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Stress Estimates from Structural Studies in Some Mantle Peridotites

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Stress estimates from structural studies in some mantle peridotites

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[Plates 1 and 2]

Deviatoric stresses acting in rock deformation can be estimated by measuring parameters connected with the dislocation microstructure, after an experimental calibration. In olivine, the available structural geopiezometers are based on dislocation curvature, dislocation density, sub-boundary size and recrystallized grain (neoblast) size. Their application in the case of olivine bearing rocks (peridotites) deformed in mantle conditions is critically assessed. The most reliable geopiezometer is the one based on olivine neoblast size. It yields values in the range of 1 kbar (1 kbar = 10^8 Pa) and over in the case of the sheared nodules in kimberlites, of 0.3–0.5 kbar in the case of basalt nodules and in the Lanzo massif, although locally the stress can be much higher. These values are compared with those ascribed to mantle flow by various independent methods and which tend to indicate a lower deviatoric stress for asthenosphere flow (10–100 bar). In the state of the art, the disagreement between this stress estimate and those in basalt nodules and in massifs, which is nearly one order of magnitude, can be explained by the various uncertainties in the estimate, thus leaving room for the possibility that the flow structures in these peridotites do represent asthenosphere conditions.

Introduction

Direct evidence on the composition and the geodynamic properties of the upper mantle is provided by peridotites either brought up to the surface by basaltic and kimberlitic magmas or intruded as mantle slices in orogenic belts. The structures and minerals preferred orientations have been investigated in these various types of peridotites and the main results concerning the flow mechanisms and kinematics have been recently reviewed (Nicolas 1976).

It is now accepted that these peridotites are largely representative of the upper mantle so far as their geochemical and geophysical properties are concerned; the question addressed in this paper is whether the structures observed in peridotite nodules from kimberlites, basalts and in peridotite massifs are representative of the asthenosphere flow in the upper mantle or, on the contrary, of local and incidental phenomena. In the latter case they could not be considered to deduce the rheological properties of the flowing asthenosphere, because both the flow mechanisms and the deviatoric stresses that they indicate would not be appropriate. By the same token their pyroxenes composition would be of no use to derive any representative geotherm for a large area in the mantle.

The analysis of structures and minerals preferred orientations in the various types of mantle peridotites indicates that the flow mechanism is dislocation creep controlled by recovery (Nicolas, Boudier & Boullier 1973). In mylonites from kimberlite nodules, evidence for structural superplasticity has been presented by Gueguen & Boullier (1976), who ascribe it to diffusion accommodated grain boundary sliding. It must be emphasized that this situation is exceptional. Dislocation creep which is the flow mechanism in natural peridotites is also that commonly accepted for the asthenosphere (Weertman 1970), although different modes of diffusion creep have been recently advocated as an important (Meissner & Vetter 1976) or a dominant (Twiss 1976) creep mechanism in the upper mantle. The flow geometry in nodules from basalt and in massifs which was found to be dominantly rotational and possibly approaching simple shear (Mercier & Nicolas 1975) is also compatible with the rotational shear flow expected for the asthenosphere. Finally, the structures in peridotite massifs from ophiolite complexes can be ascribed to asthenosphere flow as shown by the excellent agreement between the seismic anisotropy calculated for these massifs once restored to their original orientation and that measured at sea (Peselnick & Nicolas, in press). This does not preclude the possibility that some deformation structures could be due to high temperature emplacement (Mercier 1976).

The question of whether the peridotites under consideration represented the asthenosphere flow has recently arisen from considerations on stress and recovery. Goetze (1975*a*, *b*) has contended that the deformed structures in Boyd & Nixon's (1972) sheared nodules from kimberlites could not result from the asthenosphere flow as his estimation of the stress responsible for this deformation was two orders of magnitude larger than that expected in the asthenosphere (2 or 3 kbar as compared with 10 or 100 bar). This conclusion has also been attained by Boullier & Nicolas (1975) considering the limited degree of recovery in the sheared nodules compared with that in the other nodules, although the former are equilibrated at the highest temperatures. This suggested that the sheared nodules had been deforming until they were extracted by the kimberlite magmas at strain rates largely higher than that expected in the asthenosphere.

The potential geopiezometers

Empirical relations have been established in metals between the dislocation microstructures and deviatoric stress and their applications in the case of rocks discussed by Nicolas & Poirier (1976, p. 137). The main relations tie the dislocation curvature, the dislocation density and the subgrain size to the applied stress.

Durham, Goetze & Blake (1977) have considered the relation between the minimum radius of curvature (R, measured in micrometres) of dislocation loops and the stress (σ, measured in kilobars) in olivine. They observe a fairly good experimental correlation:

$$\sigma \approx 0.6\,R^{-1},$$

which when compared with the expected relation

$$\sigma = K\mu b R^{-1},$$

where μ is the shear modulus and b the Bergers vector, yields a K value of 1.84×10^{-3} kbar cm.

The relation between the free dislocation density (ρ) and the stress has been experimentally investigated by Kohlstedt & Goetze (1974), by Goetze (1975*a*, *b*) and by Durham *et al.* (1977) who find a good experimental correlation expressed in the general form:

$$\sigma = K'\mu b \rho^{\frac{1}{2}},$$

$$\sigma = 9 \times 10^{-5} \rho^{0.5} \text{ (Goetze 1975}\,a, b),$$

$$\sigma \approx 2 \times 10^{-5} \rho^{0.61} \text{ (Durham } et\ al. \text{ 1977)}.$$

The relation between the subgrain size (d, measured in micrometres) and the maximum stress is expected to have the following form:

$$\sigma = K''\mu b d^{-1}.$$

In olivine, the [100] tilt wall spacing is principally measured, due to its predominance over any other substructure and to its smallest spacing when compared to the other subboundary systems. The considered subgrains are only those optically visible and not those which subdivide them at the t.e.m. scale (Green & Radcliffe 1972). They are now observed using a new decoration technique (Kohlstedt, Geotze, Durham & Vander Sande 1976) which, making it possible to observe about ten times as many tilt walls than before, can explain the large discrepancy between Raleigh & Kirby's (1970), Goetze's (1975*a*, *b*), Mercier's (1976) and Durham *et al.* (1977) relations.

$$\sigma = 17\,d^{-1} \quad \text{(Geotze 1975}\,a,\,b),$$

$$\sigma = 115\,d^{-1} \quad \text{(Mercier 1976)},$$

$$\sigma = 10\,d^{-1} \quad \text{(Durham et al. 1977)}.$$

The size of dynamically recrystallized olivine grains (neoblasts) has also been considered as a potential geopiezometer for mantle rocks. The following experimental relations have been found:

$$\sigma = 11\,d^{-0.5} \quad \text{(Goetze 1975}\,a,\,b),$$

$$\sigma = 19\,d^{-0.67} \quad \text{(Post 1973)},$$

$$\sigma = 40\,d^{-0.81} \quad \text{(Mercier 1976)}.$$

Mercier obtains a weak temperature dependence for this relation:

$$d = 1.13\sigma^{-1.4}\exp(13500/RT).$$

Otherwise, as expected from the metallurgical literature, no temperature dependence is found for all these relations.

Critical assessment of the geopiezometers

Piezometers based on dislocation microstructure

In olivine, as in metals, the dislocation density is very sensitive to further straining or recovery. Durham *et al.* (1977) have shown experimentally that in this mineral 0.01–0.1 % strain is sufficient to completely obscure the initial dislocation structure, whereas a new steady state substructure is obtained for 2–3 % strain. Many rocks have suffered such moderate strains at lower temperature and higher stress after the major deformation which is investigated. This will result in a dislocation substructure which reflects a higher stress than the one responsible for large creep.

In all types of mantle peridotites, evidence of late high stress deformation can be found. For instance, Gueguen (1977), who has systematically investigated the dislocation substructures in olivine from kimberlite and basalt nodules, describes in some nodules (110) slip bands comprising {110} [001] dislocations which represent a low-temperature slip system (Carter & Ave'Lallemant 1970) (figure 1, plate 1). In contrast with the other dislocation systems found in these nodules, this system cannot be related to the mineral preferred orientation developed during the main flow. These bands are attributed to some late event, possibly occurring during the ascent. In the

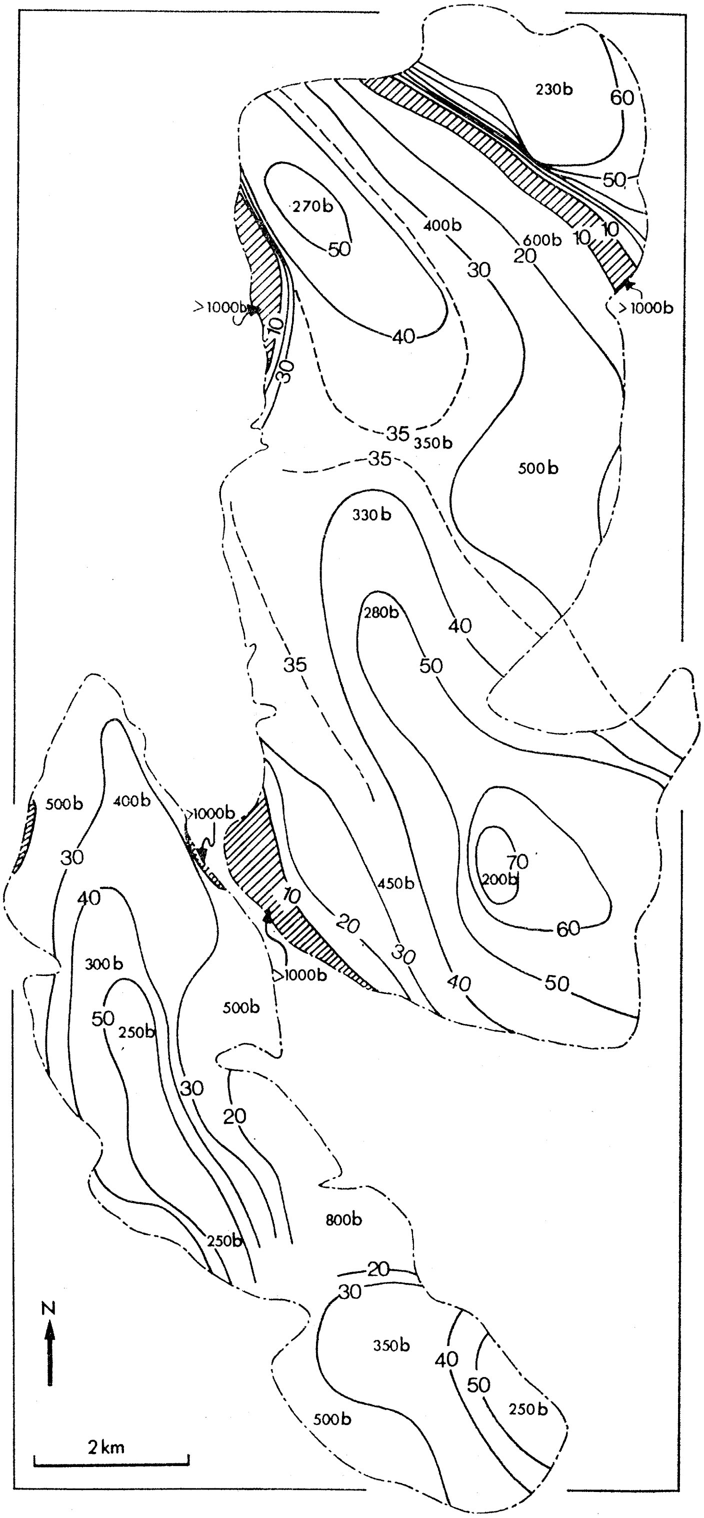
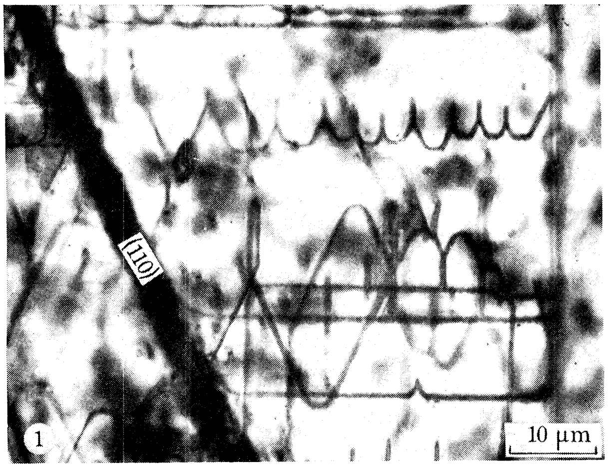


FIGURE 2. Map of olivine neoblast size (in hundredths of millimetres) in the Lanzo massif based on 125 measurements. The hatched pattern corresponds to mylonitic zones. The stress estimates in bars (b) are derived from Mercier's and Post's calibrations (see text).



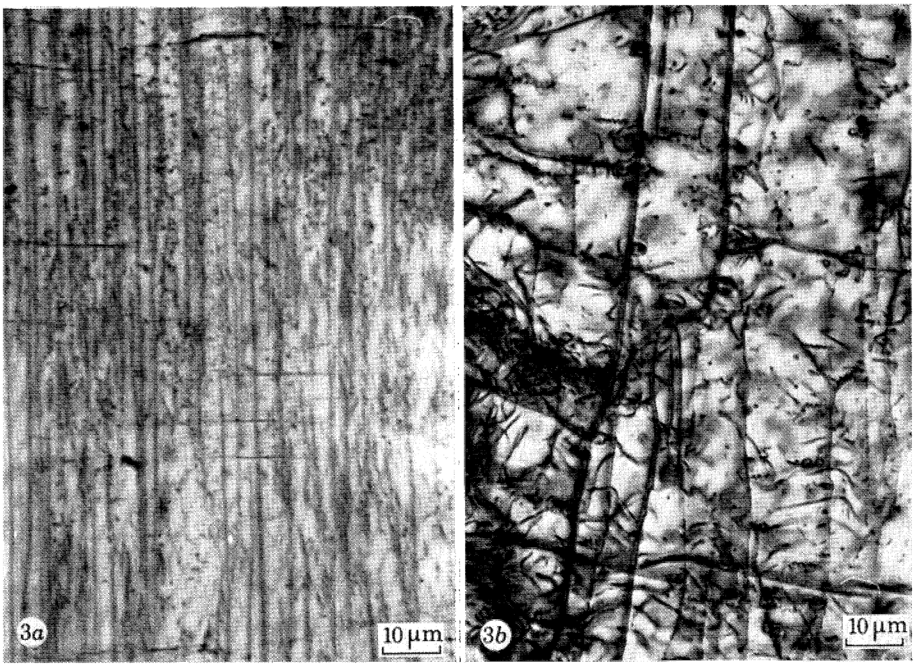
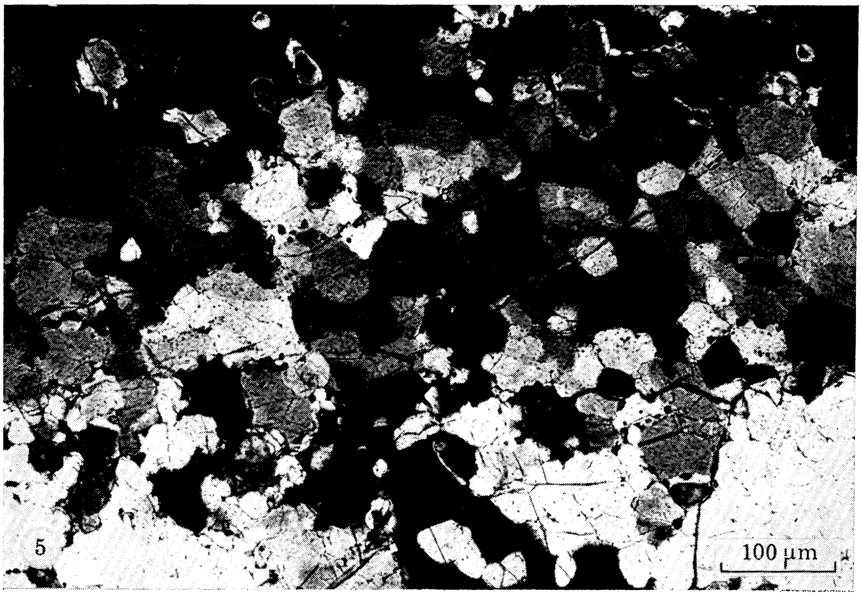


FIGURE 1. (110) slip band superimposed on the low stress dislocation substructure in a decorated olivine crystal from a basalt nodule (picture by Y. Gueguen).

FIGURE 3. This shows d_{100} spacings (vertical lines) in decorated olivine grains: (*a*) starting specimen, a dunite from Norway; (*b*) after 1 h of annealing at 1700 °C, argon atmosphere (from D. Ricoult).

(*Facing p.* 52)



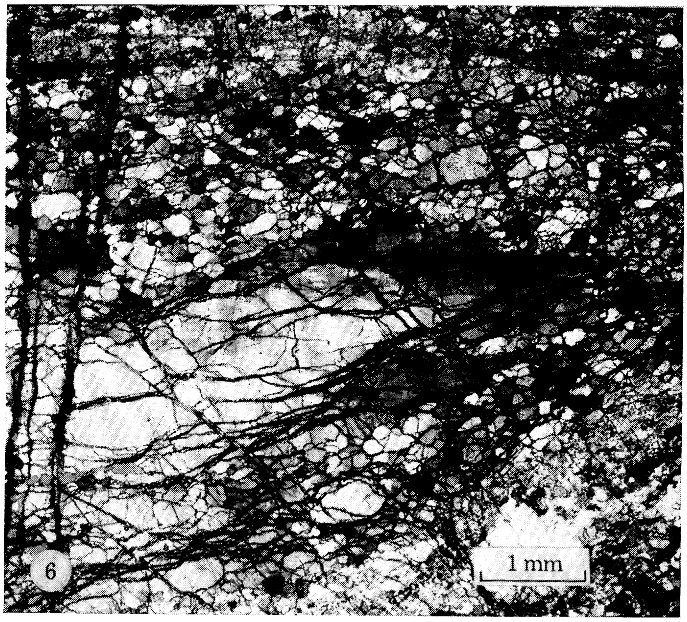


Figure 5. Partial recrystallization of an olivine porphyroclast in a peridotite nodule from Lunar Crater basalt. The shaded subgrains grade into neoblasts (slightly darker or lighter) which results from their progressive misorientation. A few smaller and often lighter neoblasts are ascribed to the nucleation–grain boundary migration mechanism.

Figure 6. Two generations of olivine neoblasts in a mylonitic peridotite from the Lanzo massif. The centre of the picture is occupied by a porphyroclast whose substructure evolves in a first generation of 100 μm neoblasts. This structure is cut by mylonitic bands at the upper and lower part of the picture in which the olivine grains are only 10 μm.

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Lanzo massif, evidence of minor strain under high stresses is provided by the discrepancy between the stress values and pattern deduced from the neoblast size (figure 2 and table 1) and those deduced from dislocation density and d_{100} spacings (table 1) observed with the decoration technique. The higher and more uniform values obtained in the latter case indicate that during the last stage of its intrusion the massif was submitted in a fairly uniform fashion to stresses in the 1 kbar range (in the mylonitic bands it would attain 5 kbar).

TABLE 1. STRESS ESTIMATES IN MANTLE ROCKS

kimberlite nodules	
$\rho \approx 2.10^7\ \text{cm}^{-2}$	$\sigma \approx 0.4$ kbar
$d_{100} \approx 12\ \mu\text{m}$	$1\ \text{kbar} < \sigma < 9\ \text{kbar}$
$d_n \approx 75\ \mu\text{m}$	$1\ \text{kbar} < \sigma < 1.3\ \text{kbar}$
basalt nodules	
$\rho \approx 9.10^6\ \text{cm}^{-2}$	$\sigma < 0.25$ kbar
$d_{100} \approx 50\ \mu\text{m}$	$0.35\ \text{kbar} < \sigma < 2.3\ \text{kbar}$
$d_n \approx 500\ \mu\text{m}$	$0.25\ \text{kbar} < \sigma < 0.5\ \text{kbar}$
Lanzo massif	
$\rho \approx 10^7\text{–}10^8\ \text{cm}^{-2}$	$0.3\ \text{kbar} < \sigma < 1\ \text{kbar}$
$d_{100} \approx 50\ \mu\text{m}$	$0.35\ \text{kbar} < \sigma < 2.3\ \text{kbar}$
$d_n \approx 400\ \mu\text{m}$	$0.3\ \text{kbar} < \sigma < 0.55\ \text{kbar}$

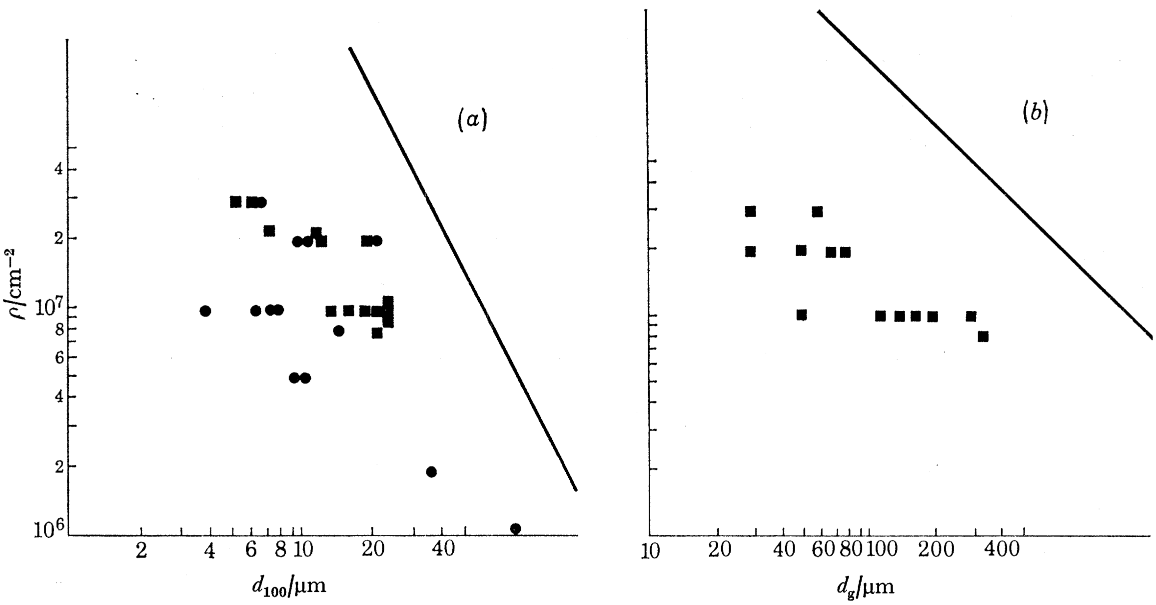

FIGURE 4. (*a*) Relation between ρ, the dislocation density, and d_{100} in olivine from kimberlite nodules. (*b*) Relation between ρ and the size of olivine neoblasts in the same suite of nodules. The solid lines are the experimental relations observed by Goetze (1975 *a*, *b*).
Circles: coarse granular and tabular nodules; squares: porphyroclastic nodules (after Gueguen 1977).

Recovery, on the other hand, can lower the dislocation density and increase the d_{100} spacing. This latter possibility is denied by Goetze & Kohlstedt (1973) but Ricoult (figure 3, plate 1) has brought experimental evidence for it. The mean d_{100} spacing observed at a magnification of 1000 with the decoration technique increases from 4 μm in the starting specimen to 16 μm after 1 h of annealing at 1700 °C. Meanwhile the optically visible d_{100} tilt walls (misorientation $\geqslant 1°$), when compared to the totality of decorated tilt walls, have a percentage which increases from 4 to 9 (D. Ricoult, personal communication). This suggests that during annealing the highly misoriented walls remain stable and that the increase in mean d_{100} spacing is due to the destruction of the least misorientated walls.

Gueguen (1977) finds in kimberlite nodules very poor correlations between the dislocation density (ρ) and the d_{100} spacing (figure 4) and between ρ and the neoblast size. Moreover, his data fall largely below the experimental line from Goetze (1975*a, b*). He concludes that all these nodules have been statically recovered. In the basalt nodules, the correlation between ρ and d_{100} is no better. The dislocation density also varies by a factor of 10–20 in a same grain at a few hundredths of microns distance, an observation that Gueguen ascribes to recovery, some microstructures being more stable than others.

Piezometer based on neoblast size

Recrystallization mechanism

During progressive deformation the olivine porphyroclasts tend to recrystallize into neoblasts. Two mechanisms have been recognized: nucleation and grain boundary migration (n.g.b.m.) and progressive subgrain rotation (p.s.g.r.). In the latter mechanism, the subgrains tend to increase their misorientation during creep until beyond 15° in olivine they evolve into independent grains (Poirier & Nicolas (1975) for olivine; Hobbs (1968), White (1973) for quartz). In peridotites experimentally deformed at high stresses (above a few kilobars), n.g.b.m. is dominant (Ave'Lallemant & Carter 1970; Nicolas *et al.* 1973; Mercier 1976), although Post (1973) ascribes to the other mechanism the recrystallization produced at 5 and 7 kbar, suggesting that the parameter controlling the recrystallization mechanism is temperature, high temperature favouring n.g.b.m. over p.s.g.r. On the basis of observations in naturally deformed peridotites, the hypothesis that stress is the critical parameter is preferred here. In these rocks, it is usually concluded that, whatever the temperatures during flow, the mechanism has been p.s.g.r. even though secondary grain boundary migration is sometimes recorded. Only in a few cases where the neoblast size is in the range of a few tenths of microns has evidence been found of n.g.b.m. A peridotite nodule from Lunar Crater basalts contains both types of neoblasts; the ones derived from the subgrains are 60 μm in diameter, a size comparable to that of the optically visible subgrains (40 μm), and those produced by n.g.b.m. $\leqslant$ 30 μm (figure 5, plate 2). Applying the experimental relations given above, this would set the limit between the two mechanisms around 2 kbar. Above this stress, provided there has been enough strain to store through dislocations a sufficient energy, n.g.b.m. would dominate; below it, the recovery processes (dislocation climb into sub-boundaries) would keep the strain energy at an insufficient level for n.g.b.m. and again, for strains larger than *ca.* 0.3% the subgrain misorientation would evolve into p.s.g.r. recrystallization.

The experimentally established relation between neoblast size and deviatoric stress corresponds to a recrystallization operating mainly by n.g.b.m. Considering this mechanism, it is not understood why such a relation exists. There is now a need for neoblast size/stress calibration in the stress field below 2 kbar where p.s.g.r. recrystallization is thought to dominate.

This type of piezometer is less sensitive to the history of the rock subsequent to the major flow, that is to annealing and high-stress low-strain deformation. Therefore, once these problems are solved, it will be superior to those based on the dislocation microstructure.

During annealing, however, a grain growth can occur, driven by the surface energy. This would evidently ruin all possibilities of using neoblast grain size as piezometers. This grain growth is documented in experiments (Mercier 1976) and in some peridotites from kimberlites (Harte, Cox & Gurney 1975; Boullier 1975), from basalts (Mercier & Nicolas 1975) and from massifs (Boudier 1976). It is illustrated by olivine growth enclosing other minerals, mainly spinel. In the case of dunites in massifs, exaggerated growth leads to a grain size attaining 50 mm. However, in most cases the olivine does not enclose the small spinel grains, indicating that the grain boundary migration is absent or at least moderate. It is also observed that the neoblast size then compares with that of *optically visible* subgrains (Poirier & Nicolas 1975) (figure 6, plate 2). The correlation between neoblast size and sub-boundary spacing is not valid for the subgrains only visible with the decoration technique and which have misorientations smaller than 1°: only those with misorientations greater than one degree are potentially able to evolve in grain boundaries. Earlier it has been proposed that the latter are also more stable during recovery.

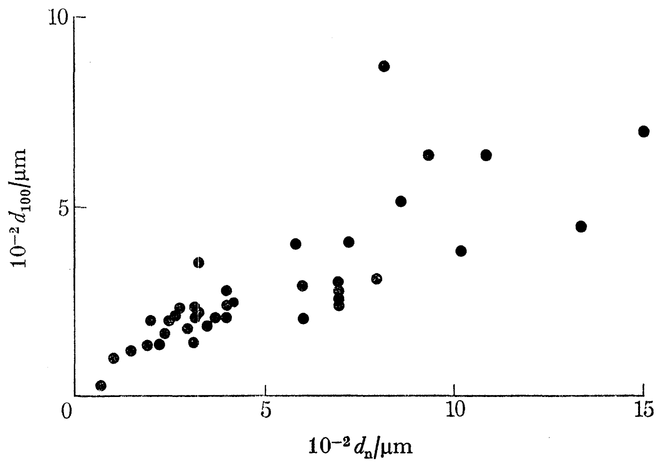

FIGURE 7. Relation between the optically visible d_{100} spacing (misorientation $\geqslant 1°$) and the neoblast size in olivine from basalt nodules.

Strains of the order of 1 % under high stress at low-temperature conditions which are sufficient to alter the dislocation substructure will not change the neoblast size as both recrystallization mechanisms require larger strains. Moreover, in the Lanzo massif where locally large strains have produced mylonitic bands at low temperatures it is still possible to distinguish the neoblasts resulting respectively from the low and high stress deformations (figure 7).

THE PERIDOTITE STRUCTURES AND THE ASTHENOSPHERE FLOW

Stresses in the mantle are estimated by three independent means: stress drop calculated from appropriate earthquakes, data on the external gravitational potential and rheological models of mantle creep.

Stress estimates from earthquakes can reasonably be suspected of being more representative of lithosphere conditions than of asthenosphere ones even for the deep earthquakes which are ascribed to a subducting lithosphere. The stress release measurements may also reflect only a part of the deviatoric stress (Kanamori & Anderson 1975). This is certainly true for shallow earthquakes in which the stress release can be only 0.01–0.1 of the total stress (Wyss & Molnar 1972); it is more dubious for deep earthquakes (H. Berckhemer, personal communication). The shallow earthquakes are also those in which the stress drop is smallest: 10–100 bar compared with 100–1000 bar for the deep earthquakes (Aki 1972). The comprehensive study of Kanamori & Anderson (1975) results in stress drop estimates of 30 bar for interplate earthquakes, 100 bar for intraplate ones and 60 bar as an average value.

Stress estimates bases on gravity data are values obtained for the whole mantle and are possibly more representative of the lower mantle (Jeffreys (1964) and Caputo (1965), cited in Clark & Ringwood 1968). Minimum stresses thus estimated are 30–40 bar. Kaula (1963) reports a stress of 160 bar for the lower mantle.

Finally, stress estimates based on the modelling of the rheology of the asthenosphere concern without ambiguity this part of the upper mantle. They all rely entirely on the rheology of olivine extrapolated from laboratory to asthenosphere conditions. The main uncertainties derive from a poor knowledge of (1) the creep mechanism in the asthenosphere, (2) the pressure dependence in the creep equation of olivine, (3) the geotherms in the asthenosphere, (4) the thickness and therefore the strain rates acceptable for the asthenosphere. For these reasons the stress estimates are considered with some diffidence: Schubert, Froidevaux & Yuen (1976) predict stresses lower than 100 bar, Melosh (1976), of at most a few tens of bars, Carter, Baker & George (1972), between 7 and 16 bar and Meissner & Vetter (1976), locally below one bar. These stress estimates are somewhat lower than the stresses derived from the structural geopiezometers contained in the various types of peridotites (table 1). The stresses for peridotites compare better with the 200–300 bar estimated by McKenzie (1972) and Artyushkov (1973) for the lithosphere.

This discrepancy can be explained by considering either that the stresses estimated for the asthenosphere are too low and/or that those estimated from the peridotites structure are too high, or that the observable peridotites do not represent the steady state asthenosphere flow. This second interpretation is accepted for the sheared nodules in kimberlites and for mylonites which are present in all categories of peridotites. In the state of the art, too many uncertainties remain about stress in the asthenosphere and stress calibration in peridotites to rule out that the other deformed peridotites do represent asthenosphere flow.

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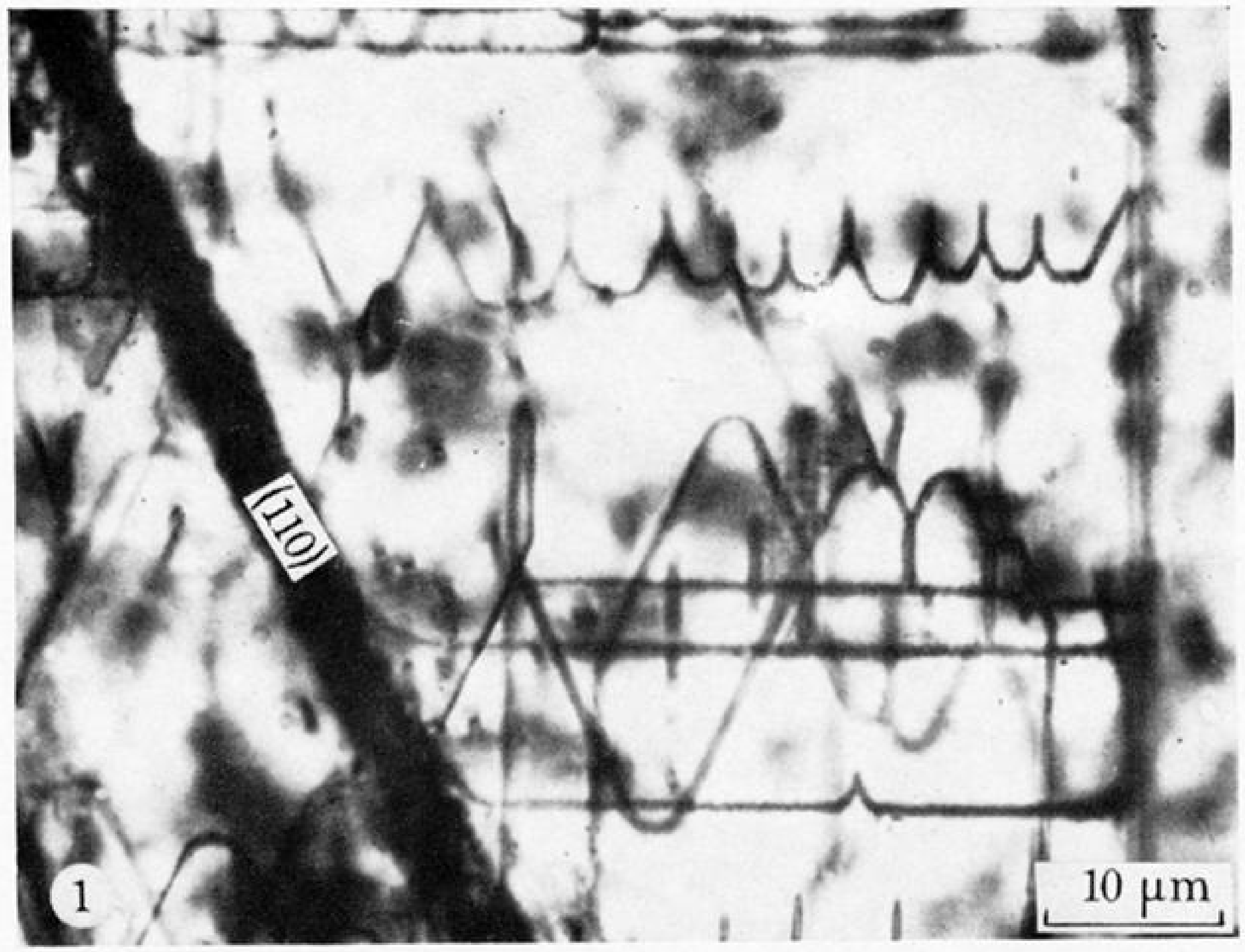


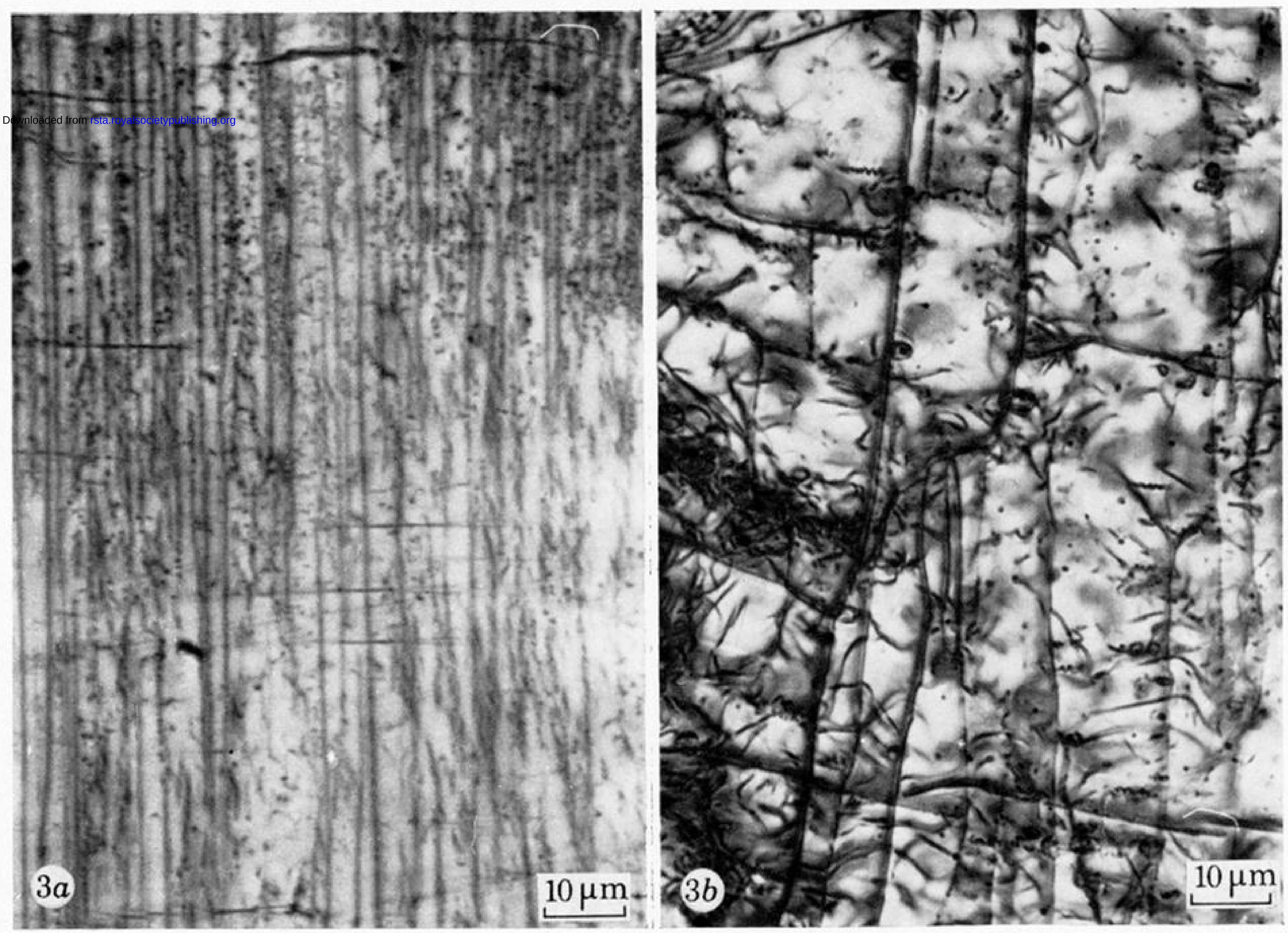
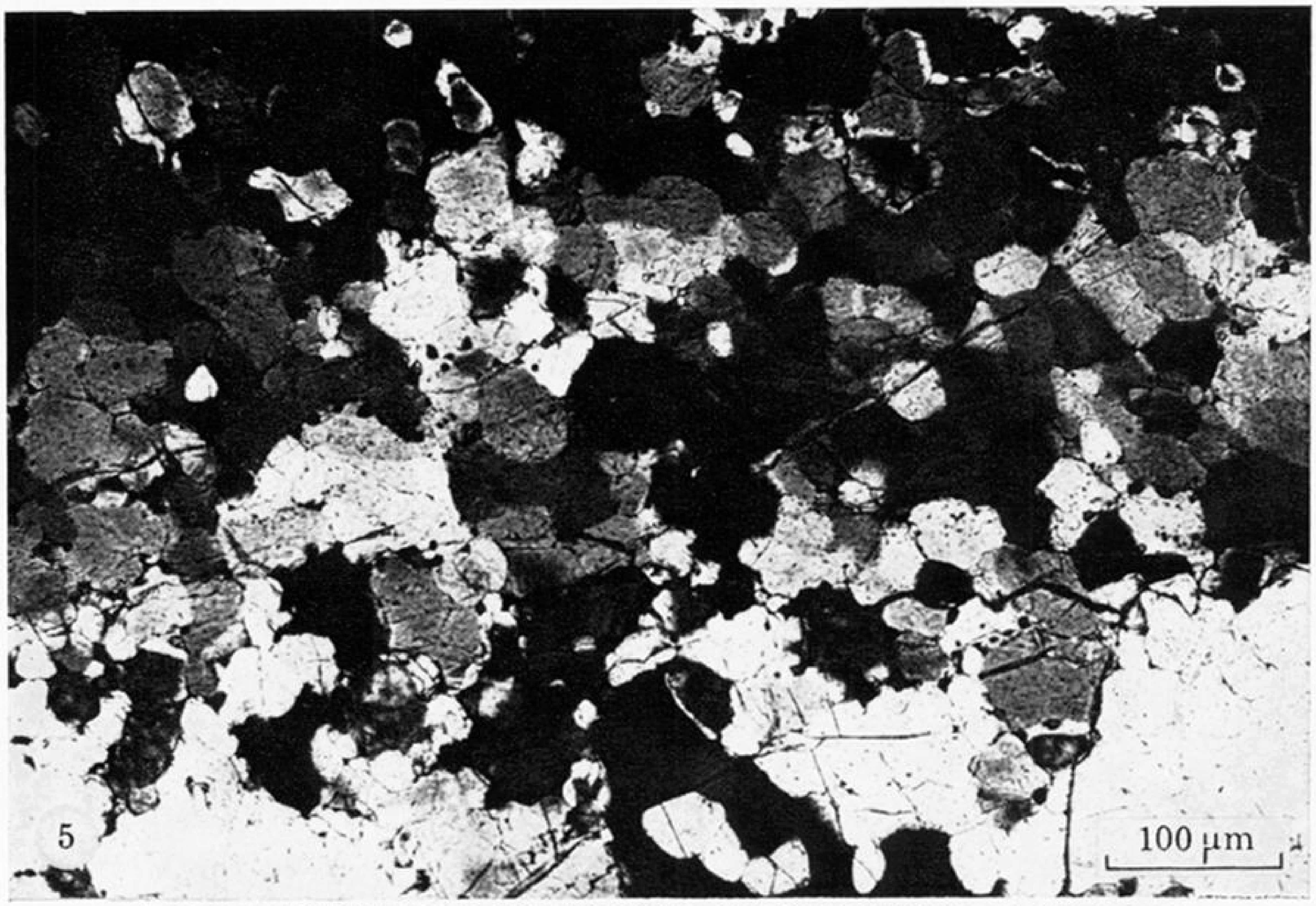


FIGURE 1. (110) slip band superimposed on the low stress dislocation substructure in a decorated olivine crystal from a basalt nodule (picture by Y. Gueguen).

FIGURE 3. This shows d_{100} spacings (vertical lines) in decorated olivine grains: (*a*) starting specimen, a dunite from Norway; (*b*) after 1 h of annealing at 1700 °C, argon atmosphere (from D. Ricoult).



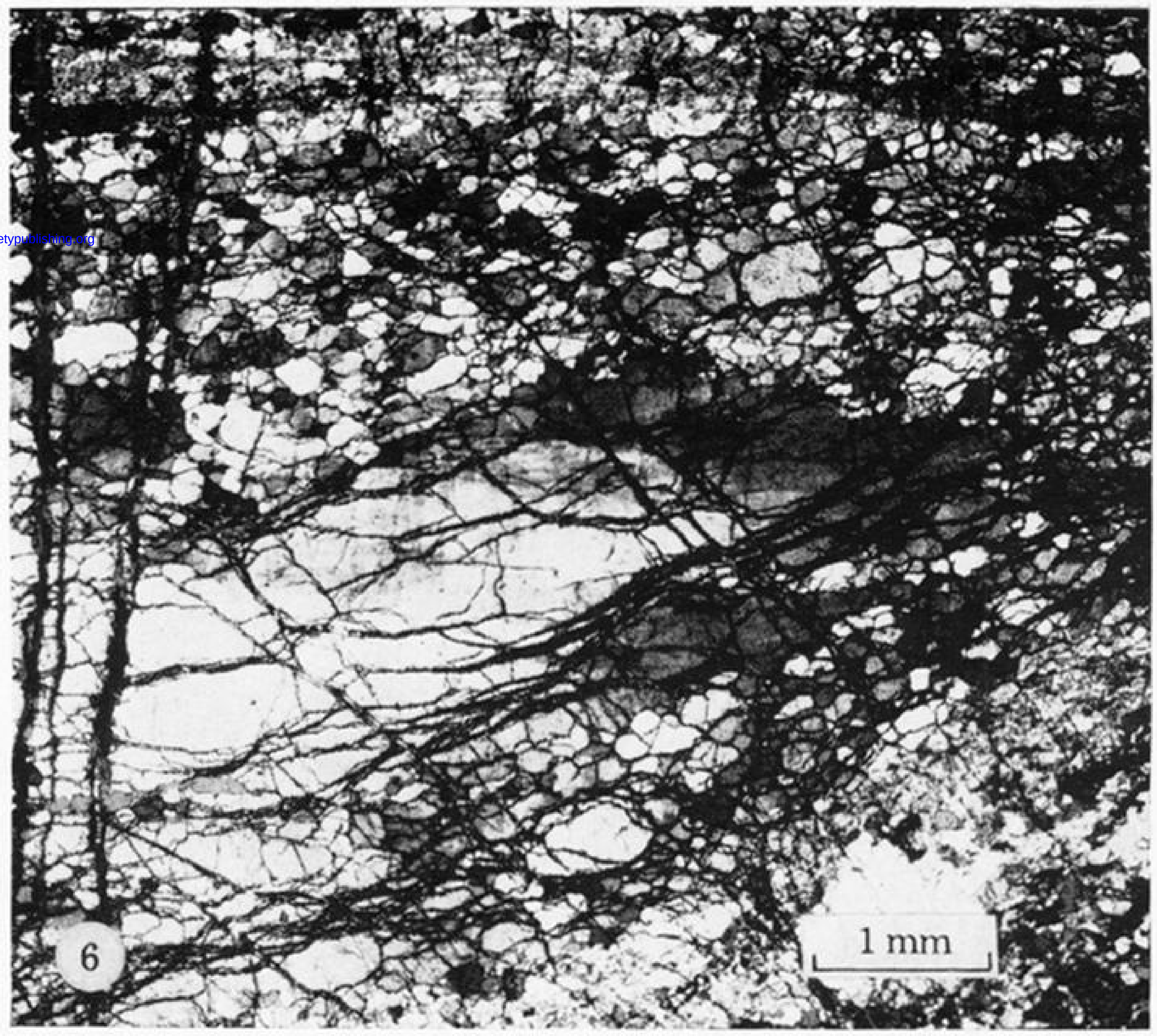


FIGURE 5. Partial recrystallization of an olivine porphyroclast in a peridotite nodule from Lunar Crater basalt. The shaded subgrains grade into neoblasts (slightly darker or lighter) which results from their progressive misorientation. A few smaller and often lighter neoblasts are ascribed to the nucleation–grain boundary migration mechanism.

FIGURE 6. Two generations of olivine neoblasts in a mylonitic peridotite from the Lanzo massif. The centre of the picture is occupied by a porphyroclast whose substructure evolves in a first generation of 100 µm neoblasts. This structure is cut by mylonitic bands at the upper and lower part of the picture in which the olivine grains are only 10 µm.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES