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Quartz shape fabric variations and c-axis fabrics in a ribbon-mylonite: arguments for an oscillating foliation

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Abstract—This paper describes quartz ribbons parallel to foliation, containing elongate recrystallized quartz grains aligned oblique to the foliation within a mylonite of the southern Tasman Belt, southeastern Australia. The shape fabric of quartz grains varies in obliquity (with respect to the foliation) and intensity (grain aspect ratio) from one ribbon to another, whereas the **c**-axis fabric pattern is stable with respect to the mylonitic foliation and lineation. It is argued that the grain shape fabric is an oscillating foliation due to competition between deformation and syntectonic recrystallization.

INTRODUCTION

IN GRAIN aggregates deforming by steady-state flow a given grain will flatten during progressive deformation and will represent a foliation-forming element. Dynamic recrystallization during the deformation will produce strain-free grains which are not foliation-forming elements until they are deformed. As a consequence there may be a strong relationship between size and aspect ratio at any particular increment of strain, giving some kind of closed loop on a plot. Means (1981) suggested that the strain sensitivity of a foliation during steady-state flow will decrease as the rate of foliation-destroying processes approaches that of foliation-forming processes. In the ideal case, such a strain-insensitive foliation would be a steady-state foliation. Elongate oblique grains within polycrystalline ribbons of quartz are common in quartz mylonites (e.g. Sander 1970 plate IIB, Eisbacher 1970, Boullier & Bouchez 1978, Evans & White 1984, Burg *et al.* 1984). These have been interpreted as either a major imprint of a late strain increment (Brunel 1980) or a steady-state foliation (Law *et al.* 1984). However, these previous interpretations have failed to document the existence of the cyclic and localized structural changes implied by a steady-state foliation. Indeed the various angles recorded in different mylonites between oblique elongate grains and foliation (Burg *et al.* 1984., Lister & Snoke 1984) could be ascribed to the effects of late events as well. This paper describes quartz ribbons and the nature of a prominent grain shape fabric and its relationship to the foliation in a mylonite of the southern part of the Tasman Belt (southeastern Australia). It is shown that the oblique shape fabric of quartz grains relative to the foliation can vary in direction and intensity between adjacent ribbons and is associated with stable **c**-axis fabrics with respect to the mylonitic foliation and lineation.

FIELD SETTING

The sample described here comes from the centre of the Fiddlers Green mylonite zone (35 km N of Cann River, Victoria), one of the anastomosing shear zones (Begg *et al.* in press) which constitute the southern extension of the NE–SW 'Burragate Fault" (Fig. 1, Beams 1980). This fault zone has a dextral transcurrent movement which offsets by 24 km a 381 ± 7 Ma granodiorite; unconformably overlying the fault are Late-Devonian clastic and epiclastic sediments (Powell 1983) so that the movement is Middle-Devonian. Post-Late Devonian faulting recorded elsewhere in the region (Begg *et al.* in press) has not been superimposed on the mylonites in the sampling area. The Fiddlers Green mylonite is ~60 m wide with a marked (few cm) transition to the weakly foliated uniform medium grained (1–2 mm) granodiorite. The strain pattern of the host granodiorite suggests a bulk shortening deformational history late during the emplacement of the magmatic body (Begg *et al.* in press). Within the mylonite zone a pronounced shape fabric and an associated grain-size reduction produce a strong foliation characterized by a millimetre scale layering of alternating mica and quartz–feldspar rich domains which strike N020° to N070° and dip steeply towards the NW (typically around 85°). This foliation contains a lineation plunging to the NE (10–20°). Following Nicolas & Poirier (1976), Ramsay (1980) and White *et al.* (1980) the macroscopic foliation and lineation have been interpreted as the principal XY plane and X axis of the finite strain ellipsoid, respectively. There is a consistent sense of dextral shear across the mylonite zone as detected from the asymmetry of microstructures, shear planes and small-scale drag folds in XZ sections of the rock.

FABRIC

The mylonite contains recrystallized quartz ribbons, small K-feldspar clasts which exhibit shear and pull-apart fractures, albitic plagioclase and variable amounts of spindle-shaped white micas, biotites and chlorites aligned parallel to the foliation. Granular epidote is present and appears as either strung out aggregates or single grains. The albite–epidote–chlorite mineralogy is

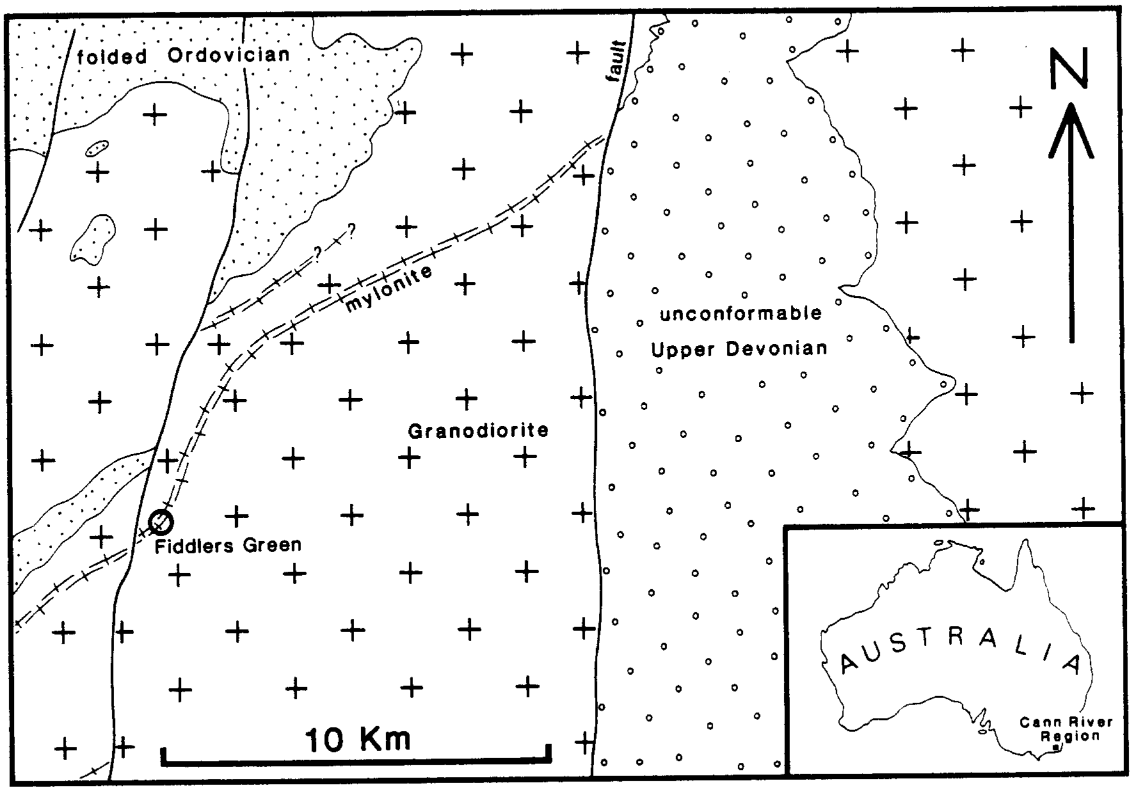

Fig. 1. Location of the Fiddlers Green mylonite on a simplified geological map of the Cann River region (modified after Spurgeon 1978 and Woodfull 1984). The dominant plutonic rocks are granodiorites, the symbols for which may locally include other granitoid types. The sample area is circled.

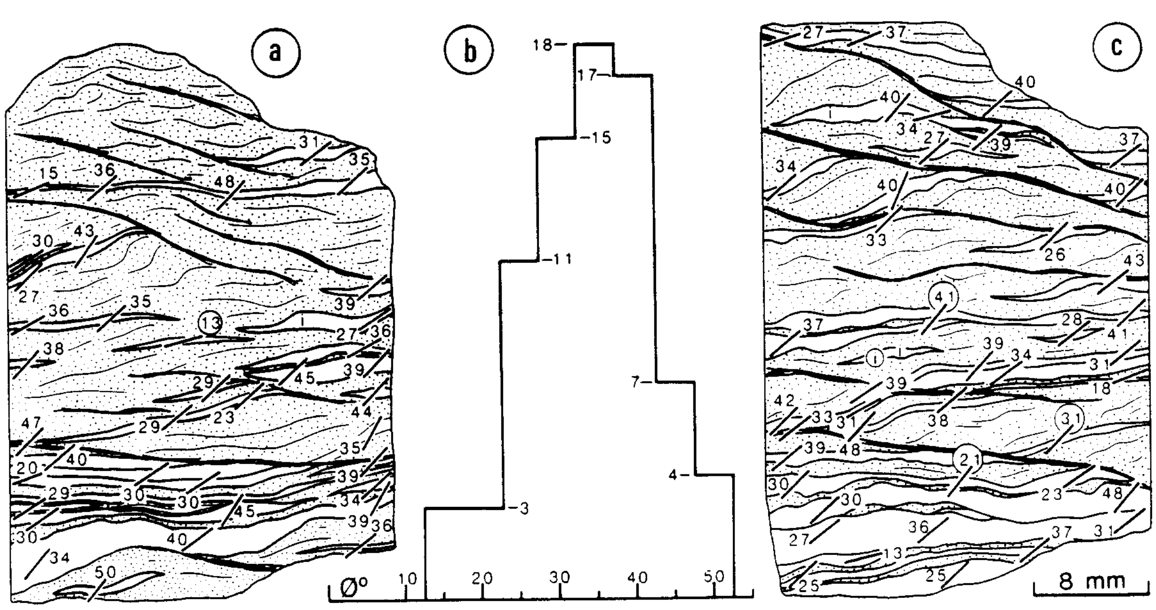

Fig. 2. (a) and (c) Sketches from photographs of the two XZ thin sections (sample no. R35029. University of Melbourne collection), illustrating the angular relationships between the long axes of elongate quartz grains (numbered line-segments) and the mylonitic foliation (fine lines). In the area indicated by (i) this angle is difficult to determine due to equiaxed grains. The ribbons in which the measurements recorded in Fig. 4 were made are circled. The sense of shear is dextral as shown by the obliquity between shear planes (thickened lines) and foliation planes. (b) Histogram of the obliquity between long axes of quartz grains and the mylonitic foliation; 78 measurements.

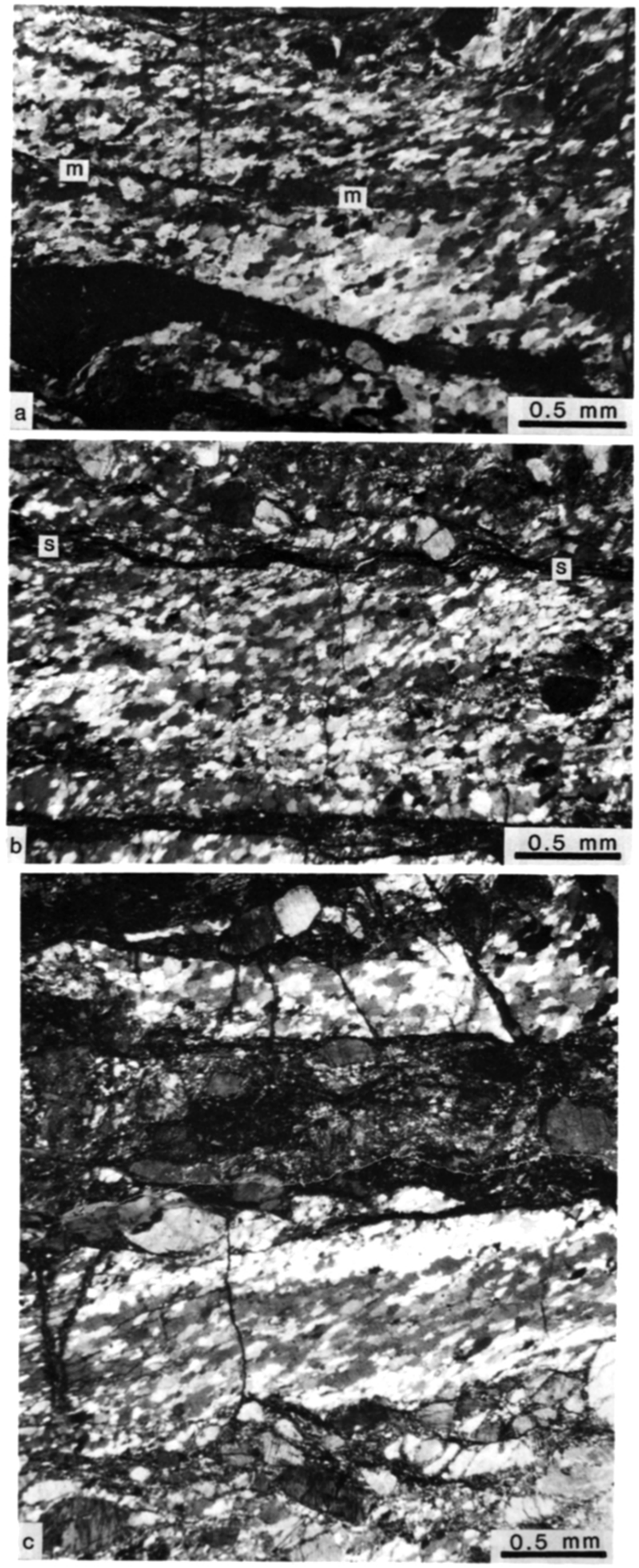

Fig. 3. (a) Typical quartz ribbon with obliquely elongate grains. The dextral sense of asymmetry in the ribbon is the same as that deduced from a spindle-shaped mica. Note the trails of very small (non-recrystallized) micas along a shear plane (m–m) within the quartz ribbon. (b) Quartz ribbon whose top boundary (s–s) is reused by small, higher, shear planes. (c) Two adjacent quartz ribbons with different shape fabrics. Note within the lower ribbon the juxtaposition of elongate grains at the bottom and equiaxed grains at the top.

indicative of deformation at greenschist facies grade of metamorphism (Winkler 1974).

The two thin sections described in this paper were cut in the XZ plane of the rock sample, that is parallel to the lineation and perpendicular to the foliation. These two fabric elements provide a reference framework for the quartz fabrics. The shape fabric of the quartz grains with respect to the ribbon elongation (X) or flattening (XY) is usually weak and subparallel to the mylonitic foliation in the YZ and XY sections, which therefore do not provide any information in this work.

Microstructures

Microstructural criteria such as the asymmetry of recrystallized domains around porphyroclasts and spindle shaped micas (Burg *et al.* 1981, Simpson & Schmid 1983) clearly show that deformation within the mylonite zone has been non-coaxial, with consistent dextral sense of shear. The foliation anastomoses in and out between C-type shear bands (Berthé *et al.* 1979) which are related to localized zones of high shear strain inclined at an angle of 10–25° to the mean foliation direction (Fig. 2). The sense of obliquity between macroscopic fabric and shear bands is also consistent with dextral shearing.

Quartz occurs as isolated equiaxed grains within the mica-rich layers and as elongate (ribbon) aggregates aligned parallel to the macroscopic foliation. The ribbons are up to 1 mm thick and usually longer (length/width > 30/1) than the thin section. They are composed of predominantly inequidimensional (50–100 μm) recrystallized grains of similar orientation (within individual ribbons) aligned oblique to the foliation, the sense of obliquity (Figs. 2 and 3a) being consistent with the dextral sense of shear indicated by both field studies and other microstructural criteria of shear sense. Quartz grain boundaries are irregular and serrate, and the grains show internal strain features (undulose extinction, deformation bands and subgrains) which suggest that the quartz shape fabric formed during dynamic recovery and recrystallization (White 1977). There is no evidence of volume loss (stylolites, concentrations of iron oxides), extensive cataclasis (fractures) or static thermal annealing (straight grain boundaries, triple point junctions).

Shape fabric of quartz grains

Elongate grains that wrap around feldspar clasts (Beta region of Lister & Price 1978) are not considered in the following analysis because they are due to heterogeneous deformation and a complicated strain path on the microscale. The shape of an individual quartz grain in a ribbon can be specified in terms of (1) the axial ratio (R) or the long vs short dimension in XZ sections and (2) the obliquity (ϕ) between the long dimension and the trace of the foliation. Figure 4 illustrates the relationship between the shape fabric R and the degree of obliquity ϕ in adjacent quartz ribbons for the sections sketched in Figs. 2(a) & (c). The axial ratio of each grain was calculated from the dimensional data. The arithmetical mean ($\bar{R}$) is a way to describe the intensity of the foliation F_q defined by the quartz grains in a given ribbon. The arithmetical mean ($\bar{A}$) of the axial product of a grain (A = long × short dimensions) also helps to describe the grain size. The R/ϕ diagrams (Fig. 4) similar to those of Dunnet (1969) show a complete range from the least pronounced fabric (ribbon *a*) to the most intense one (ribbon *e*). For ribbon *a* the plot reveals an unsuspected asymmetry of the population with $\bar{\phi} = 21°$ (ϕ has a fluctuation ≃ 180°). This R/ϕ plot can be interpreted in two separate ways. (1) Preferred growth within a random grain shape fabric of inequant grains whose long axes are inclined at an angle of $\bar{\phi} = 21°$. In that case the preferred alignment of grain long axes post-dates the random fabric. (2) Recrystallization of an earlier population of grains with a strong preferred alignment at $\bar{\phi} = 21°$. In this case the preferred orientation of grain long axes pre-dates the random fabric. The low angle between foliation and preferred grain shape alignment suggests that the second interpretation may be correct. The presently non-oriented fabric may be inherited from a strong one like those of types *d* or *e*. This is a significant observation and will be discussed below.

For all the ribbons studied, the average grain size as measured by $\bar{A}$ remains relatively unchanged in comparison to the average alignment $\bar{\phi}$ (Fig. 4) although the range of grain sizes may be very large (Fig. 6). This supports the idea that the rate of grain growth during deformation has produced a stable grain size (Poirier & Guillopé 1979). It is also worth noting that the ribbon *e* has the highest value of $\bar{R}$ and the lowest value of $\bar{\phi}$, which suggests that this ribbon contains the most highly strained grains and possibly that a critical accumulation of strain may have been reached at this stage before recrystallization.

Quartz **c**-*axis fabrics*

The type of **c**-axis preferred orientation in a quartz-rich area devoid of a second phase depends on (1) the intracrystalline deformation mechanisms (i.e. the operative slip systems and the relative importance of climb and cross-slip), (2) the deformation regime and (3) the intensity of the deformation (Lister & Hobbs 1980). In order to determine whether deformation was coaxial or non-coaxial and to reveal variations in deformation intensity, measurements of the **c** axes of the quartz grains used for the shape fabric analysis were undertaken. The elongate grains display a complete or incomplete crossed girdle pattern (Sander 1970, Lister & Hobbs 1980) intersecting in Y (or contracted towards the Y axis for ribbon *d*) with a unique girdle (ribbon *a*) or a dominant one leading to a marked asymmetry with respect to the mylonitic foliation (Fig. 4). By analogy with other fabric studies in non-coaxial environments (e.g. Burg & Laurent 1978, Lister & Price 1978, Lister & Hobbs 1980, Bouchez *et al.* 1983, Simpson & Schmid 1983, Evans & White 1984), the sense of **c**-axis fabric

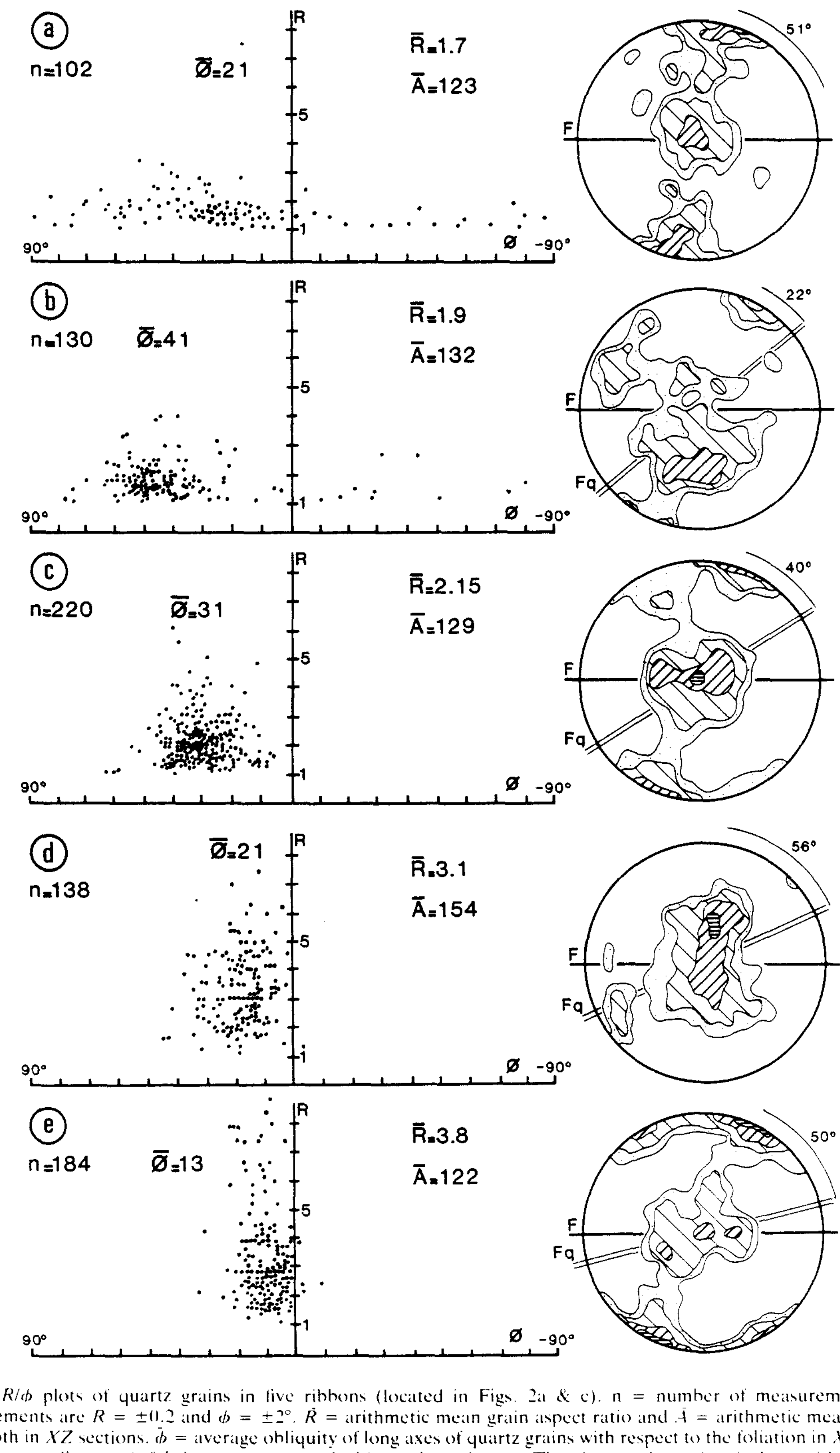

Fig. 4. R/ϕ plots of quartz grains in five ribbons (located in Figs. 2a & c). n = number of measurements. Error measurements are $R = \pm 0.2$ and $\phi = \pm 2°$. $\bar{R}$ = arithmetic mean grain aspect ratio and $\bar{A}$ = arithmetic mean grain size area, both in XZ sections. $\bar{\phi}$ = average obliquity of long axes of quartz grains with respect to the foliation in XZ sections. The corresponding c-axis fabrics were measured with a universal stage. The plots are lower hemisphere with contours at 1, 2, 5 and 10% per unit area. F = mylonitic foliation. F_q = quartz foliation. Indicated angles are between F_q and the dominant girdle, and are +ve in the anticlockwise sense.

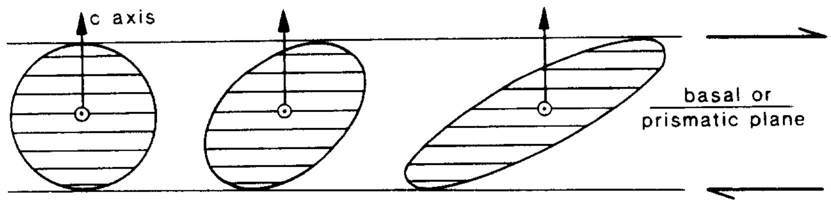

Fig. 5. Sketch to illustrate a progressive increase in aspect ratio of a quartz grain with a constant c-axis direction (vertical or pointing out) when the glide plane (basal or prismatic, respectively) is parallel to the shear plane.

asymmetry with respect to macroscopic foliation indicates a dextral shear. There is no constant angular relationship between the quartz foliation (F_q in Fig. 4) and quartz **c**-axis distribution; in contrast little variation is observed in the obliquity of the dominant girdle to the foliation (Fig. 4). Domainal variations of shape and **c**-axis fabric patterns, as documented in other mylonites (Garcia Celma 1982, Behrmann & Platt 1982) are therefore not important. The existence of a strong **c**-axis fabric in ribbons *a* or *b*, having low $\bar{R}$ values, and its persistence in ribbons *c*, *d* and *e* which have elongate grains suggests that the crystallographic preferred orientation was acquired before the elongate quartz grains were formed in the latter ribbons. More generally it can be deduced that a certain amount of shear strain had been achieved prior to the development of the quartz shape fabric. The basic **c**-axis pattern in ribbons *c*, *d* and *e*, with high point maxima close to *Y*, is generally attributed to glide dominated by the {1010} ⟨a⟩ system and to some associated activity on (0001) ⟨a⟩ (White 1976), which is in accord with the pressure–temperature conditions (Nicolas & Poirier 1976) proposed above for the Fiddlers Green mylonite. Minor activity on other slip systems is due to constraints from neighbouring grains in the polycrystalline aggregate (Bouchez *et al.* 1983). Further deformation with a steady-state end-orientation of the quartz **c** axes was then possible following an evolution as sketched in Fig. 5. This single-slip deformation model (which departs from the multiple-slip theory based on Taylor–Bishop–Hill analysis, e.g. Lister & Hobbs 1980) is possible in the case of progressive simple shear because grains having a slip plane and direction coinciding with the direction of the bulk shear plane are able to deform using one dislocation glide system only.

DISCUSSION

The marked asymmetry of **c**-axis fabrics shows that the deformation of quartz in the Fiddlers Green mylonite includes a significant non-coaxial component. Thus the heterogeneous angular variation between the long axes of quartz grains within the ribbons and the mylonitic foliation cannot be related to axially symmetric shortening. The fact that the ribbon boundaries are neither crenulated (Fig. 3) nor display stylolitic features precludes any effect of a late major deformation. It is concluded that the increase in average axial ratio $\bar{R}$ correlated with a rotation of the quartz grain shape fabric (decreasing angle between grain shape alignment and macroscopic foliation) developed during a progressive non-coaxial deformation.

The variation in orientation of the quartz shape fabric is not progressive and continuous from one side of the sections to the other (Figs. 2a & c). Consequently this variation is not related to a progressive increase in finite strain as observed in a shear-zone model (Ramsay 1980) or to homogeneous shear on the scale of the specimen. The heterogeneous distribution of the shear deformation is rather associated with the 'degeneration' of the mylonite foliation, mainly along the quartz ribbon boundaries, into localized shear planes (Fig. 3b). Some other evidence of localized zones of high shear strains within the ribbons themselves are the trails of very small mica clasts (Fig. 3a) which may represent transient displacement discontinuities, and probably superplastic behaviour in the sense of Boullier & Gueguen (1975). In this respect it is interesting to note that at least two examples of oblique shape fabrics described in the literature (Burg *et al.* 1984, Lister & Snoke 1984) were developed in quartz ribbons or aggregates parallel to shear bands. In rocks having comparable microstructures Brunel (1980) considered that the main mylonitic foliation became a generalized shear plane after its development. Hence we may assume that quartz shape fabrics occurred after mylonitic foliation rotated towards subparallelism with the shear plane and became activated as shear planes. The worst 'subparallelism' of foliation and shear plane observed in the studied sections is 15° which corresponds to a shear strain $\gamma \simeq 3.5$. However, observations in other mylonites commonly provide lower values of this angle ($\simeq 5°$) implying minimum shear strain higher than $\gamma = 11$. Taken as critical shear strains, these estimates are sufficient to account for the quartz **c**-axis fabrics established in ribbons *a* or *b* (Fig. 4) and perhaps for the development of the quartz ribbons themselves which, in any model, need high shear strains for their formation (Boullier & Bouchez 1978).

The different quartz shape fabrics in the Fiddlers Green mylonite result from the combination of deformation and syntectonic recrystallization and the question arises as to whether the structural changes may be cyclic. A cyclic change would account for the unexpected asymmetry of the population for ribbon *a* (both for **c**-axis and shape fabric) accepting that the present fabric overprints a strongly oriented one. This would imply that the deformation sequence would not be *abcde* as presented in Fig. 4 but *bcdea*, before repetition. A fitting scenario would be as follows: A quartz foliation at an angle of

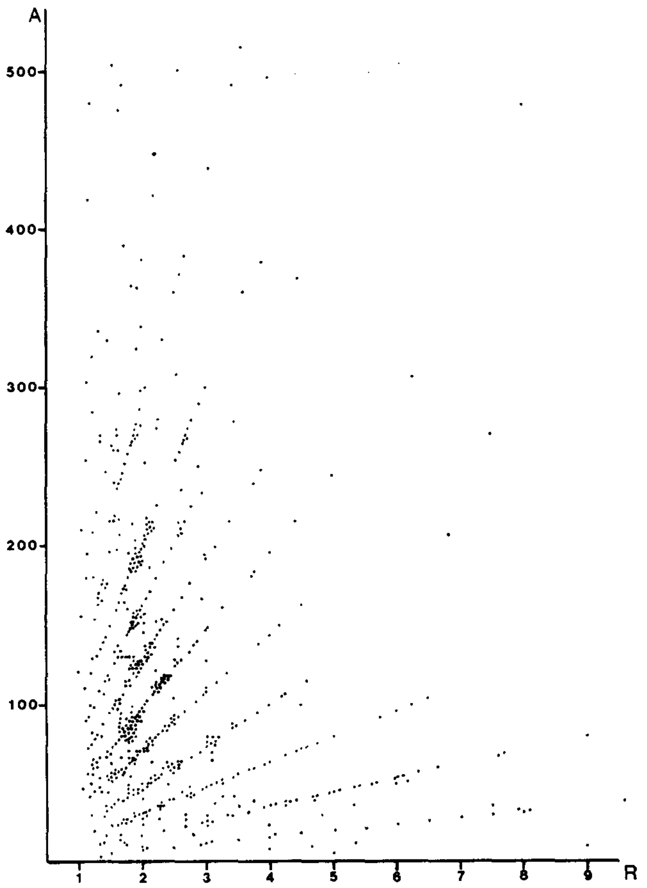

Fig. 6. Plot of grain size (A = area) vs grain aspect ratio (R). Three measurements lie off the plot; they are A/R = 702/2.35; 848/3.3 and 1476/4.55. A few plotted points represent several grains.

30–40° to the mylonitic foliation (as suggested by the obvious preferential obliquity, Fig. 2b) is formed after a critical shear strain of the rock (say $\gamma = 3.5$) is reached (ribbons *b* and *c*, Fig. 4). In places, where localized C-type shear bands develop, this fabric is 'destabilized', leading to a 'catastrophic' evolution towards smaller obliquities (ribbons *d*, then *e*) and becoming rapidly overprinted by (sub)equiaxed fabrics (ribbon 2*a*) which are in turn deformed to result in a ribbon *b* and *c* type fabric. This kind of evolution has also been suggested by Lister & Snoke (1984) who argued that during deformation, grains elongate and rotate towards parallelism with the shear plane; under appropriate conditions grain boundary migration may continuously restore equiaxed grain shapes. The measurements presented here suggest that a critical finite strain for quartz may be reached, before the shape fabric becomes parallel with the shear plane, and that the grain size seems to remain constant during such a deformation–recrystallization history. The expected loop-like plot of grain aspect ratio vs grain size as described by Means (1981) was therefore not found (Fig. 6). It is suggested that the grain growth was inhibited by the low energy of the boundaries, and a low mobility due to nearly identical crystal orientations between neighbouring grains as supported by the strong quartz c-axis fabrics. Since kinetics of grain boundary migration can be a fundamental factor controlling asymmetric shape fabric development, the temperature at which deformation took place must also be important (Higgins 1974, Ohtomo & Wakahama 1983).

A major requirement for a 'steady-state' foliation is that foliation weakening processes operate as effectively as foliation strengthening processes. It appears that in the Fiddlers Green mylonite, the transformation of foliation planes into localized shear planes (Fig. 3c) could be an efficient foliation-destroying process.

In summary, the recording of non-parallel, coeval foliations in a quartz mylonite is not new (see the references in the Introduction), but this is the first study in which increasing aspect ratios along with decreasing obliquities of the long axes of quartz grains with respect to the macroscopic foliation have been reported in a single sample. This observation in a rock which has suffered non-coaxial deformation and within which foliation planes have been transformed into localized and narrow zones of high shear strain, leads to the interpretation that some of the oblique shape fabrics in quartz mylonites are oscillating microstructures. These microstructures may be due to competition between deformation and syntectonic recrystallization, and they are encompassed by the perhaps ill-termed 'steady state' foliation concept. As a consequence, oblique grain shape fabrics could be one of the most reliable shear-sense criteria.

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