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Grain-boundary migration microstructures in a naturally deformed quartzite

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Abstract—In this study several grain-scale microstructures are presented that are thought to demonstrate the migration direction of once-mobile grain boundaries in a naturally deformed quartzite. An analysis is presented of the sense of migration of the boundaries, and the characteristics of the patterns of relative grain growth and shrinkage. Grain-boundary migration seems to be correlated with the relative crystallographic orientations of neighbouring grains for the quartz–quartz grain boundaries, and the pattern of preferred grain growth is roughly symmetrical about the mica foliation plane.

INTRODUCTION

EVIDENCE HAS been accumulating recently to suggest that grains in certain crystallographic orientations in deforming materials will grow at the expense of differently oriented grains (Duval 1981, Urai & Humphreys 1983, Culshaw & Fyson 1984, Jessell 1986, Schmid & Casey 1986). The growing grains are typically characterized by having one of the major slip systems parallel to an orientation of maximum resolved shear stress, which is assumed to be an orientation that accumulates lower levels of stored energy than other orientations. This idea has also been investigated by Knipe & Law (1987), who relate subgrain sizes and dislocation densities to crystal orientations. It is the contrasts in stored strain energy that are thought to drive grain-boundary migration. The object of this study was to identify microstructures that reveal which way grain boundaries were migrating, and to see in turn if these structures revealed an orientation dependence. This paper represents a first attempt to correlate the polarity of grain-boundary migration with crystallographic orientations in a naturally deformed rock.

SAMPLE DESCRIPTION

The specimen described here was collected by T. C. Ray at a road outcrop in Avery's Gore, Belvidere, Vermont, U.S.A., from the Cambrian Ottauquechee Quartzite, which forms part of the Green Mountain anticlinorium. The sample was part of a 3 m thick quartzite unit interlayered with black phyllites and thin quartzite layers. The outcrop displays refolded fold structures, and is thus probably not an ideal test specimen, but it shows numerous grain-boundary migration microstructures. The sample breaks along lineated cleavage surfaces that in thin-section (Fig. 1a) are seen to be semi-continuous films of muscovite. The rock is about 90% quartz, with 5% muscovite, 5% graphite, small amounts of plagioclase, calcite, magnetite and a few scattered zircons.

The quartz does not display any grain shape foliation and the variably irregular grain boundaries suggest that it has been at least partially recrystallized. Visual inspection suggests that the grain size of the quartz varies inversely with the amount of mica present, but grain diameters in two dimensions averaged about 60 μm.

In sections cut perpendicular to the lineation there are anastomosing muscovite films with a few relict fold noses present. It needs to be emphasised that it is this cylindrically anastomosing fabric that produces the lineation on the cleavage surfaces, rather than any preferred quartz grain elongation. Perpendicular to the foliation and parallel to the lineation the muscovite films are essentially straight and sub-parallel (Fig. 1b). As well as these crenulated films of muscovite, which are associated with locally dense amounts of graphite, there is a set of much cleaner, spatially more evenly distributed, more idioblastic muscovite grains. Perpendicular to the lineation these have a much more variable orientation than the muscovite films.

The plagioclase grains occur within the quartz-rich layers, singly or as aggregates of two or three grains. They are pink in plane-polarized light, occasionally twinned and they have approximately the same grain size as the quartz grains. Some of the larger grains contain dense cores of foliated opaque inclusions, and all contain more inclusions than the quartz groundmass.

Calcite occurs as large (grain size 300 μm), very irregular grains within the quartz groundmass, with many of the enclosed quartz grains being almost circular in section.

The *c*-axis fabric for quartz grains was compiled from measurements on a square grid. A lower hemisphere equal-area projection of the fabric is shown in Fig. 2, and it can be seen that the *c*-axes are more or less evenly distributed, with only a weak preferred orientation perpendicular to the lineation.

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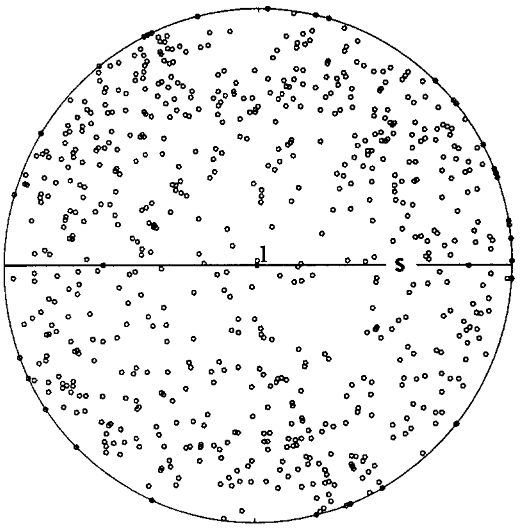

Fig. 2. Lower hemisphere equal-area projection of *c*-axis orientations in the study area, chosen on an orthogonal grid. 693 points. S: foliation. l: lineation.

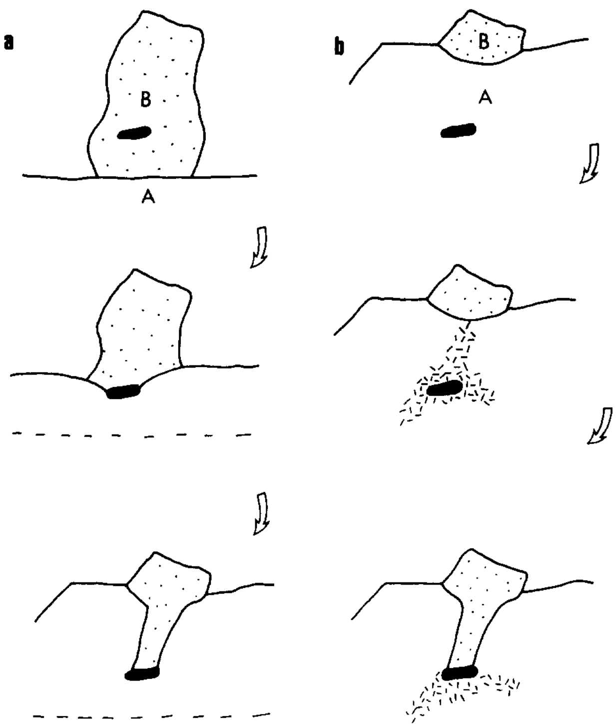

Fig. 4. (a) Postulated mode of formation of 'pinning' microstructure. A and B are quartz grains, the black grain is a mica. (b) Alternative hypothesis to explain 'pinning' microstructure. Cross-hatched area represents area of damaged quartz lattice around mica grain, which is preferentially consumed by grain B.

GRAIN-BOUNDARY MIGRATION MICROSTRUCTURES

The classical view of grain-boundary migration in a deforming polycrystal originates from studies on metals. Interpreting experiments on statically recrystallizing aluminum, Bailey & Hirsch (1962) envisaged the bowing out of an initially straight grain boundary driven by a difference in stored strain energy. Thus, it is often assumed that in dynamically recrystallized rocks the preserved grain-boundary curvature reflects the sense of motion of the boundary, specifically that the direction of convexity is the direction of migration. My observations of grain boundaries in *in situ* experiments show that the curvature of the boundary is an unreliable indicator of its sense of motion (Jessell 1986). Consequently more dependable microstructures need to be found if once-mobile boundaries are to be interpreted with confidence. In this study four microstructures are presented that seem to indicate the sense of grain-boundary migration, together with a fifth inferential method for determining which of the two neighbouring grains would consume the other. Although in reality a single grain can be gaining volume on one boundary while simultaneously losing material on another boundary, or even on another part of the same boundary, in this paper the terms 'growing' and 'shrinking' will be used to signify the local gain or loss of material across a boundary, without any regard for the net volume change of the grain as a whole. For Figs. 4–7 grain A is 'growing' at the expense of grain B.

Pinning microstructure

The simplest microstructure observed in thin-section, the pinning microstructure, consists of a quartz–quartz boundary which contains a small second-phase grain, usually muscovite, but occasionally magnetite. When there is a distinct change of curvature of the quartz–quartz boundary across the second-phase grain, as in Fig. 3(a), one hypothesis is that the second phase is pinning the position of the boundary, and the curvature of the boundary shows the sense of motion of the boundary prior to its being pinned. Gladman (1966) showed iron grain boundaries being pinned by aluminum nitride particles during grain growth experiments. Figure 4(a) shows a cartoon of the suggested history of the observed microstructure. An alternative hypothesis (Knipe pers. comm. 1986) is that the mica was present in the interior of grain A, and that its differing mechanical properties resulted in localized damage to the quartz lattice, and that grain B, bulged into this damaged zone (Fig. 4b). The formation of subgrains has indeed been observed at the tips of fibers embedded in norbornene (C_7H_{10}) deformed in a see-through apparatus (Teixell pers. comm. 1986), and microcracks have been observed extending into quartz grains from micas by Simpson (1981) and Brunel (1986). If this is true here, one would expect to see similarly damaged zones, such as subgrains, adjacent to micas; but these are not found. In this study the pinning hypothesis was adopted in the analysis. This is the most common grain-boundary migration microstructure found, making up 61 examples out of the total of 78 measured. Thin-sections which fail to section the mica grain will show grain B bulging into grain A, and thus the simple use of the curvature of the boundary would in this case lead to the opposite interpretation of the migration direction, again suggesting that bulges alone can be unreliable indicators of the sense of migration.

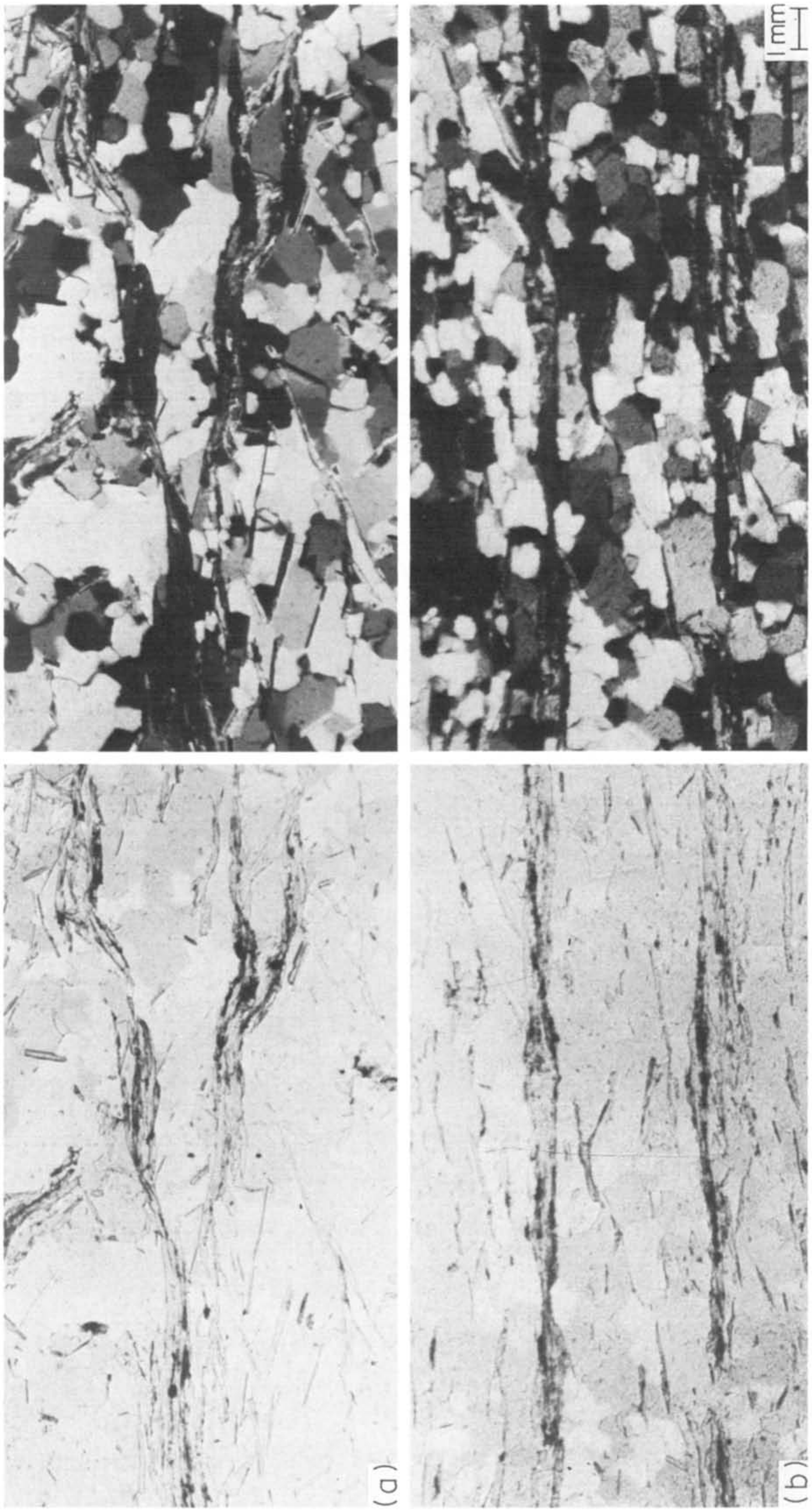

Fig. 1. (a) Photomicrographs in plane and polarized light of quartzite; slide cut perpendicular to foliation and to lineation, showing anastomosing nature of muscovite films. (b) Photomicrographs in plane and polarized light of quartzite cut perpendicular to foliation and parallel to lineation.

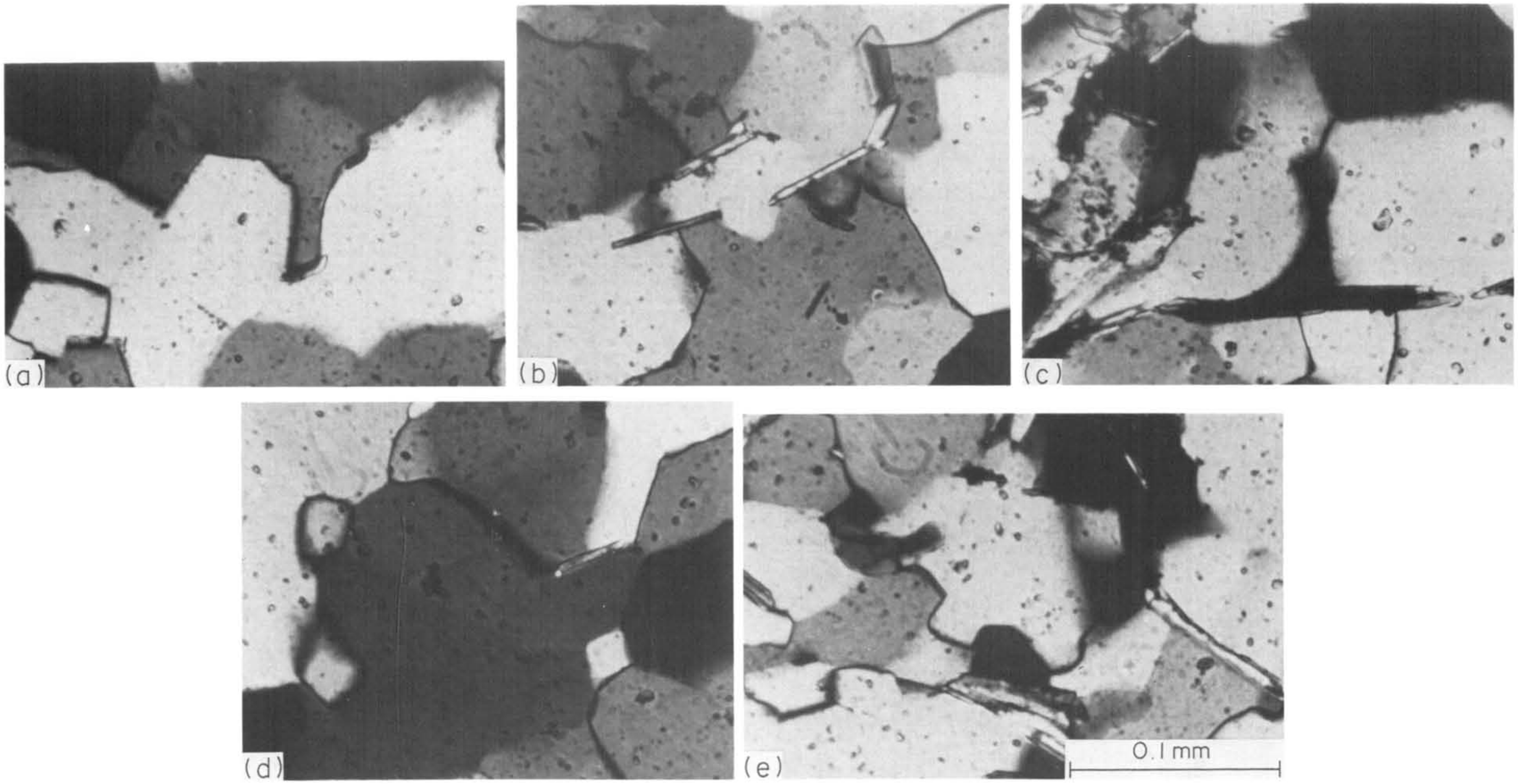

Fig. 3. (a) Photomicrographs of (a) 'pinning' microstructure, (b) 'window' microstructure, (c) 'dragging' microstructure, (d) 'left over grains' and (e) 'castellate' microstructure.

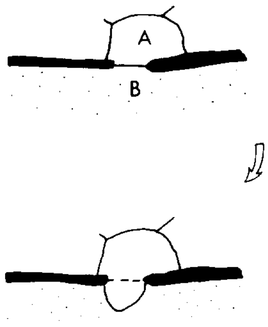

Fig. 5. Postulated mode of formation of 'window' microstructure. A and B are quartz grains, the black grains are micas.

Window microstructure

A related microstructure is made up of two colinear (in thin-section) muscovite grains with a gap between them forming a window between two quartz grains (Fig. 3b). In this case any bulge of one grain into the other is most likely to have resulted from the simple migration of the boundary, as depicted in Fig. 5. This microstructure was less common (only nine examples), since the likelihood of encountering the required geometry of mica grains is relatively low.

Dragging microstructure

The interpretation of the third microstructure, the dragging microstructure, depends on the observation that in the first case the quartz–quartz boundaries appear to be pinned by mica grains. When quartz–quartz boundaries meet muscovite grains at a high angle to the basal planes of the micas, in two recorded instances the boundary shows a sharp deflection as it approaches the mica, this results in an acute angle (Fig. 3c). The boundary near a quartz–quartz–mica triple junction is interpreted as having been inherently less mobile than a free quartz–quartz boundary, so that the acute angle points towards the growing grain (Fig. 6). Again, localized disruption of the quartz lattice adjacent to mica grains could lead to the same geometry with the opposite interpretation, but the former hypothesis is the one adopted in the analysis.

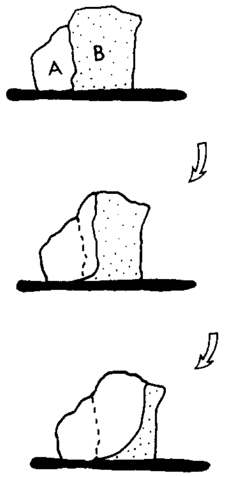

Fig. 6. Postulated mode of formation of 'dragging' microstructure. A and B are quartz grains, the black grain is a mica.

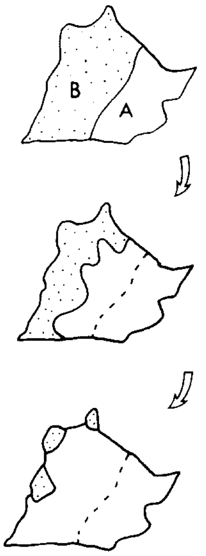

Fig. 7. Postulated mode of formation of 'left-over grains', after Urai (1983). A and B are quartz grains.

Left-over grains

The fourth sense of motion indicator (observed in four instances) differs from the first three types in that it does not depend on the presence of a second phase. By observing the extinction directions of nearby grains, followed by confirmation using a U-stage, it was possible to show that isolated grains (at least in two dimensions) shared common *c*-axis orientations (Fig. 3d). *In situ* experiments on deforming salt-rock (bischovite) by Urai (1983), showed how left-over grains could form as the result of one grain consuming all but a few areas of a neighbouring grain (Fig. 7). It is conceivable that the three isolated grains are fingers of one grain that connect out of the plane of the specimen and that this lobate grain was growing preferentially along grain boundaries; such complex shapes, however, are not observed anywhere in this thin-section or one cut perpendicular to the foliation and parallel to the lineation.

Castellate microstructure

Although it is not strictly a sense of motion indicator, a fifth microstructure was observed and recorded, because as in the last case, it does not depend on the presence of a second phase, and it still provides the same type of information as the previous indicators. This microstructure is shown in Fig. 3(e) and consists of a larger quartz grain sharing a castellate boundary with two or more smaller quartz grains. There are two likely interpretations of this microstructure: either the large grain (grain D of Fig. 8) was preferentially consuming the small grains that it indents (grains A and C) or the larger grain was itself being preferentially consumed by the indenting grain (grain B). In either case the impli-

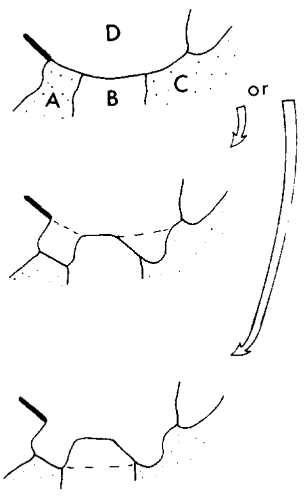

Fig. 8. Alternative postulated modes of formation of 'castellate' microstructure. A–D are quartz grains.

cation is that grain B had some property that would better lead to its survival, either in terms of its orientation or some other characteristic, compared to its neighbours (grains A and C).

ANALYSIS

The results in this section are based on data collected from a 1.8 × 1.5 cm rectangular area of the thin-section cut perpendicular to the foliation and to the lineation. In all, 78 microstructures of the five types described above were documented, with each type randomly distributed within this area. Only one thin-section was examined as part of this preliminary study, as there proved to be a sufficient range of crystallographic orientations present.

Figure 9 shows the orientations of the *c*-axes of growing and shrinking grains, plotted on separate lower hemisphere equal-area projections, and the analysis that follows is based on these data. The distributions of growing and shrinking grains at first sight do not look very different, although the distributions will in part reflect the overall *c*-axis distribution, so direct comparisons are not that useful. One means of testing the hypothesis of orientation-dependent grain-boundary migration is to investigate variations in the ratio $G/(G + S)$, where G is the number of growing grains for a given orientation, and S is the number of shrinking grains for that orientation. The stereonet was divided up into 36 segments of equal area and for each segment this ratio was then calculated (Fig. 10a). This ratio gives the probability of a grain in a given orientation being a growing grain, but can also be thought of as an 'index of survivability', with orientations having an index of 1 being most likely to have been growing. Segments which did not contain any growing or shrinking grains are left empty. It should be noted that this analysis does not take into account grain-boundary orientations nor the full crystallographic misorientation of the two grains, so that only two of the seven degrees-of-freedom for a grain boundary are compared. A uniform distribution of the 78 data points amongst the 36 segments would result in 2.17 points per segment, so the individual ratio values in Fig. 10 do not have a high significance; however taken as a whole the pattern reflects an orientation dependence. In Fig. 10(a) grains with *c*-axis orientations within the plane of the foliation and perpendicular to the lineation have the highest indices, with systematically decreasing values away from this orientation. This pattern is more clearly displayed in the contoured stereonet (Fig. 10b) and to a first approximation the pattern seems to have two reflection symmetry planes: one parallel to the foliation, and the other perpendicular to the foliation and parallel to the lineation.

DISCUSSION

The identification of grain-boundary migration micro-

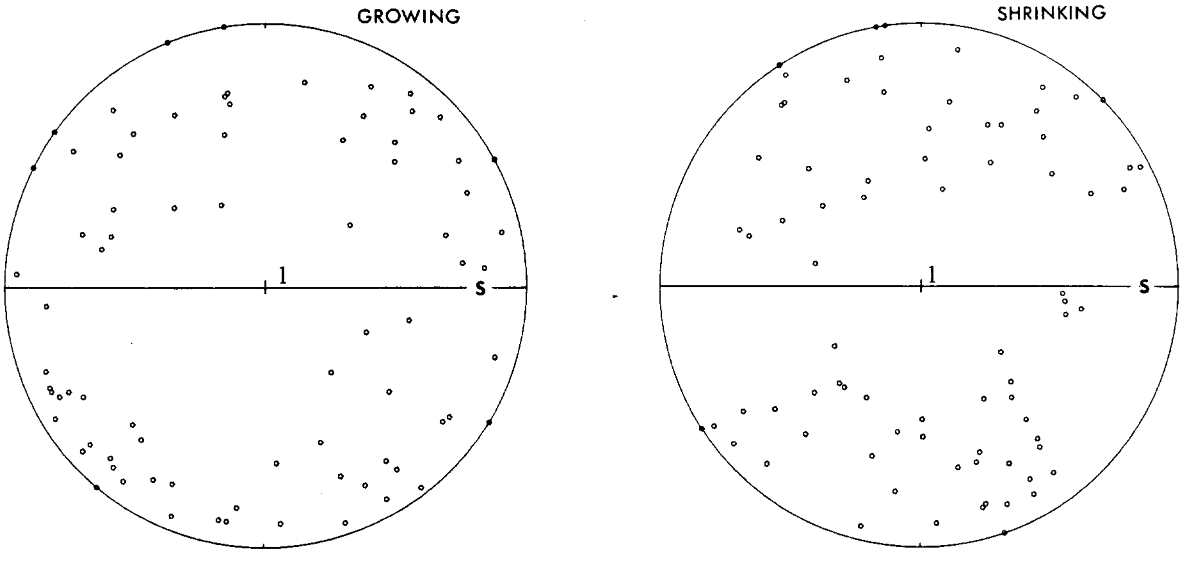

Fig. 9. Lower hemisphere equal-area projections showing *c*-axis orientations of growing and shrinking grains. S: foliation. l: lineation.

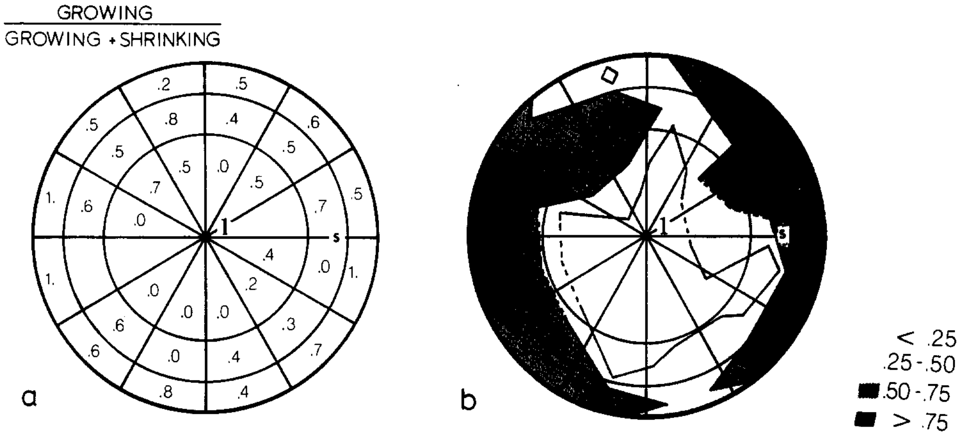

Fig. 10.(a) The ratio $G/(G + S)$ for 36 orientation segments plotted on a lower hemisphere equal-area projection. (b) Same data as (a), contoured at levels of 0.25, 0.50 and 0.75. S: foliation. l: lineation.

structures in this rock provides a test of whether grain-boundary migration was dependent on orientation in a naturally deformed quartzite. Unfortunately the limited data set ensures that only tentative conclusions can be made. The maximum of preferred grain growth is roughly symmetrically disposed with respect to the major fabric elements, which suggests that this pattern is not due to chance. This sub-parallelism also suggests that the interpreted microstructures and the mica fabric developed simultaneously, although of course it is possible that two deformation events had similar geometries but took place at different times, or even that the mechanical behaviour of the muscovite films locally controlled a later deformation event.

The use of the geometry of microstructures to infer the sense of motion of grain boundaries does not in itself make any assumptions as to the conditions of recrystallization. In order for this analysis to be interpreted it has to be demonstrated that the grain boundaries migrated in a deforming rock, rather than after the deformation event. If the recrystallization was static, and the driving force was the reduction of grain-boundary energy, the 'window', 'dragging' and 'castellate' microstructures would not still remain, as they represent unfavourable boundary configurations, so this case can be ruled out. If the recrystallization was static, but driven by stored strain energy within the grains left over from deformation, i.e. a metadynamic recrystallization, the given interpretation of these microstructures should be correct as they still reflect the orientation of the principal stresses at the time of the deformation.

The diffuse nature of the *c*-axis fabric and the lack of a grain shape foliation mean that little information pertaining to the nature of the deformation geometry and processes that formed these rocks is revealed by these normally more useful analyses. Assuming that the grain-boundary migration is driven by variations in stored energy reflecting the plastic anisotropy of quartz, it is possible to interpret the pattern of the 'growth index' as mimicking the underlying pattern of stored energy. Application of this analysis to areas where a strong crystallographic preferred orientation is present may allow interesting comparisons to be made between the developed fabric and the inferred pattern of stored energy, since this may reveal which part of the fabric can be ascribed to recrystallization processes.

CONCLUSIONS

(1) It proved possible to identify a number of microstructures which are thought to indicate the migration direction of once-mobile quartz grain boundaries.

(2) Given the small data set, the pattern of migration of the once-mobile boundaries suggests an orientation dependence, and the *c*-axis orientation of maximum preferred grain growth is roughly within the plane of the foliation and perpendicular to the lineation.

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REFERENCES

Bailey, J. E. & Hirsch, P. B. 1962. The recrystallisation process in some polycrystalline metals. *Proc. R. Soc. Lond.* **A267**, 11–30.
Brunel, M. 1986. Ductile thrusting in the Himalayas: shear sense criteria and stretching lineations. *Tectonics* **5**, 247–267.
Culshaw, N. G. & Fyson, W. K. 1984. Quartz ribbons in high grade gneiss: modification of dynamically formed quartz *c*-axis preferred orientations by oriented grain growth. *J. Struct. Geol.* **6**, 663–668.
Duval, P. 1981. Creep and fabrics of polycrystalline ice under shear and compression. *J. Glaciol.* **27**, 129–140.
Gladman, T. 1966. On the theory of the effect of precipitate particles on grain growth in metals. *Proc. R. Soc. Lond.* **A294**, 298–309.
Jessell, M. W. 1986. Grain boundary migration and fabric development in experimentally deformed octachloropropane. *J. Struct. Geol.* **8**, 527–542.

Knipe, R. J. and Law, R. D. 1987. The influence of crystallographic orientation and grain boundary migration on microstructural and textural evolution in an *S–C* mylonite. *Tectonophysics* **135**, 155–169.

Schmid, S. M. & Casey, M. 1986. Complete fabric analysis of some commonly observed quartz *c*-axis patterns. *A.G.U. Geographical Monograph* 36.

Simpson, C. 1981. Ductile shear zones: a mechanism of rock deformation in the orthogneisses of the Maggia Nappe, Ticino. Unpublished Ph.D. Thesis, ETH, Zürich.

Urai, J. L. 1983. Deformation of wet salt rocks. Unpublished Ph.D. Thesis, University of Utrecht.

Urai, J. L. & Humphreys, F. J. 1981. The development of shear zones in polycrystalline camphor. *Tectonophysics* **78**, 677–685.