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Oblique fabrics in porphyroclastic Alpine-type peridotites: a shear-sense indicator for upper mantle flow

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Abstract—A detailed structural study in Alpine-type peridotites of the ultramafic Voltri Massif in NW Italy reveals the existence of oblique fabrics in porphyroclastic tectonites. The dominant foliation of these tectonites is defined by stretched pyroxenes and aligned grains of spinel, which formed as a result of high-temperature flow in a km-scale shear zone bounded by a wall-rock of granular, virtually undeformed spinel-lherzolites. The oblique fabrics in these tectonites are characterized by elongate olivine grain shapes and a marked grain boundary alignment oriented at an angle of up to 40° to the tectonite foliation. In addition, kink-type subgrain boundaries are frequently parallel to (100), and show a preferred orientation at large angles to the tectonite foliation. Olivine lattice preferred orientation patterns in tectonites with this oblique grain shape fabric show bimodal distributions of [100] and [001]. The oblique fabrics and bimodal orientation distributions are inferred to result from the formation of high-angle kink-like grain boundaries followed by deformation-induced grain boundary migration at the expense of unfavourably oriented grains.

The sense of shear derived from the oblique fabrics is consistent with the sense of shear derived from the lattice preferred orientation patterns, asymmetric pyroxene porphyroclast systems and the map-scale geometry of the shear zone in which these microstructures occur. It is therefore suggested that these oblique grain shape fabrics represent a reliable kinematic indicator for high-temperature flow in upper mantle shear zones.

INTRODUCTION

LARGE-SCALE, regionally imposed deformation of the middle and lower crust is often localized within ductile shear zones. This has motivated structural research into the kinematics of ductile flow in such zones and, more specifically, into practical ways by which various small-scale and microscale structures in shear zones can be used to infer details of the kinematics of the deformation. These studies have resulted in the recognition of a growing number of monoclinic fabric elements which may serve as kinematic or shear-sense indicators (e.g. White *et al.* 1982, Simpson & Schmid 1983, Passchier 1986). One such monoclinic fabric element is a grain shape fabric of elongate recrystallized grains, oriented oblique to the dominant mylonitic foliation. These structures are currently referred to as oblique fabrics (e.g. Law *et al.* 1984), and form the *S*-component of type II *S–C* mylonites (Lister & Snoke 1984). Oblique fabrics have been described from shear zones in many different rock types including quartzites (e.g. Law *et al.* 1984, Lister & Snoke 1984, Burg 1986, Platt & Behrmann 1986, Dell'Angelo & Tullis 1989) and carbonate rocks (Simpson & Schmid 1983, Schmid *et al.* 1987, De Bresser 1989), as well as from experimentally deformed analogue materials such as ice (Burg *et al.* 1986) and octachloropropane (Jessell 1986).

In this study we investigate a microstructure, similar to the oblique fabrics reported from crustal shear zone rocks, developed in a km-scale high-temperature shear zone in the Erro–Tobbio peridotites of the Voltri Massif (Ligurian Alps, NW Italy). The aim of this paper is to examine the oblique microstructure and its development, and to evaluate its significance as a shear-sense indicator for high-temperature non-coaxial flow in the upper mantle.

GEOLOGICAL SETTING

The Voltri Massif in the Ligurian Alps (Fig. 1) includes the largest exposure of ultramafic rocks in the Alpine suture zone. The massif is located at the southernmost extremity of the Alpine arc, immediately northwest of Genova, and is separated from the Apennines to the east by the Sestri–Voltaggio zone. Previous

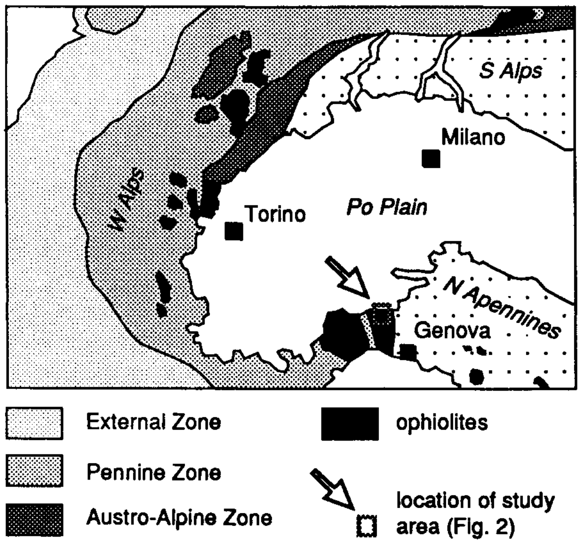

Fig. 1. Geological sketch map of the Western Alps, with location of study area in the NE Voltri Massif.

work (Chiesa *et al.* 1975, Piccardo *et al.* 1977) has shown that the large-scale structure of the massif is dominated by a number of subhorizontal thrust sheets, dismembered by younger N–S-trending faults. The uppermost thrust sheet is made up of a subcontinental to transitional, lherzolite-dominated peridotite body, the Erro–Tobbio peridotite.

The microstructure of concern in this paper occurs in lherzolites exposed in the eastern part of the Voltri Massif, in an area around Mt. Tobbio (Fig. 2). The main thrust contact between the Erro–Tobbio peridotite and underlying serpentinites is strongly dissected by dextral and sinistral oblique slip faults. However, coherent outcrop of the Erro–Tobbio peridotite occurs around Mt. Tobbio in the eastern part of the map area, as well as further west in the Gorzente River section and around Mt. Tugello. In these exposures, which are less affected by later movement zones, a gradual transition occurs over a distance of several hundreds of metres between granular, virtually undeformed peridotites in the north and intensely foliated, porphyroclastic peridotite tectonites to the south (Drury *et al.* 1990, Vissers *et al.* 1991). This transition is marked by a gradually increasing intensity of the tectonite foliation, suggesting an increasing strain from the granular peridotites towards the strongly foliated tectonites. In the more intensely deformed rocks, elongate and locally asymmetric pyroxene porphyroclast systems (Passchier & Simpson 1986) define a stretching lineation, which runs subhorizontal in the Gorzente River section, but is more steeply oriented around Mt. Tobbio, presumably as a result of rigid-body rotations related to Alpine imbricate stacking. The asymmetric porphyroclast systems as well as the sense of progressive rotation of pyroxenite and dunite layers into parallelism with the tectonite foliation are consistent with a sinistral transcurrent shear during deformation, but we emphasize that rigid-body rotations, e.g. during thrusting and emplacement of the km-scale peridotite fragments, are entirely unconstrained. Irrespective of these geometrical problems induced by the later stages of Alpine thrusting, it is evident from the map pattern (Fig. 2) that the tectonics occur in a km-scale zone of localized deformation. Minor but systematic changes in the orientation of the tectonite foliation, over distances of the order of 50 m, associated with small variations in the angle between pyroxenite layers and the foliation probably reflect variations in strain magnitude. However, apart from such variations, the structures are remarkably homogeneous at outcrop to 50 m scale. This suggests that the oblique microstructures described below are unrelated to local heterogeneities of the flow field.

Thermobarometry by Hoogerduijn Strating (1991) indicates that deformation in the tectonite shear zone occurred at temperatures >950°C in the spinel-lherzolite stability field, which implies that the tectonites formed in the upper mantle and that they are unrelated to the later stages of deformation associated with emplacement at crustal levels and uplift of the peridotite to the surface. The tectonites and adjacent granular peridotites are interpreted as a relict of a km-scale shear zone system, formed during localized non-coaxial flow in the upper mantle at the onset of lithosphere extension and continental breakup, prior to the development of the Piemonte–Ligurian Ocean (Vissers *et al.* 1991).

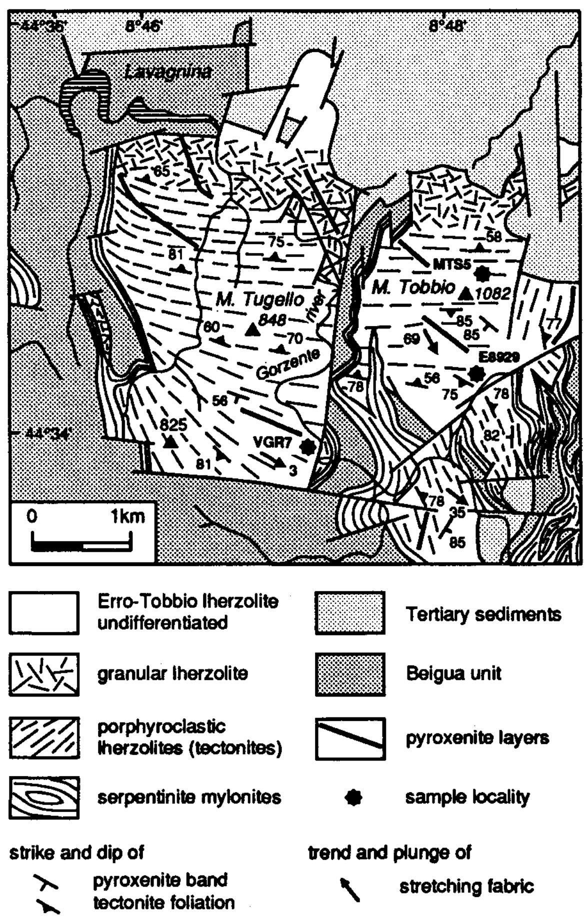

Fig. 2. Structural map of the Mt. Tobbio area, with sample locations.

MICROSTRUCTURES

The microstructure of the tectonites is dominated by aligned elongate and tabular olivine grains, parallel to the long dimensions of stretched orthopyroxenes and partly recrystallized clinopyroxene aggregates (e.g. Bouillier & Nicolas 1975, Drury *et al.* 1990). However, several samples from the Erro–Tobbio tectonites (labelled MTS5, E8929 and VGR7, sample localities shown in Fig. 2) show a microstructure characterized by elongate olivines oriented at angles of 25–40° to the tectonite foliation (Fig. 3a), similar to the *S*-component of a type II *S–C* mylonite as defined by Lister & Snoke (1984). Unfortunately, late serpentinization and weathering completely conceal the oblique microstructure in outcrop, such that its extent is as yet poorly documented. Line drawings on the basis of photomicrographs (Fig. 3b) reveal the details of the deformation and recrystallization microstructures which, at first inspection, are not immediately obvious due to a strong lattice preferred orientation and a variable degree of serpentinization. Serpentinization, in particular, often obscures the oblique microstructure, however, in some cases it strongly accentuates a grain boundary alignment.

The microstructure shown in Fig. 3 is oriented such that the tectonite foliation defined by stretched pyroxenes and elongate spinel aggregates is horizontal. Oblique to this foliation, a grain shape fabric is defined by slightly inequant to highly elongate olivine grains. The elongate grains commonly dominate the microstructure (~70%), they show aspect ratios of up to 5:1 and have smoothly curved to serrate grain boundaries. The grain size of the olivines ranges between 0.2 and 2 mm, with average values of 0.5 mm. Kink-type subgrain boundaries are <10° to (100), and are mostly oriented at somewhat larger angles (70–80°) to the tectonite foliation than the oblique grain shape fabric. It appears that at least some grain boundaries are high-angle kink-type boundaries.

Lattice preferred orientation patterns

Petrofabrics in domains with the oblique fabric have been determined optically, in thin sections oriented parallel to the stretching lineation and perpendicular to the foliation. The main characteristic of the lattice fabrics is a double point maximum distribution of olivine [100] and [001] (Fig. 4c). The dominant [100] concentration is oriented close to the tectonite lineation, while a second concentration is oriented at a large angle (70°) to this dominant maximum and at a small angle to the trace of the oblique fabric. Olivine [010] is concentrated in a point maximum within the plane of foliation and perpendicular to the stretching lineation. Olivine [001] also shows a double maximum pattern, with the dominant concentration subperpendicular to the foliation and a second maximum close to the lineation.

AVA analysis

In order to investigate the topology of the bimodal olivine [100] and [001] distributions, we applied an AVA analysis (Achsen-Verteilungs-Analyse, Sander 1950) of a sample with the oblique fabric and associated bimodal lattice preferred orientation patterns (Fig. 4). This analysis shows that the two-point maxima of olivine [100] and [001] are related to two classes of grains, with the dominant olivine [100] and [001] point maxima corresponding to the non-shaded grains in Fig. 4(b), whilst the secondary point maxima are related to the shaded grains.

We will now consider these two groups of grains in some detail. From careful inspection of Fig. 4(b), it follows that some microstructural differences exist between both grain groups. The unshaded grains are often relatively large, they show the highest aspect ratios and commonly host the (100) tilt walls. Instead, the shaded grains are much smaller and show lower aspect ratios. They tend to occur in elongate clusters, with dimensions similar to those of the large, unshaded grains. They also occur as narrow elongate grains, located at the grain boundaries of the non-shaded grains. Note also that tilt walls sub-parallel to (100) are distinctly less common in the shaded grain group.

The traces shown in the individual grains have been drawn parallel to the trace of the olivine (001) plane, which is known as a high temperature olivine slip plane (Carter & Avé Lallemant 1970). As all high-temperature slip systems of olivine are of the form {Okl} (Carter & Avé Lallemant 1970, Phakey *et al.* 1972), it follows that the unshaded grain group is oriented *favourably* for intracrystalline slip on the high-temperature olivine slip systems, and that the shaded grain group is *unfavourably* oriented for slip on these systems, both with respect to feasible orientations of the kinematic framework during development of the foliation in the tectonite shear zone (oriented horizontal in Fig. 4).

Dislocation substructure

Two different recrystallization mechanisms can account for the microstructure of the unfavourably oriented grains located at the grain boundaries of large, favourably oriented grains: (1) nucleation recrystallization, i.e. the unfavourably oriented grains may have nucleated at high-angle kink-type boundaries during deformation; and (2) progressive overgrowth of unfavourably oriented grains by favourably oriented grains (Urai *et al.* 1986, Drury & Urai 1990). These two alternatives are illustrated in Figs. 6(a) & (b), respectively. In each case the newly recrystallized phase would be expected to show the lowest dislocation density; the two different options may be discriminated by investigating the dislocation substructure of both grain types. In order to do this, we have decorated the dislocations in the samples at 900°C for a time span of 20 min according to the decoration technique described by Kohlstedt *et al.*

(1976) and extended by Karato (1987). This method allows a first-order approximation to the dislocation densities in the two grain types. Figure 5 shows the dislocation substructure of favourably oriented grains (left column) vs unfavourably oriented grains (right column). With the number of decorated dislocations per unit area as a measure of the dislocation density, it follows that the dislocation density of the unfavourably oriented grains ranges from about the same to approximately twice the dislocation density of the favourably oriented grains. This can possibly be explained by tangling of dislocations in unfavourably oriented grains, during slip on *non-easy* slip planes, resulting in a high dislocation density. This suggests that the unfavourably oriented grains are remnants with high dislocation densities rather than newly nucleated grains with low dislocation densities, and that migration recrystallization during deformation led to progressive overgrowth of the unfavourably oriented grains by favourably oriented ones.

DISCUSSION

Based on the above microstructural observations we suggest the following deformation and recrystallization mechanism to explain the development of oblique fabrics in the high-temperature tectonites of the Erro–Tobbio lherzolite (Fig. 7). A dominantly simple shear deformation will cause intracrystalline slip on the olivine high-temperature slip systems (Fig. 7a). With progressive strain, (100) tilt walls develop and a subgrain boundary alignment initiates an oblique fabric. With progressive shear, shown dextral in Fig. 7, the tilt walls rotate into high-angle grain boundaries or kinks (Fig. 7b), and some of the favourably oriented grains rotate away from their favourable orientation (subgrain rotation), which eventually results in a bimodal lattice preferred orientation pattern. The grain shape fabric, characteristic for dextral shear, is now well developed. With ongoing deformation, a heterogeneous dislocation density between favourably and unfavourably oriented grains is introduced and deformation-induced grain boundary migration leads to progressive overgrowth of the unfavourably oriented grains (Fig. 7c).

The above mechanism accounts for the oblique microstructure as well as for the lattice fabric, by explaining these as the results of progressive subgrain rotation and deformation-induced migration recrystallization. From the geometry of the process it follows that the sense of shear inferred from the oblique fabric should be consistent with that inferred on the basis of an oblique orientation of the associated lattice fabrics. In the Erro–Tobbio tectonites the sense of shear derived from the oblique fabrics is entirely consistent with the sense of shear inferred from all other shear-sense indicators. The microstructure is effectively reset when all unfavourably oriented grains are completely consumed and (100) tilt walls may form again. This allows a steady-state microstructure to develop during ongoing flow in the shear zone.

Although some similarities exist between the oblique fabrics described from mylonitic quartzites and the olivine microstructures documented here from deformed lherzolites, they are quite different in many respects. First, many of the oblique fabrics in quartzose tectonites show much more equant grain shapes. Secondly, most quartz fabrics in quartz mylonites with an oblique grain shape fabric show a lattice fabric dominated by an oblique girdle rather than a double maximum pattern of [001] axes. This may be largely due to differences in crystallography between the two minerals and inherent differences in the relative contribution of potential slip systems during flow. Lister & Snoke (1984) ascribe the inequant grain shapes to a number of effects, the most important of which is the progressive deformation of small quartz grains formed by rotation recrystallization and counterbalanced by migration of the grain boundaries tending to reset the inequant shapes. Such progressive deformation of the obliquely oriented grains is less marked in the olivine microstructures dominated by a kink-type glide polygonization process. However, the olivine grain shape fabric is strongly reminiscent of some quartz microstructures dominated by prismatic subgrain boundaries primarily controlled by slip on the quartz basal plane (e.g. Lister & Snoke 1984, fig. 10c).

It may be expected that oblique grain shape fabrics of the type described here also occur in some lherzolite xenoliths sampled by volcanic vents. In small xenoliths, which do not include a coarsely developed tectonite fabric defined by stretched pyroxenes, oblique grain shape fabrics may be confused with tabular microstructures of the type described by Mercier & Nicolas (1975). These tabular shape fabrics, however, are almost parallel to a distinct unimodal [100] axis lattice fabric, which is readily recognized in these samples by a large angle between kink-type tilt walls and the shape fabric, as opposed to the distinctly smaller angles observed in the oblique microstructure (e.g. Fig. 3).

CONCLUSIONS

The oblique olivine grain shape fabrics observed in the Erro–Tobbio tectonites developed as the result of intracrystalline slip, subgrain rotation and concomitant deformation-induced grain boundary migration. This process resulted in a monoclinic fabric element with a consistent orientation relative to the sense of shear. The oblique fabric can thus be used as a reliable kinematic indicator for high-temperature flow in upper mantle lherzolites.

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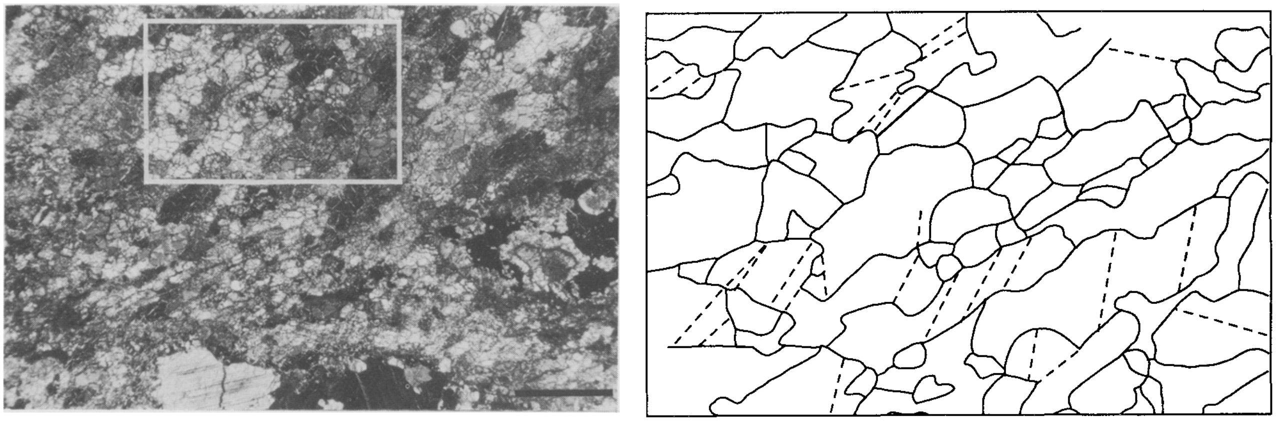

Fig. 3. (a) Photomicrograph of oblique fabric, sample MTS 5. Oriented clinopyroxene aggregates at bottom of micrograph define tectonite foliation shown horizontal. Scale bar 2 mm. (b) Line drawing of the oblique microstructure within inset shown in (a).

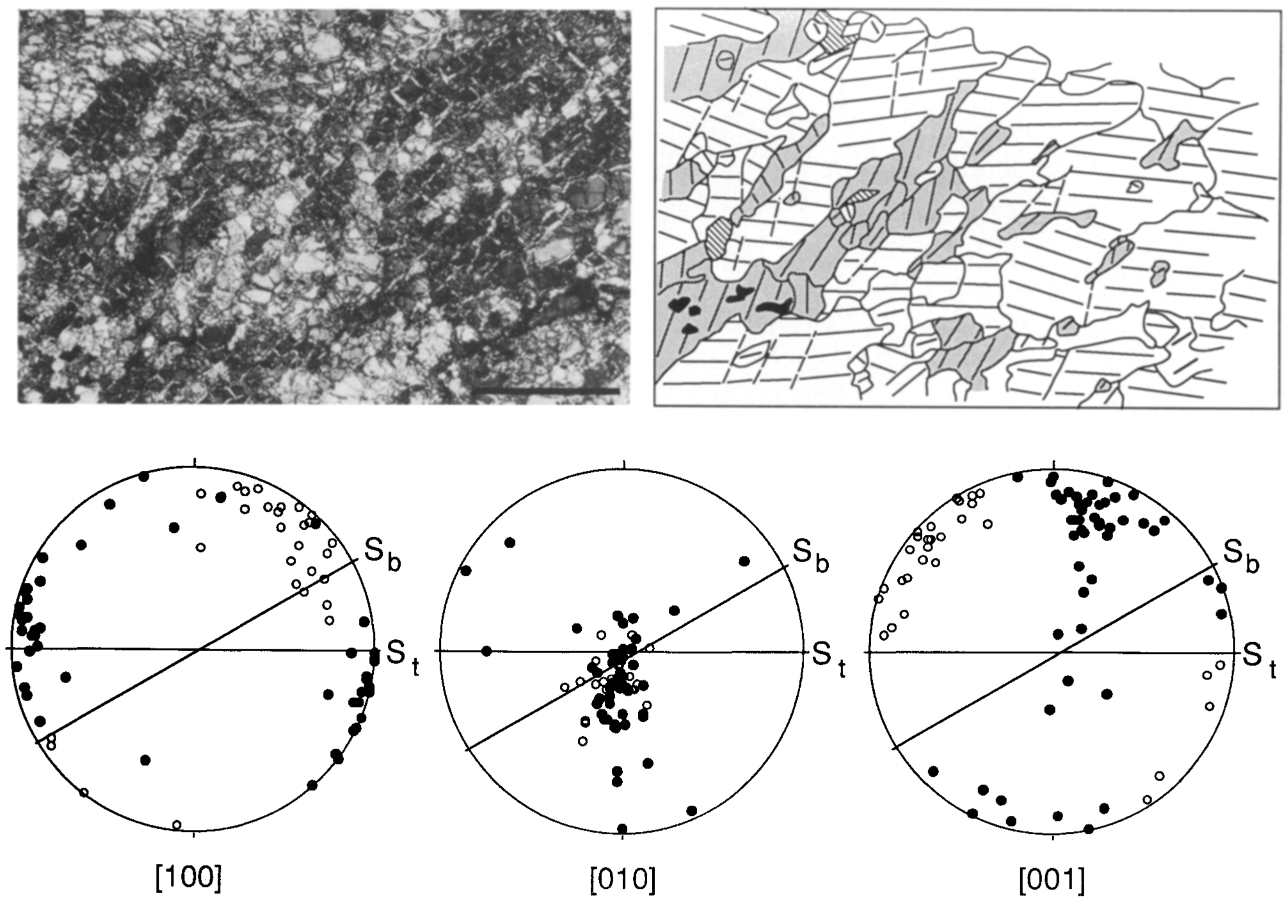

Fig. 4. (a) Photomicrograph (b), AVA-diagram and (c) corresponding petrofabric diagram of oblique fabric, sample E8929. Scale bar = 1 mm. Black dots in fabric diagrams correspond to unshaded grains, open circles to shaded grains. For further explanation see text.

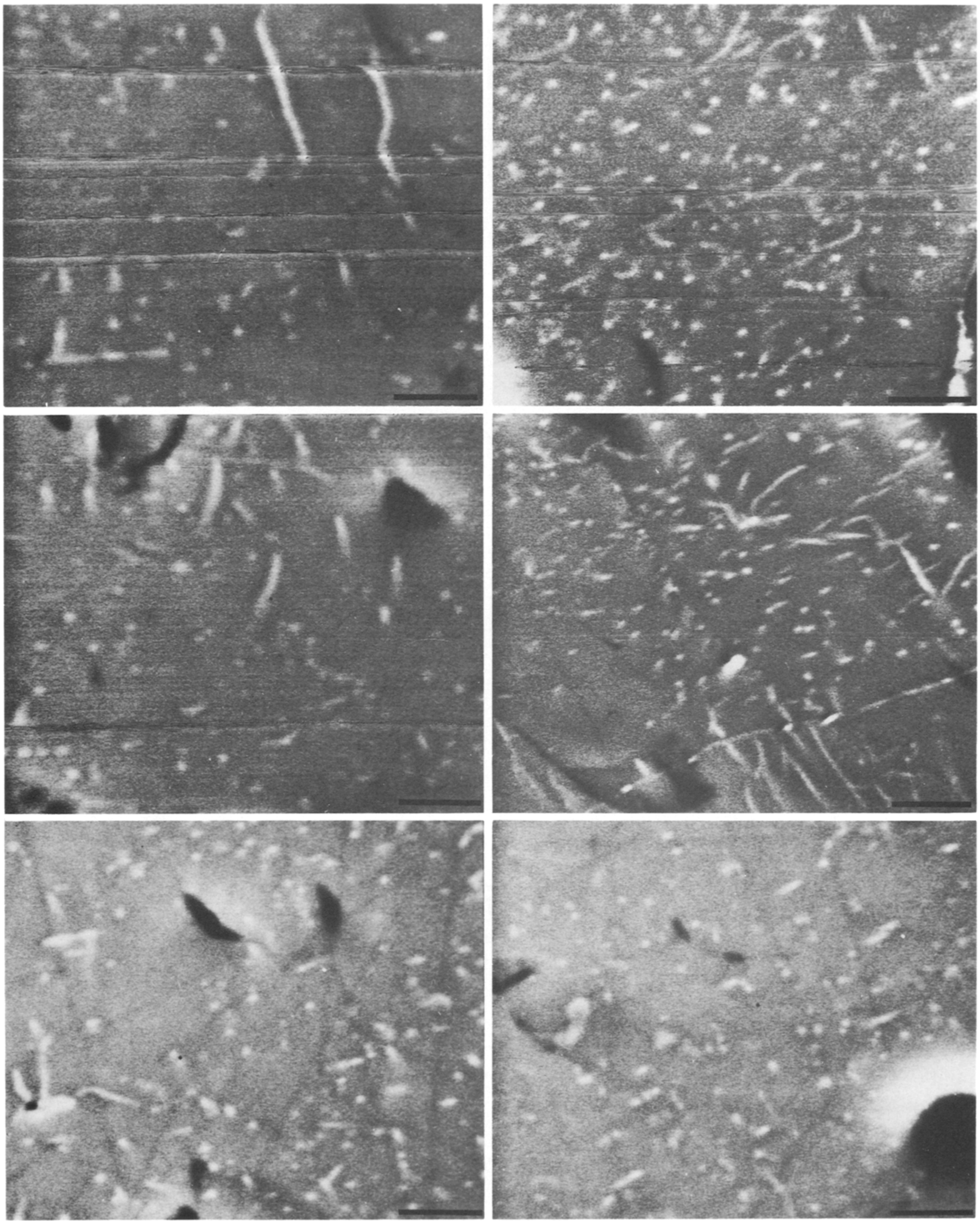

Fig. 5. Backscattered electron micrographs of dislocation substructure in olivine grains with oblique microstructure (sample MTS5). Left column shows dislocation density of favourably oriented grains, right column shows dislocation density of unfavourably oriented grains. Scale bar = 2 μm in all micrographs.

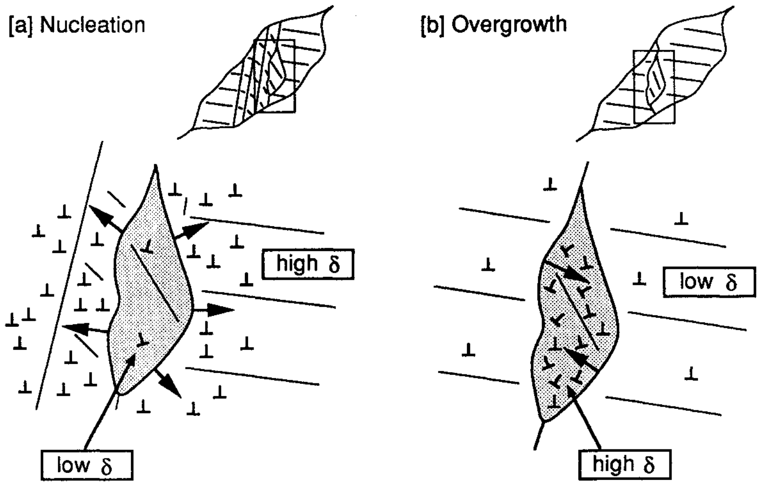

Fig. 6. (a) Diagram showing expected effect of nucleation recrystallization vs (b) progressive overgrowth, on dislocation density distribution. The newly recrystallized phase (shaded: unfavourably oriented grains in the nucleation case and favourably oriented grains in the overgrowth case) will have the lowest dislocation density. Arrows indicate direction of grain boundary migration.

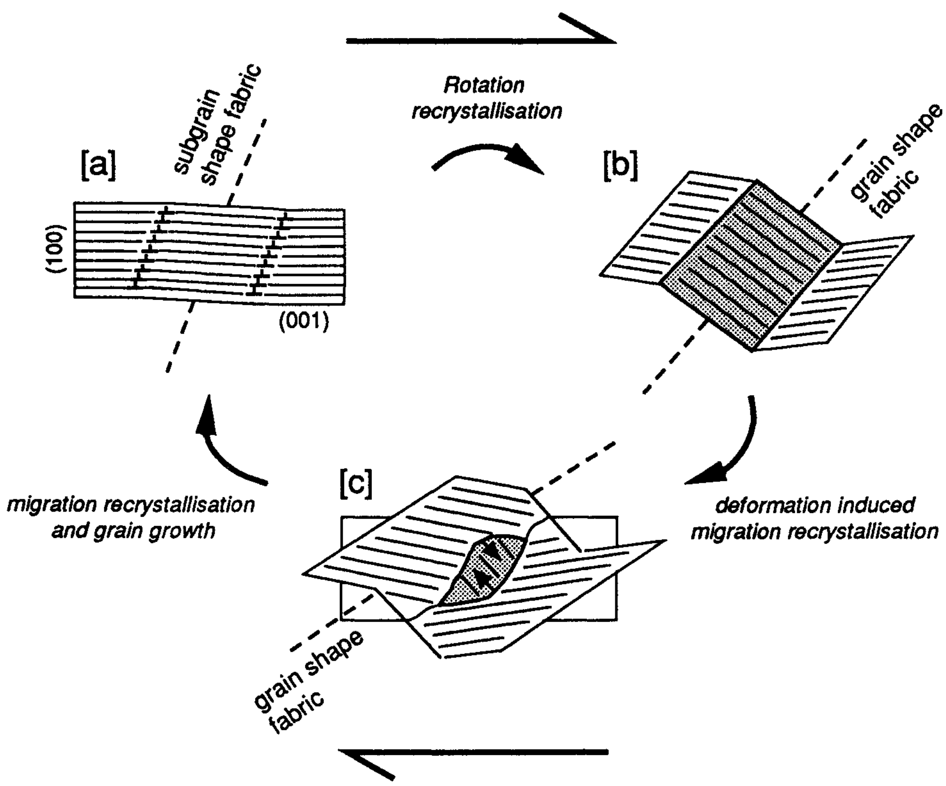

Fig. 7. Synoptic diagram illustrating the inferred evolution of the oblique grain shape fabric during progressive dextral shear. The shaded grain becomes unfavourably oriented for high-temperature flow due to rotation recrystallization, such that slip on the easy slip systems becomes difficult. Other slip systems are activated instead, leading to tangling of dislocations and an increase of the dislocation density, which drives deformation induced grain boundary migration.

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