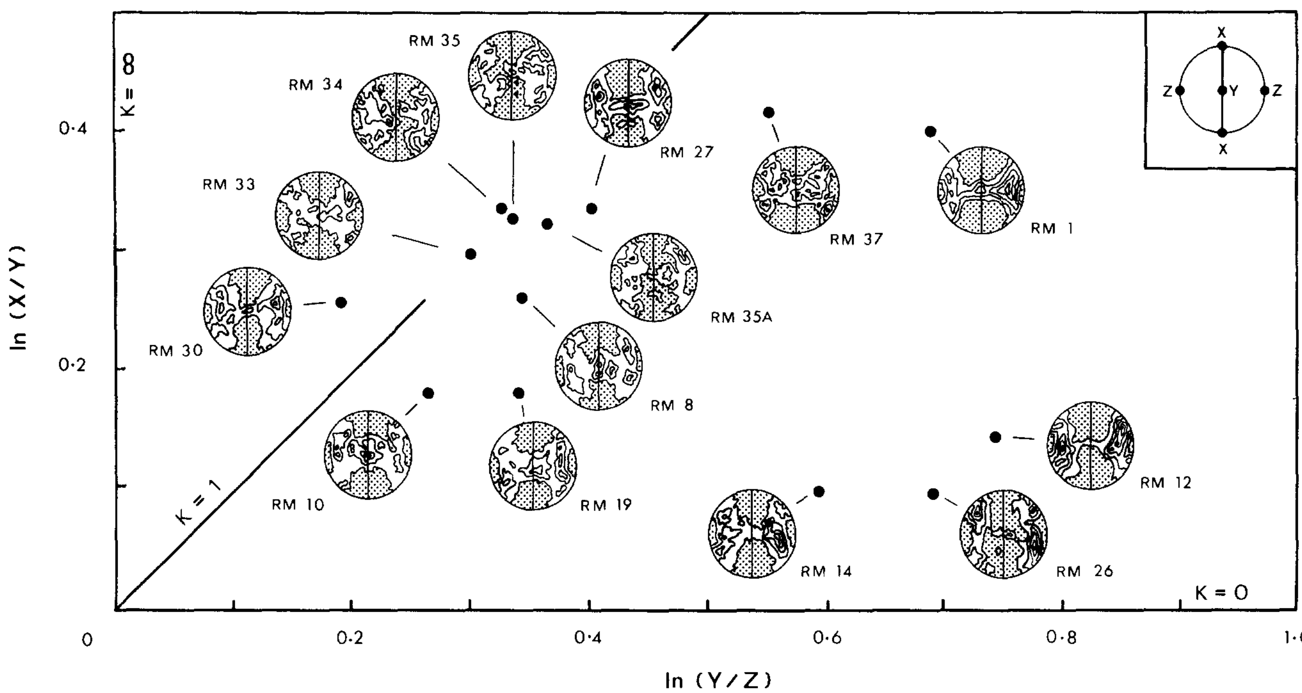


Fig. 11. Natural log. Flinn Plot illustrating relationships between c-axis fabrics of detrital quartz grains and calculated strain states. For explanation of contour intervals see Fig. 10.

projections in which cleavage is vertical and lineation lying within the foliation is horizontal. In geographical terms all these stereograms (with the exception of Fig. 14) represent approximately NE–SW striking projection planes viewed from above, with the NE-plunging X axis (bedding–cleavage intersection lineation) located at the 'top' of each diagram.

PREFERRED c-AXIS ORIENTATION OF DEFORMED DETRITAL QUARTZ GRAINS

On the basis of morphology, three detrital (old) grain types have been distinguished in XZ thin sections: (1) globular grains, (2) ribbon-like grains and (3) elongate grains with less extreme aspect ratios. In this section of the paper the c-axis preferred orientations of these grain types will first be described separately (Figs. 10a, b), and then correlated with the bulk strain estimates for each specimen (Fig. 11).

Globular detrital grains

These grains have equant shapes with aspect ratios, in any section, rarely exceeding 2:1, irrespective of the bulk strain magnitude. Two distinct varieties of these grains have been recognized, the most common of which is characterized in XZ thin sections by diffuse deformation bands aligned perpendicular to the foliation trace (Fig. 8b); c axes from these grains (Fig. 10) are aligned at low angles to the foliation pole (Z). The less common variety of globular grains are characterized by sharply defined deformation bands orientated sub-parallel to the foliation trace (Fig. 5d); c axes within these grains (Fig. 10, specimens RM 33, 35 and 27) are aligned at low angles to the calculated bulk principal extension direction (X).

Ribbon-like grains

These highly elongate grains, by definition, always display aspect ratios greater than 5:1 in XZ sections, with typical ratios commonly exceeding 10:1. Ribbon grains become more commonly developed with increasing bulk finite strain magnitude (cf. Figs. 9 and 10). In specimens of low strain magnitude, c axes of ribbon grains are scattered about the intermediate principal axis (Y) of the bulk strain ellipsoid, whereas in the more highly deformed quartzites they form cross-girdle fabrics intersecting in Y.

Ribbon-like quartz grains have been recorded within mylonites from many different geological environments (e.g. Christie 1963, Wilson 1975, Bouchez 1977, Burg & Laurent 1978, Boullier & Bouchez 1978, Mawer 1983, Law *et al.* 1984, Culshaw & Fyson 1984). Commonly these ribbon grains are characterized by c-axis point maxima parallel to Y, suggesting (Wilson 1975, Bouchez 1977) that intracrystalline deformation within these grains is dominated by prism ‹a› slip. In the most highly deformed Roche Maurice quartzites, however, ribbon grains are characterized by cross-girdle fabrics (Fig. 10) suggesting that other slip systems (or combinations of slip systems) may also have operated. In addition, it will be recalled that many of the ribbon grains that are separated by narrow bands of recrystallized quartz may have developed by intracrystalline kinking and selective recrystallization of larger, more equant, grains.

Elongate detrital grains of moderate aspect ratio

c-axis fabrics measured on these most commonly observed detrital grains (those displaying aspect ratios of between 2:1 and 5:1 in *XZ* thin sections) are shown in Fig. 10. They are characterized by a diffuse small circle girdle centred about *Z*, which, in some specimens (e.g. RM 27), is connected by an additional partial girdle aligned about the *YZ* plane close to *Y*.

Correlation between bulk strain estimates and quartz c-axis preferred orientation of deformed detrital grains

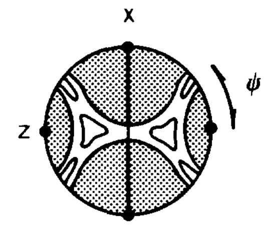
A general impression of the patterns of preferred crystallographic orientation produced by intracrystalline slip may be obtained by combining, for each specimen, the *c*-axis fabric diagrams obtained from the ribbon-like (Class 2) and more moderately deformed (Class 3) detrital quartz grains. These composite fabric diagrams have been contoured (Fig. 10) and may be correlated with the bulk strain estimates for each specimen (Fig. 11). Data for the globular detrital quartz grains were not included in these composite fabric diagrams because it will later be argued that their crystallographic preferred orientation has remained constant during deformation and is not related to *c*-axis rotations associated with intracrystalline slip. Study of Figs. 9 and 10 indicates that the degree of *c*-axis preferred orientation is proportional to strain magnitude. In specimens with calculated flattening ($k = 0$) strains, *c* axes lie on a small circle girdle centred about *Z* (Fig. 11). For specimens that exhibit approximate plane strain ($k = 1$), Type I (Lister 1977) cross-girdle fabrics were detected, consisting of a small circle girdle centred about *Z* and connected through *Y*. Opening angles about *Z* for these fabrics range between 28 and 42°, and are listed for individual specimens in Table 2. The fabric patterns for the deformed detrital quartz grains are symmetrically disposed (both in terms of skeletal outline and intensity of distribution) with respect to foliation (*XY*) and lineation (*X*).

A far poorer correlation between *c*-axis fabrics and bulk strain symmetry is detected for ribbon grains (Class 2) (Fig. 10) than for moderately deformed (Class 3) detrital quartz grains. For example, specimens RM 12 ($k = 0.14$) and RM 1 ($k = 0.55$) have both yielded ribbon grain cross-girdle fabrics (Fig. 10).

PREFERRED *c*-AXIS ORIENTATION OF RECRYSTALLIZED QUARTZ GRAINS

Both equant and elongate recrystallized (new) quartz grains have been recognized in *XZ* thin sections from the deformed Roche Maurice quartzites and *c* axes of both types of grain have been measured in the more highly recrystallized specimens. For a given specimen, they were found to form similar fabrics (Fig. 12). Complete recrystallization of quartz was only observed within two of the specimens collected (RM 20 and 36); both are S > L tectonites.

Table 2. Opening angles (ψ) of *c*-axis fabrics for individual quartzite specimens



Specimen	Opening angle ψ	
	Old grains	New grains
RM 30	36°	36°
33	36°	
34	32°	
35	34°	
35A	42°	
36		40°
27	36°	36°
37	32°	36°
26	36°	40°
1	28°	32°
20		45°
19	36°	
8	38°	
10	40°	
12	30°	32°
14	34°	

Contoured composite fabric diagrams produced by combining data for equant and elongate grains (Fig. 12) may be compared for each specimen with the appropriate fabrics for deformed detrital quartz grains (Fig. 13). Fabrics from recrystallized grains were found to be similar to, although more diffuse than, those of deformed detrital grains within individual specimens. The *c* axes of recrystallized (new) grains in specimens with flattening strains lie on a small circle girdle centred about *Z*. For specimens that indicate approximate plane strain, a Type I (Lister 1977) cross-girdle fabric was detected.

c-axis fabrics for these recrystallized quartz grains are symmetrically disposed (both in terms of skeletal outline and intensity of distribution) with respect to foliation (*XY*) and lineation (*X*). For a given specimen, the small circle distribution of *c* axes for recrystallized (new) grains is of similar, or slightly larger, opening angle about *Z* than the corresponding distribution for deformed detrital (old) quartz grains (Table 2).

Within all the specimens so far described in this paper, the calculated *X* axis (grain shape lineation) was found to lie, within observational error, parallel to the bedding–cleavage intersection lineation (i.e. local fold hinge). However, in one specimen (RM 36), a completely recrystallized S > L tectonite collected from the limb of a minor fold (Fig. 4), the linear element of the grain shape fabric was perpendicular to the intersection lineation. *c* axes for this specimen define an approximately symmetric Type I (Lister 1977) cross-girdle fabric consisting of a small circle girdle (opening angle 40°)

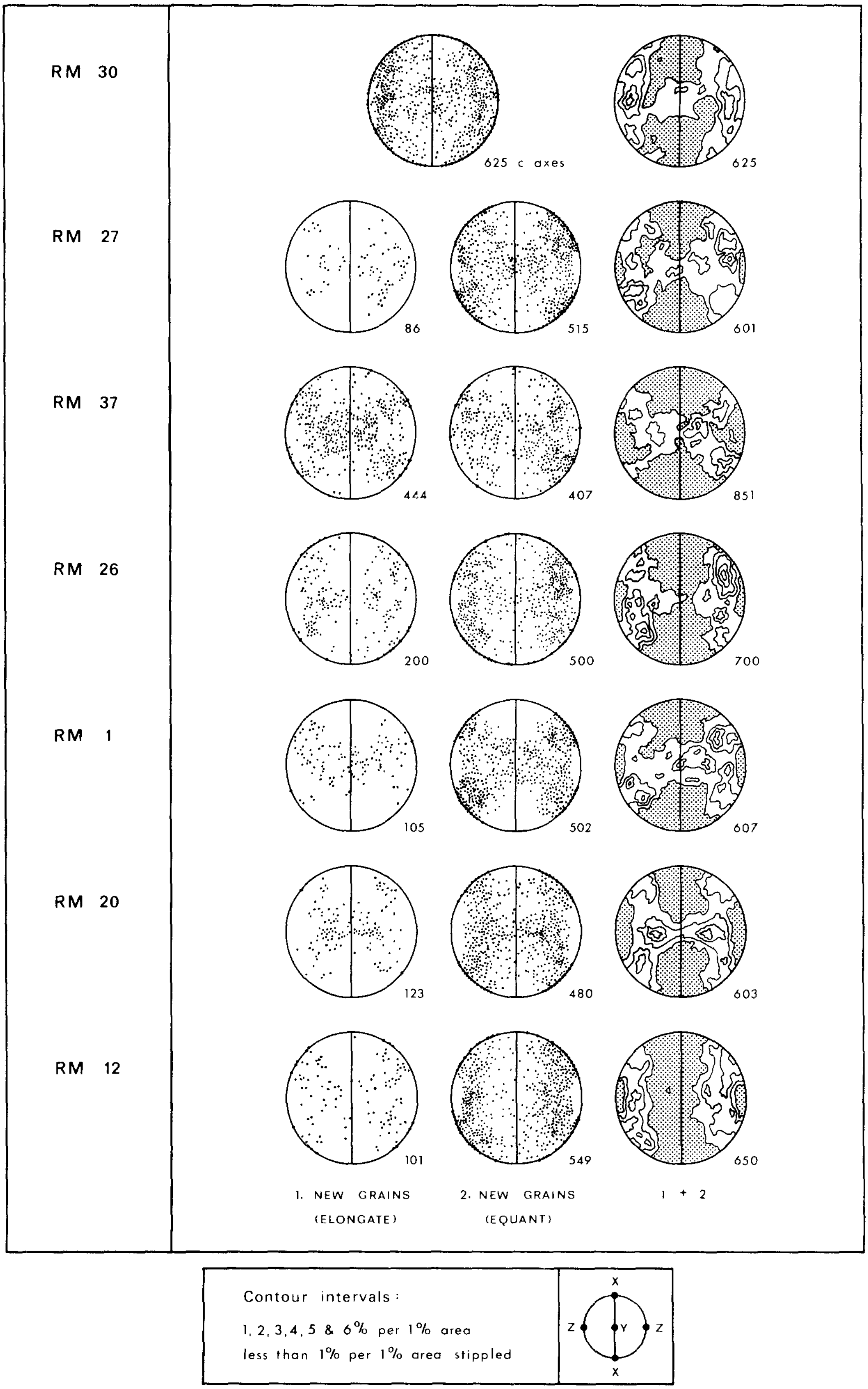


Fig. 12. *c*-axis fabrics for new (recrystallized) quartz grains within the Roche Maurice quartzites. Cleavage and bedding–cleavage intersection are orientated parallel to the XY plane and X axis of the calculated finite strain ellipsoid, respectively.

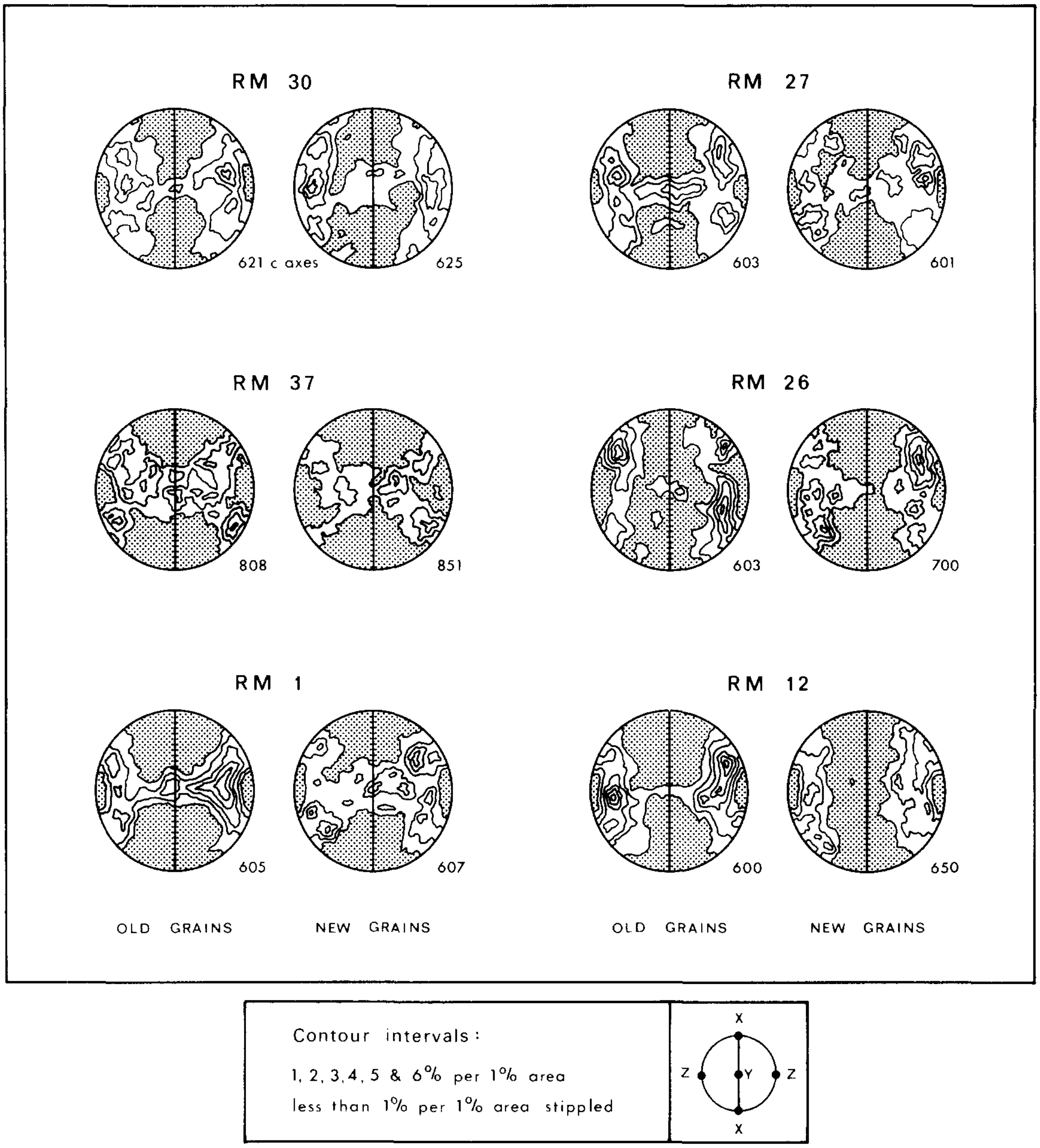


Fig. 13. Comparison of c-axis fabrics for detrital (old) and recrystallized (new) grains within the Roche Maurice quartzites.

centred about the pole to cleavage (Z) and connected through the bedding–cleavage intersection lineation (Fig. 14).

ANGULAR RELATIONSHIPS BETWEEN *c* AXES OF HOST AND RECRYSTALLIZED QUARTZ GRAINS

In five specimens of deformed (and partially recrystallized) Roche Maurice quartzite a detailed study was made of the angle between the c axes of host detrital grains and the c axes of new grains within the hosts. It should be noted that these new grains are located in the relatively undeformed sections of the hosts and not along structures such as deformation band boundaries.

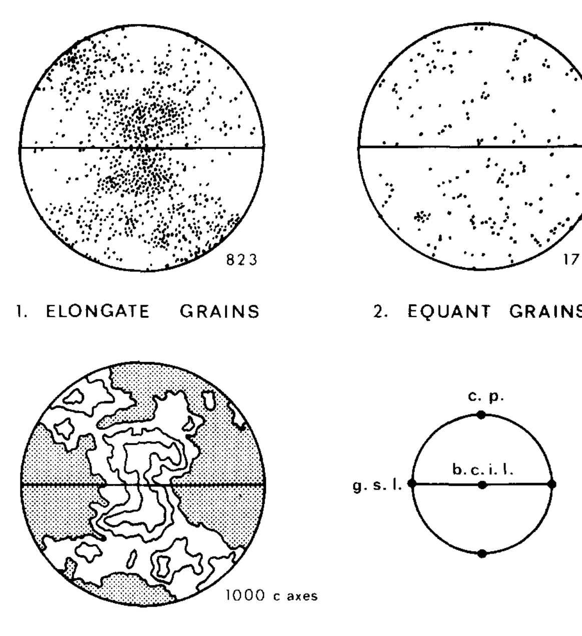


Fig. 14. New grain c-axis fabric for specimen RM 36. Orientation convention: c.p., cleavage pole; b.c.i.l., bedding–cleavage intersection; g.s.l., grain shape lineation. In geographical terms these stereograms are viewed towards the SW (see also Fig. 4). For explanation of contour intervals see Fig. 10.

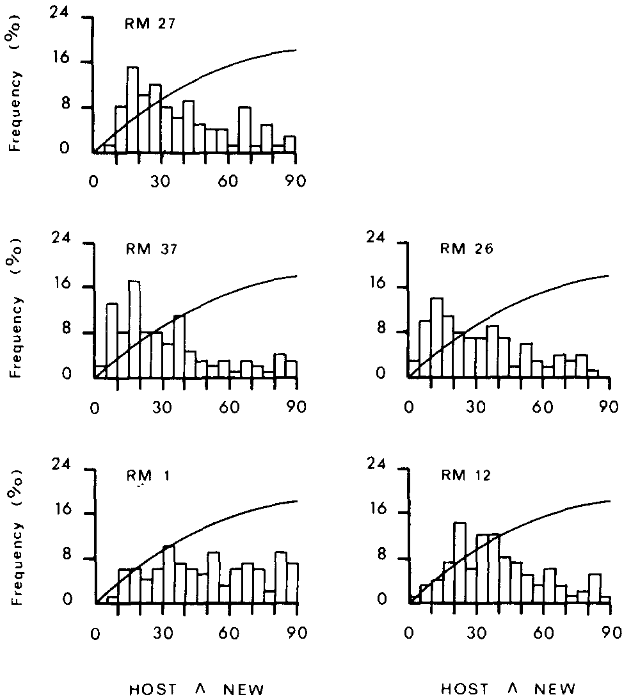


Fig. 15. Frequency distributions of angle between the c axes of related host and new grains. One hundred sets of measurements in each specimen. Curves superimposed on histograms represent the calculated distribution for random orientations of new grains (Plummer 1940).

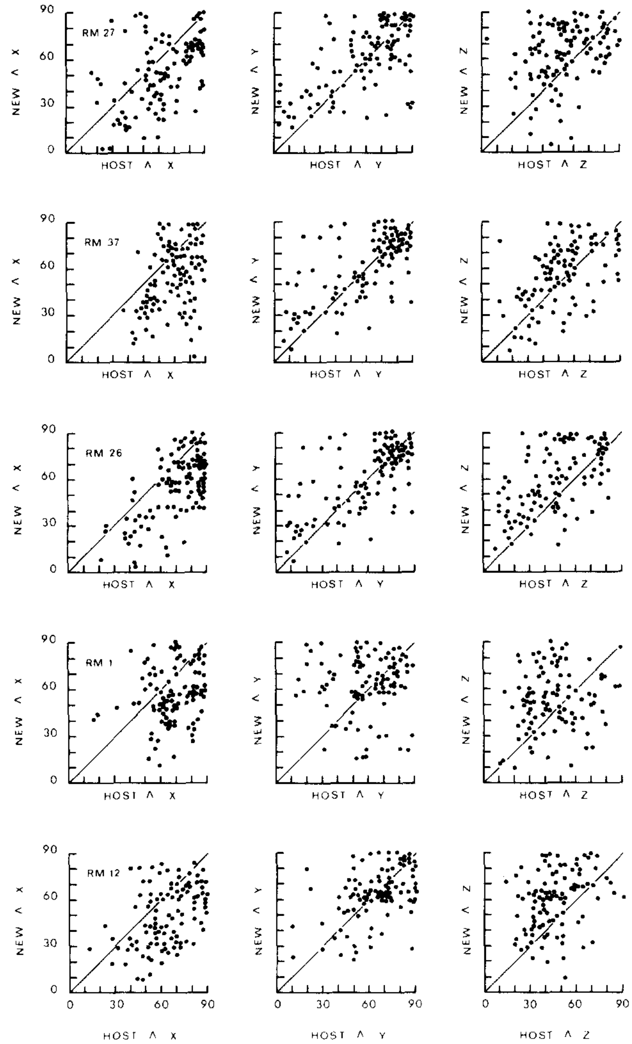


Fig. 16. Angular relationships between the c axes of related pairs of host and new grains and the X, Y and Z axes of the calculated finite strain ellipsoid. Lines of equal angular relationship indicated. One hundred sets of measurements in each specimen.

One hundred host: new grain c-axis relationships were measured in each specimen. A clear relationship (with the exception of specimen RM 1) exists, c axes of new grains being most commonly orientated at angles of between 10 and 40° to their host grain c axis (Fig. 15). In addition, more detailed study indicates that the final orientation of new grain c axes appears (at least statistically) to have involved a rotation of the new grain c axis (relative to the host grain c axis) away from Z towards Y, the angle between host c axis and Y remaining statistically similar to that between the new grain c axis and Y (Fig. 16). Identical relationships have been detected within quartz mylonites from NW Scotland by Law *et al.* (1984).

The angular relationships between c axes of host and new quartz grains and principal axes of the calculated strain ellipsoid may also be expressed in the form of histograms (Fig. 17). The histograms clearly indicate that new grain c axes are statistically: (1) orientated at lower angles to X than their host grain c axes (left hand column of Fig. 17), (2) orientated at higher angles to Z than their host c axes (right hand column) and (3) are orientated at a similar angle to Y as their host grain c axes (middle column). No obvious correlation, however, was detected within these specimens between angular relationships associated with recrystallization and calculated bulk strain symmetry.

Optical studies can only provide information on the orientation of one crystallographic direction (the c axis) within the host: new grain pairs. In order to specify the complete relative orientation within each grain pair it is obviously necessary to determine the complete crystallographic orientation of both grain types. In one study of a quartz mylonite from NW Scotland, White (1976) has found, using selected area diffraction patterns obtained by transmission electron microscopy, that new grains are usually related to their hosts by a simple rotation of between 1 and 25° about a shared a axis. Such a study of the Roche Maurice quartzites is planned for future research. At present, no direct information is available on the complete crystallographic relationships between host and new grains within these quartzites.

Poles to planes containing the c axes of individual host: new grain pairs are plotted in Fig. 18. These poles determine the orientation of the line along which the basal planes of each host: new grain pair 'intersect'. By analogy with the findings of White (1976, fig. 5) it may be tentatively proposed that these basal planes 'intersect' in an a axis which is common to each host: new grain pair. When combined for all specimens studied, poles to planes containing c axes of individual host: new grain pairs define a broad small circle distribution (of large opening angle) centred about Z (Fig. 18).

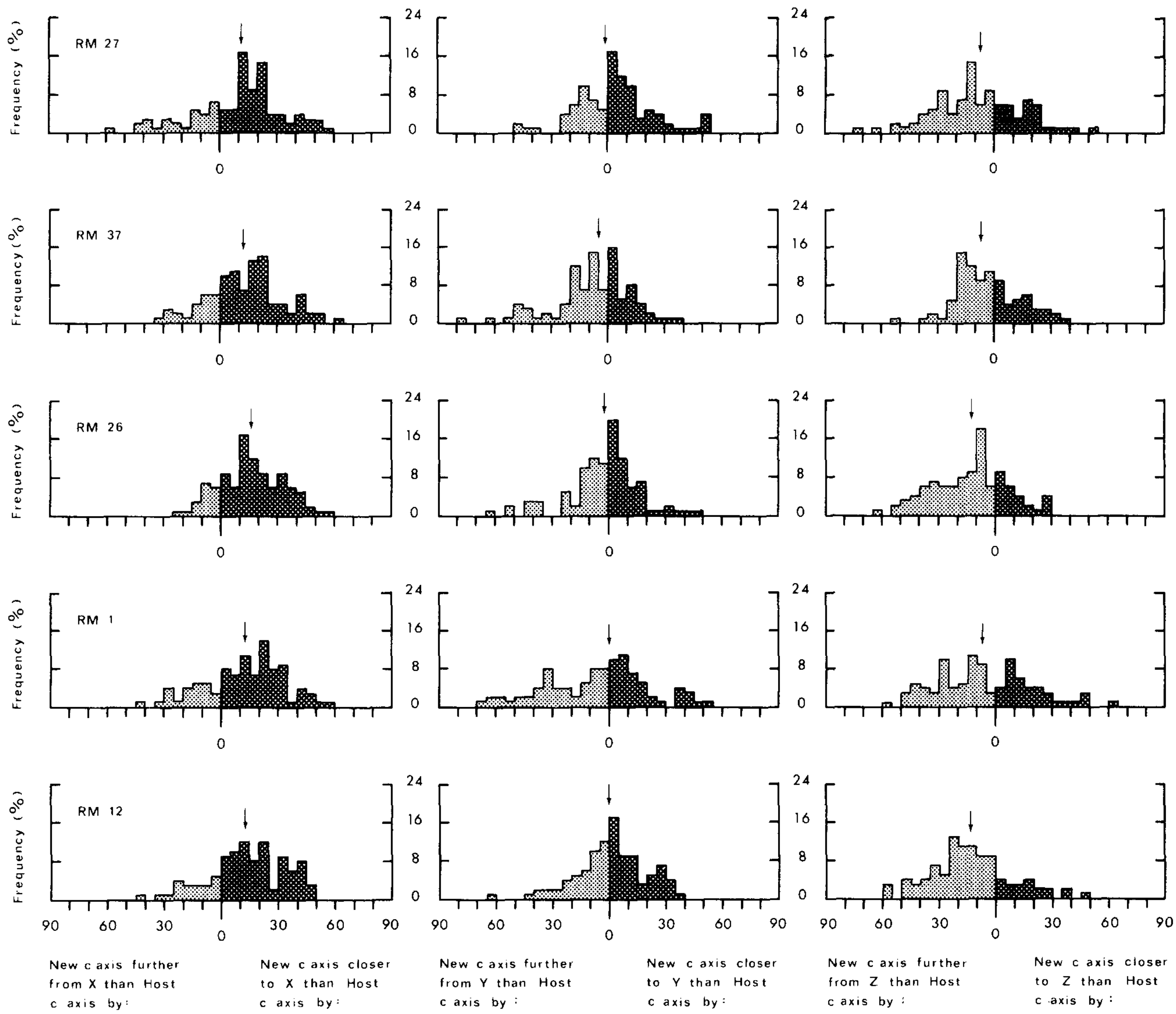


Fig. 17. Frequency distribution of angular relationships between *c* axes of related pairs of host and new grains and the *X* (left hand column), *Y* (middle column) and *Z* (right hand column) axes of the calculated finite strain ellipsoid. Arithmetic means are indicated by arrows. One hundred sets of measurements in each specimen.

QUARTZ *a*-AXIS FABRICS

Quartz *a*-axis fabrics obtained by X-ray texture goniometry studies of the Roche Maurice quartzites are presented in Fig. 19. These fabrics are, in general, weakly defined, but approximate to broad small circle girdle (of large opening angle) distributions centred about *Z*. All these fabrics display obvious minima centred about *Z*, with subsidiary minima centred about *X*. Due to their generally diffuse nature it is difficult to correlate these fabrics with calculated bulk strain symmetries (cf. Fig. 1). However, within specimen RM 12 (an S tectonite with flattening strain symmetry) a strongly developed small circle girdle (of large opening angle) centred about *Z* is detected. The individual maxima on this girdle may reflect the preferred orientation of a relatively small number of large detrital quartz grains within this coarse grained, weakly recrystallized tectonite.

The *a*-axis fabrics, measured by scanning over both detrital and recrystallized quartz grains, are compared in Fig. 19 with the relevant *c*-axis fabrics (combined detrital and recrystallized grains) obtained by optical microscopy.

GENERAL INTERPRETATION OF MICROSTRUCTURES

Two major grain types are recognised within the Roche Maurice quartzites: deformed detrital (old) grains and recrystallized (new) grains. Within the detrital grains, undulose extinction, deformation bands and sub-grains are commonly observed. These optical features are considered (White 1973a) to indicate intracrystalline (dislocation) slip and recovery.

New quartz grains are frequently observed within the detrital grains, being particularly common close to the

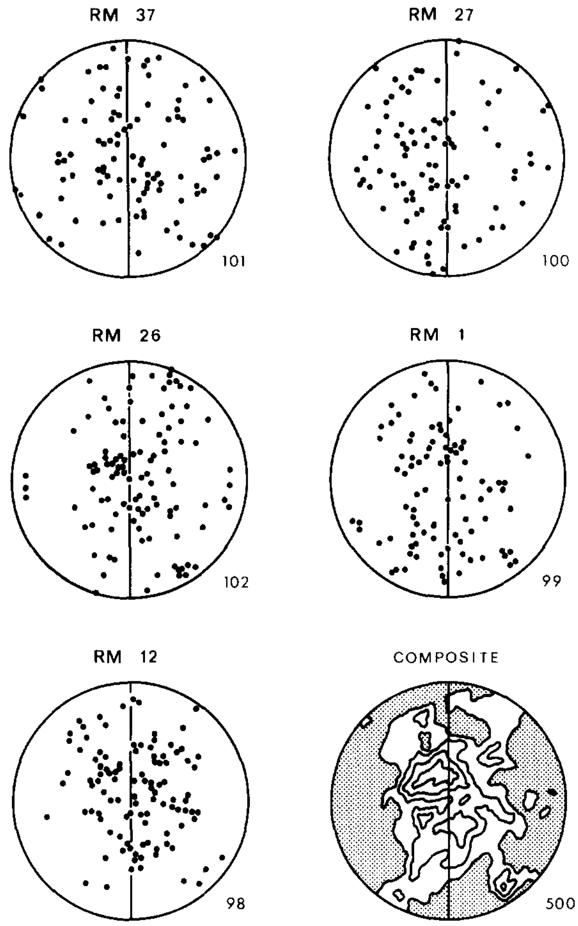


Fig. 18. Poles to planes containing the *c* axes of individual host and new grain pairs. One hundred measurements in each specimen. For explanation of orientation convention and contour intervals see Fig. 10.

boundaries of the detrital grains and also along deformation band boundaries. Within the host detrital grains, new grains are of a similar size to sub-grains (approximately 50 μm) and are characteristically equant in outline. By analogy with the observations of Hobbs (1968) and White (1973b) it is suggested that these new grains may have developed by some mechanism involving progressive sub-grain rotation.

With increasing strain magnitude a steady increase in the volume of new grains is observed, the majority of new grains forming a fine-grained (approximately 50–70 μm) matrix in which the relic detrital grains are dispersed. Undulose extinction is most commonly observed within the matrix new grains and, in general, is less well developed in new grains located either within, or immediately adjacent to, the relic detrital grains. These microstructural features are thought to indicate (White 1977) that recrystallization within these quartzites is essentially syntectonic.

Both equant and elongate new quartz grains are locally observed in *XZ* thin sections; new grains within, and immediately adjacent to, the relic detrital grains being characteristically equant in outline. No convincing correlation has been established between bulk strain magnitude and the aspect ratios of matrix new grains; equant new grains are, in general, the predominant matrix grain

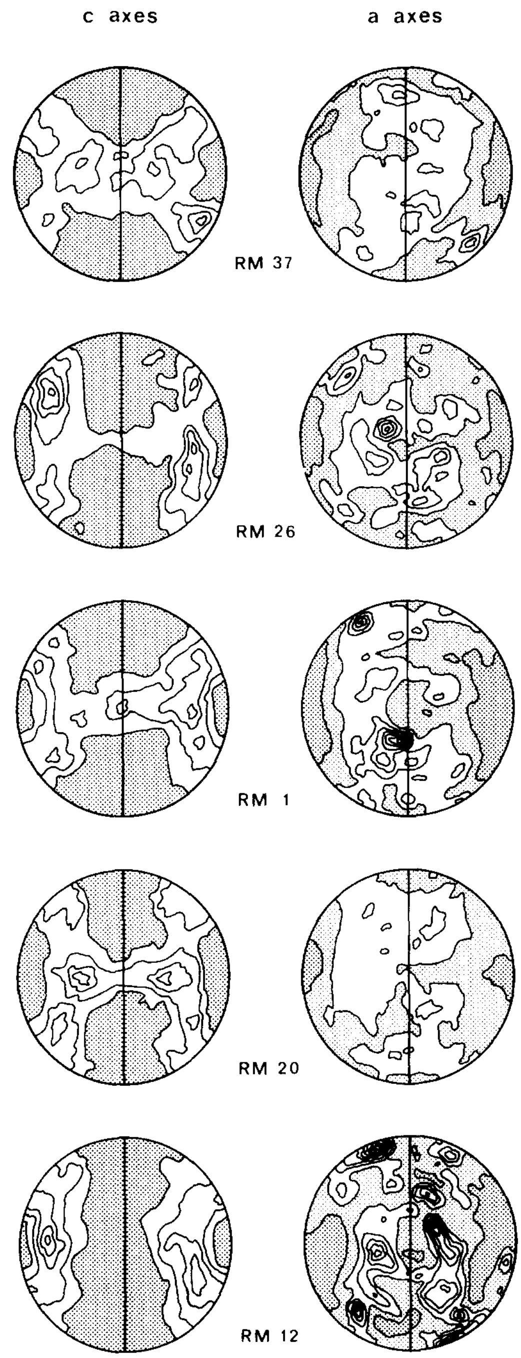


Fig. 19. Comparison of *c*-axis fabrics measured optically and *a*-axis fabrics measured by X-ray texture goniometry. Old and new grains are included; 1658, 1303, 1212, 603 and 1207 *c* axes were measured in specimens RM 37, 26, 1, 20 and 12, respectively. For explanation of orientation convention and *c*-axis fabric contours see Fig. 10. Quartz *a*-axis fabrics contoured by M. Casey at E.T.H., Zürich, using a modified version of the computer program described by Starkey (1970). Contour intervals of *a*-axis fabrics are 0.5, 1.0, 1.5, . . . 5.0 times uniform distribution. Regions of less than 0.5 and 0.5–1.0 times uniform distribution shown by heavy and light stipples, respectively.

type. If the new grains are syntectonic, it could be argued that the matrix new grains should (as in the experiments of Tullis *et al.* 1973) be flattened within the foliation. However, other experimental studies (Green *et al.* 1970, Masuda & Fujimura 1981) have shown that flattening of syntectonic recrystallized quartz grains will only occur at relatively high strain rates and/or low temperatures; at lower strain rates and/or higher temperatures an aggregate of predominantly equant new grains is presumably maintained by cyclic recrystallization and deformation (cf. Means 1981). Only in specimens RM 12, 20 and 36 are recrystallized matrix grains predominantly elongate, displaying a preferred alignment parallel to the macroscopic foliation (Fig. 8d); even within these elongate grains, however, sub-grains are characteristically equant. By analogy with the experiments of Green *et al.* (1970) and Masuda & Fujimura (1981) it is proposed that cyclic deformation and syntectonic recrystallization of quartz may have been of major importance in the microstructural evolution of the Roche Maurice quartzites.

KINEMATIC INTERPRETATION OF GLOBULAR DETRITAL QUARTZ GRAINS

In XZ thin sections of deformed Roche Maurice quartzite, elongate detrital quartz grains are locally observed to wrap around globular detrital quartz grains (Fig. 8b) whose c axes are aligned sub-parallel to the principal shortening direction (Z). During coaxial deformation these anomalously low strain globular grains would have extremely low resolved shear stresses on their theoretically most easily activated slip planes, the basal and prism planes. Rare, globular detrital quartz grains, with c axes aligned at low angles to the principal extension direction (X) have also been observed within some of the more obviously lineated quartzites. During coaxial deformation these grains would have low resolved shear stresses on their basal slip planes.

Similar relationships between microstructure and crystallographic orientation relative to finite strain axes have been observed in experimental coaxial deformation of quartzites (Tullis *et al.* 1973, Tullis 1977) and in naturally deformed quartzites considered to have been subjected to coaxial deformation histories (Mancktelow 1981, Mawer 1982, Law *et al.* 1984, Law *et al.* in press). In non-coaxial deformation the lattices of these globular grains would rotate relative to the kinematic framework and the resolved shear stresses on their potential slip planes would vary during the deformation history. The proposal that weakly deformed quartz grains can only survive in an effectively coaxial deformation is supported by the experiments of Tullis *et al.* (1973, p. 311) who found that the preservation of 'augen' grains in unfavourable orientations for deformation rapidly diminished in the boundary regions of their specimens, where the component of shear became significant.

KINEMATIC INTERPRETATION OF QUARTZ CRYSTALLOGRAPHIC FABRICS

Within all the Roche Maurice quartzite specimens examined, c- and a-axis fabrics measured in detrital and recrystallized quartz grains are symmetrically disposed (both in terms of skeletal outline and intensity of distribution) with respect to foliation (XY) and lineation (X).

By analogy with computer simulation studies of the influence of deformation paths and dislocation glide on the development of quartz c-axis fabrics (Lister *et al.* 1978, Lister & Hobbs 1980), it is proposed that the symmetric relationship between c-axis fabrics (measured in detrital grains) and finite strain axes may be taken to indicate a coaxial deformation history. This interpretation is in accord with the proposed kinematic interpretation of globular detrital quartz grains within these tectonites and is also supported by experimental studies of c-axis fabric development in quartzites subjected to coaxial deformation histories (Tullis *et al.* 1973, Tullis 1977).

By analogy with the experimental studies of Green *et al.* (1970), it may be proposed that the symmetric c-axis fabrics from recrystallized grains within the Roche Maurice quartzites also indicate coaxial deformation histories. In their experimental studies of the influence of syntectonic and annealing recrystallization on crystallographic fabric development within fine grained quartz aggregates subjected to coaxial deformation, Green *et al.* (1970) found that the coaxial strain paths imposed on their specimens were clearly reflected in the resultant symmetric new (recrystallized) grain c-axis fabrics.

Thus both microstructural and petrofabric studies indicate that the Roche Maurice quartzites have been deformed along essentially coaxial strain paths.

The specimens for this study were collected from both the limbs and hinge zones of minor folds in which individual quartzite beds show only slight thickening towards the hinge. Similar examples of coaxial flow associated with the development of parallel folds have been described by Lister & Williams (1983). Such folding in which the degree of non-coaxiality is reduced to zero at all points has been referred to as coaxial spinning deformation paths by Means *et al.* (1980).

DEVELOPMENT OF QUARTZ CRYSTALLOGRAPHIC FABRICS: DISCUSSION

Integrated microstructural and petrofabric analyses have revealed that c-axis fabrics within the Roche Maurice quartzites have developed, during coaxial deformation, by the two distinct, but possibly related, processes of intracrystalline slip (old grain fabrics) and syntectonic recrystallization (new grain fabrics).

Influence of strain ellipsoid and crystallographic slip systems

A clear correlation has been established between the pattern of c-axis fabrics displayed by detrital (old) quartz grains and the symmetry of the calculated strain ellipsoid (Figs. 10 and 11). In specimens with flattening ($k = 0$) strains, c axes lie on a small circle girdle centred about Z. For specimens that exhibit approximate plane strain ($k = 1$), Type I (Lister 1977) cross-girdle c-axis fabrics, consisting of a small circle girdle centred about Z and connected through Y, were detected. These fabrics are very similar to those predicted by Lister *et al.* (1978) when basal <a> glide is the easiest slip system to operate and the r and z rhomb systems have equal, but higher, critical activation stresses. The correlation between fabric pattern and strain symmetry is also in close agreement with experimental studies of c-axis fabric development in quartzites subjected to flattening (Tullis *et al.* 1973) and plane strain (Tullis 1977) deformation. Similar correlations have also been detected (Marjoribanks 1976, Law *et al.* 1984) in suites of naturally deformed quartzites exhibiting strain symmetries ranging from flattening ($k = 0$) to constrictional ($k > 1$). Few small circle girdle c-axis fabrics have been recorded in the geological literature, in contrast to the commonly described cross-girdle fabrics. In the few cases described (e.g. Sander 1930, figs. 43 and 45, Christie & Raleigh 1959, Marjoribanks 1976, Lister & Dornsiepen 1982, Law *et al.* 1984, Price 1985, Schmid & Casey in press) such small circle girdles centred about Z appear to be associated with S tectonites.

For coaxial deformation, theoretical studies (e.g. Hara 1971, Schmid & Casey in press) indicate that quartz a-axis fabrics should reflect the symmetry of deformation in the manner indicated in Fig. 1. These predictions are broadly in agreement with petrofabric analyses of naturally deformed quartzites (Bouchez 1978, Bouchez *et al.* 1979, Schmid & Casey in press, Law *et al.* in press). Quartz a-axis fabrics from the Roche Maurice quartzites (Fig. 19) are, in general, too diffuse to allow exact correlation with calculated bulk strain symmetries. However, in close agreement with theoretical and experimental studies, a strongly defined small circle girdle a-axis fabric (of large opening angle) centred about Z has been detected in specimen RM 12. Strain analysis indicates (Fig. 9) that this specimen is characterized by an oblate ($k = 0.14$) strain ellipsoid.

Recrystallization

c-axis fabrics from recrystallized (new) quartz grains are similar to, although slightly more diffuse than, c-axis fabrics of deformed detrital (old) grains within individual specimens of Roche Maurice quartzite (Fig. 13). Microstructural arguments suggest that these new grains are essentially syntectonic. Similar relationships between fabrics of old and new quartz grains have been recorded from many different geological environments (e.g. Philips 1945, Wilson 1973, Marjoribanks 1976, Bell & Etheridge 1976).

Within the Roche Maurice quartzites the preferred crystallographic orientation of detrital grains is clearly due to rotations associated with intracrystalline dislocation slip. A major question which therefore has to be asked is whether the similarity in crystallographic fabrics displayed by the detrital grains and recrystallized grains is due solely to host grain control on crystallographic orientation of new grains, or if the process of recrystallization is more directly influenced by the local stress and/or strain field.

It has been shown that the c axes of new grains located within the relatively undeformed sections of host detrital grains are commonly orientated at angles of between 10 and 40° to the c axes of their hosts (Fig. 15). This angular relationship is similar to that observed within many naturally deformed quartzites (e.g. Wilson 1973, Marjoribanks 1976, Bell & Etheridge 1976) and is usually attributed (e.g. Ransom 1971) to a host grain control over the process of recrystallization. However, within the Roche Maurice quartzites, the process of recrystallization would appear to be more complex as c axes of new grains are statistically orientated at higher angles to the principal shortening direction (Z) than the c axes of host grains (Figs. 16 and 17) suggesting that there is at least a contributory influence of stress and/or strain on the process of recrystallization. The exact mechanism by which these new grains were formed is unknown.

Similar angular relationships appear to have been detected by Hobbs (1968) in experimentally deformed and recrystallized single quartz crystals. In his coaxial flattening experiments, Hobbs (1968, fig. 7) found that intracrystalline (dislocation) slip within host single crystals loaded oblique to the c axis resulted in a rotation of the host c axis towards the axis of shortening (Z). However, except for single crystals loaded perpendicular to c, the c axes of new grains were predominantly at higher angles to Z than the c axis of the host. The c-axis fabrics of new grains in these experiments were characterized (Hobbs 1968, fig. 8) by maxima lying on small circle girdles (opening angle 50°) centred about Z (σ_1) and were interpreted (Hobbs 1968, p. 390) as indicating a tendency for new grains to form with c at about 50° to σ_1. However, there was also a marked tendency for new grains to form with their c axes orientated at 30–50° to the host grain c axis, suggesting (Hobbs 1968) a host grain control on recrystallization. The relative influence in these experiments of stress (and/or strain) and host grain control on crystallographic fabrics produced during syntectonic recrystallization therefore remains uncertain.

The observation that new grains produced during syntectonic recrystallization associated with coaxial strain paths are statistically characterized by c axes orientated at higher angles to Z than the c axes of the host grains may have important rheological implications. Lister *et al.* (1978, p. 127) have pointed out that ". . . during coaxial deformation associated with intracrystalline (dislocation) slip the crystal axes of the deforming grains will rotate so as to bring the dominant glide systems towards the most unfavourable orientation for continued operation . . .". This process is referred to (Lister & Hobbs 1980, p. 369) as orientation hardening. For continued intracrystalline deformation either slip must commence on other, less easily activated, glide systems, or the crystal lattice of individual grains must be reorientated for continued slip on the more easily activated slip systems. If, as detected in the Roche Maurice quartzites, syntectonic recrystallization results in the formation of new grains whose c axes are aligned at higher angles to Z than the c axes of the host grains, then deformation accommodated by dislocation glide may be able to recommence. This recrystallization process could be driven by the preferential build up of distortional lattice energy within grains in locked up positions.

The suggestion that syntectonic recrystallization may be necessary for the development of large strains in coaxial deformation may be supported by the experiments of Tullis *et al.* (1973). These authors found that in coaxial deformation of quartzites the strength of individual specimens was related to the threshold conditions for recrystallization, recrystallization being promoted by high temperatures and low strain rates. Below the threshold conditions, specimens work hardened continuously and very high differential stresses were needed to achieve even moderate strains; deformation in this regime was dominated by intracrystalline dislocation slip. However, under conditions necessary for the onset of recrystallization, specimens did not work harden appreciably and high strains could be achieved at low–moderate differential stresses.

To achieve large bulk strains in coaxial deformation it may therefore be proposed that a cyclic process involving dislocation slip and elimination of locked up grains by syntectonic recrystallization may be necessary. Similar deformation models have previously been proposed for general strain paths by Schmid & Casey (1982) and Schmid & Casey (in press). It should be noted that models which involve cyclic deformation and syntectonic recrystallization also offer an explanation for why the preferred crystallographic orientation of recrystallized tectonites can still be interpreted in terms of stable orientations for easy dislocation slip.

GEOLOGICAL IMPLICATIONS OF MICROSTRUCTURAL AND PETROFABRIC ANALYSIS

Strain analysis of the Roche Maurice quartzites indicate that (with the exception of specimen RM 36) the principal extension direction (X) is always aligned parallel to the sub-horizontal fold hinges developed in the quartzites. Quartz c-axis fabrics confirm, by analogy with theoretical and experimental studies, that these minor fold hinges are aligned parallel to X. Calculated hinge-parallel extensions vary from 25 to 70%. Similarly orientated hinge-parallel extensions of 15–35% are indicated (Law 1981a) by fibrous overgrowths within the adjacent Brioverian turbidites and Plougastel Formation (Fig. 2). Ries & Shackleton (1976) have recorded the widespread development of similarly orientated hinge-parallel extensions of Hercynian age throughout western and central Brittany.

Clearly these sub-horizontal extensions present a considerable space problem. One possible explanation is that these structures may have developed in a strike-slip orogen (Gapais & Le Corre 1980, Badham 1982). Within western and central Brittany the domain of predominantly horizontal, WSW–ENE trending hinge-parallel extension is bounded by the WNW–ESE striking North and South Armorican Shear Zones (Fig. 2). Recent studies (Jegouzo 1980) indicate that these vertical, dextral strike-slip shear zones have been active throughout Palaeozoic times, and that displacement magnitudes, although not calculated with accuracy, are estimated to be in the order of tens to hundreds of kilometres (Berthé *et al.* 1979, Watts & Williams 1979). Dextral movement on these fundamental basement fault zones may have resulted in the nucleation, within the flat-lying cover rocks, of folds with hinges inclined at approximately 45° to the trend of the faults. Continued dextral strike slip movement would have caused a rotation of these hinges towards parallelism with the faults and, as pointed out by Badham (1982, p. 498), would be characterized by a major component of hinge-parallel extension. Similar structures have been produced in analogue models by Odonne & Vialon (1983). Supporting evidence for this model has been found within the Rennes region of central Brittany (Fig. 2) where, on the basis of detailed regional strain analysis, Percevault & Cobbold (1982) have suggested that Hercynian deformation was controlled by dextral strike slip on these crustal scale faults. If this model is correct, rotation of the Roche Maurice folds towards parallelism with these faults must have been associated, at the scale of individual quartzite layers, with coaxial spinning deformation paths. Such progressive deformation must, on a larger scale, have involved strain path partitioning (cf. Lister & Williams 1979, Fig. 14).

CONCLUSIONS

The integration of microstructural observations, strain analysis and petrofabric studies within the Roche Maurice quartzites leads to the following conclusions:

(1) Strain analysis indicates that fold hinges and cleavage within the quartzites are orientated parallel to the principal extension direction (X) and XY plane of the finite strain ellipsoid, respectively. This conclusion is strongly supported by quartz c-axis fabric studies.

(2) Essentially coaxial deformation within the quartzites is indicated by both microstructural and petrofabric studies.

(3) The intensity of c-axis preferred orientation of detrital grains is directly proportional to calculated strain magnitude. A correlation is also established between the pattern of c-axis preferred orientation and strain symmetry. Oblate strains are characterized by small circle distributions of c axes centred about Z, whereas plane strain tectonites display Type I cross-girdle fabrics connected through Y. This correlation is in close agreement with theoretical and experimental studies.

(4) Within individual specimens, the c-axis fabrics are similar for syntectonically recrystallized grains and deformed detrital grains. The c axes of new grains within detrital hosts are commonly orientated at angles of between 10 and 40° to the c axes of their hosts. The c axes in the new grains are, in addition, statistically orientated at higher angles to Z than the c axes of their hosts. These relationships are interpreted as indicating that both host

grain control and the local strain (and/or stress) field may have influenced the process of recrystallization; the relative influence of these factors is, however, unknown.

(5) To achieve large bulk strains in coaxial deformation it is proposed that a cyclic process involving dislocation slip and elimination of locked up grains by syntectonic recrystallization may be necessary.

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