

Relation Between Dislocation Density and Subgrain Size of Naturally Deformed Olivine in Peridotites

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Abstract. The subgrain size and the dislocation density of subgrain interiors were measured by the oxidation-decoration method under the optical microscope on naturally deformed olivine from peridotite xenoliths and alpine-type peridotites. Relation of the subgrain size, d and the dislocation density, ρ , within subgrains is represented by the equation, $d=15/\sqrt{\rho}$. Combining with relations of the differential stress and the dislocation density proposed by Kohlstedt and Goetze (1974), relation between the stress (σ) and the subgrain size becomes $d=45 Gb/\sigma$, where G and b are the rigidity and the magnitude of the Burgers vector of olivine. This relation is in good agreement with those in a simple oxide (MgO), and alkali halides (NaCl, LiF) given by Hühner and Reppich (1973), Poirier (1972), and Streb and Reppich (1973), respectively.

Introduction

The subgrain enclosed by small-angle grain-boundaries (subboundaries) in a single grain of deformed olivine has been paid a lot of attention as a useful indicator of the differential stress in the upper mantle by many authors (Raleigh and Kirby, 1970; Nicolas and Poirier, 1976; Gueguen, 1977). The relation between the differential stress and the subgrain size has been determined on many kinds of crystalline materials, for examples, MgO (Hühner and Reppich, 1973), NaCl (Poirier, 1972), LiF (Streb and Reppich, 1973), and metals (Takeuchi and Argon, 1976), and they are very close to each other (Nicolas and Poirier, 1976). Raleigh and Kirby (1970) discussed a relation between them by applying such relations for metals

that the subgrain size is inversely proportional to stress, but their relation for olivine is not consistent with those of simple compounds and metals.

Recently, Green (1976) and Gueguen (1977) noticed that the relation between the spacing of neighboring subboundaries and stress obtained from the dislocation density are deviated from Raleigh and Kirby (1970)'s one. They considered that the discrepancy results from static annealing of olivine grains in which the dislocation density decreases but the subgrain boundary remains stable. Toriumi and Karato (1978) proposed the annihilation rate of dislocations in static annealing, and they have concluded that the static annealing in basaltic liquid does not give a large effect on the dislocation density of olivine. Further, decreasing rate of the dislocation density depends strongly on the initial density, so that the static annealing makes the relation change at high dislocation density. Therefore, results by Gueguen (1977) do not imply the static annealing.

In this paper, the author will propose the relation between the dislocation density and the subgrain size on naturally deformed olivine grains from peridotite xenoliths and alpine-type peridotites, and also the relation between the stress and subgrain size, applying the relation between the stress and the dislocation density proposed by Kohlstedt and Goetze (1974).

Dislocation Structure

Samples studied here were taken from peridotite xenoliths of Ichinomegata, Northeast Japan, Takashima and Oki-Dogo, Southwest Japan, and San Carlos of Arizona, Salt Lake of Hawaii, and Dreiser Weiher of West Germany and from alpine-type peridotites of the Mt. Higashi Akaishi, and Kamogawa of Japan. All the samples are from the collection of the University Museum, University of Tokyo.

Spinel lherzolite xenoliths of Ichinomegata commonly contain plagioclase, hornblende, and clinopyroxene-spinel symplectite, but

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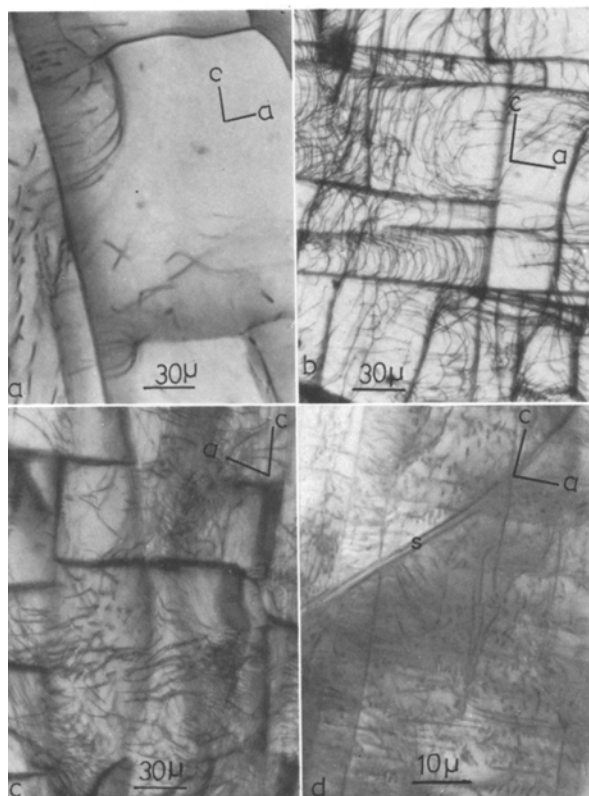


Fig. 1a-d. Cellular dislocation structure in which the simple dislocation walls are a network of dislocations nearly on (010), and parallel alignments of dislocations on (100) and (001). **a** San Carlos olivine; **b** Takashima olivine; **c** Dreiser Weiher olivine; **d** Mt. Higashi Akaishi olivine. *S* is crack filled with serpentine

those of Oki-Dogo and Takashima have no hornblende. The peridotite mass of the Mt. Higashi Akaishi is in the Sambagawa metamorphic belt (high pressure and low temperature type regional metamorphic belt) of Shikoku, southwestern Japan, and it has recrystallized during the metamorphism. The rocks of the mass commonly show porphyroclastic. The Kamogawa massive peridotite composed with plagioclase bearing harzburgite is found in the tectonic zone of the central Boso peninsula, central Japan. The rocks of the Kamogawa mass display usually equigranular.

Dislocations in olivine grains were etched by the oxidation-decoration method of Kohlstedt and Vander Sande (1975). Samples were oxidized at 900° C in air for one hour. Thin section of oxidized sample was observed under the optical microscope.

Olivine crystals in the studied samples usually display a cellular dislocation structure (Toriumi and Karato, 1978), consisting of dislocations of simple subboundaries and subgrain interiors (Fig. 1). The subboundaries are the simple dislocation walls such as tightly knitted network of dislocations on (010) (Fig. 2a), and narrow arrays of straight dislocation lines on (100) and (001) (Fig. 2b). These dislocation walls form the boundaries of subgrain in olivine grains which show usually equant. The subgrain size is defined as the mean distance between subboundaries. Dislocation density within a single subgrain was measured by counting the

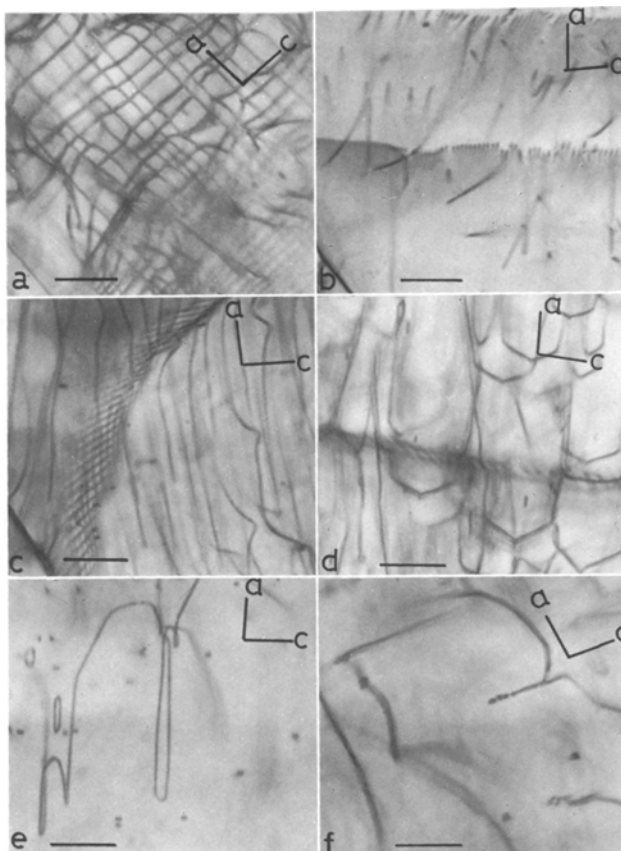


Fig. 2 a-f. Structures of the simple dislocation walls and dislocation substructure inside the subgrains. Each bar represents 10 μm in length. **a** network of dislocations nearly on (010) of Takashima olivine; **b** dislocation alignment nearly on (100) of San Carlos olivine; **c** wavy surface of network of dislocations of San Carlos; **d** bowing-out dislocations from subboundaries of Takashima olivine; **e** dislocation dipoles of Oki-Dogo olivine, **f** alignment of small loops formed by collapse of dislocation dipole of Takashima olivine

number of dislocations in 100 square microns for the case of the low density, and in 10 square microns for the high density.

(a) Structure of Dislocation Walls

Typical dislocation walls are the simple array of parallel dislocation lines on (100) and (001) (Fig. 2b), and simple network of dislocation lines (Fig. 2a) of which one set of dislocation lines is running along [100] and another along [001]. Structures of dislocation walls are same as the tilt boundaries of (100) and (001) and the twist boundary of (010) observed by Green and Radcliffe (1972), Green (1976) and Buis-kool Toxopeus and Boland (1976) using TEM technique.

Network of dislocations forming wavy and rounded wall surface is abundant (Fig. 2c), but the spacings between the dislocations are wider than those

of planar dislocation walls. Bowing-out of dislocation lines (Buiskool Toxopeus and Boland, 1976) from the dislocation wall is also common, and their segments form other dislocation wall (Fig. 2d).

Spacings between the dislocation lines forming walls show a wide range from 0.1 to 10 μm . Many of the (100) walls have a narrow spacing less than 0.5 μm , while (010) walls have a wide spacing of 0.5–10 μm . These dislocation walls are called as the subboundaries in this paper.

(b) Dislocations Within Subgrains

Dislocations within subgrains are almost always knitted with wall-dislocations and sometimes tangled with free dislocations within subgrains. Bowing-out dislocations are abundant, and they display a rectangular half-loop which is composed of three segments: two of them run parallel with each other but have opposite signs and same dislocation type (edge or screw types), and one of them shows different type. Bowing-out dislocations are considered to be emitted from dislocation walls by the same mechanism as Frank-Read dislocation source. In a subgrain, several of half loops with similar shape commonly expand from a dislocation wall, and some of their segments are very close to another wall, suggesting the pileup of dislocations. From those observations, straight dislocations running across a subgrain from one wall to another wall are interpreted as one of the three segments of a half-loop, and the other segments of a half-loop should be annihilated with wall-dislocations at the subboundary.

Cross-slipping dislocations are found within a subgrain (Fig. 2e). Such dislocations slip both on (010) and (001) as recognized in Fig. 2e. Small loops commonly follow dislocation half-loop (Fig. 2f), suggesting partial collapse of dislocation dipole as demonstrated by Groves and Kelly (1962) and Narayan and Washburn (1972).

(c) Preservation of Dislocation Density and Structure

Goetze and Kohlstedt (1973) examined the static annealing of olivine crystals in order to estimate the effect of natural annealing in basaltic liquid on dislocation density. Though they did not obtain clear evidences for the dislocation annihilation, they suggested that number of dislocations were absorbed in wall during annealing. Radcliffe and Green (1973) found no marked change of the dislocation structure in similar experiments. Recently, Toriumi and Karato (1978) experimentally determined the annihilation rate of

dislocations in olivine crystals during static annealing for various dislocation structures. They concluded that the decreasing rate of dislocation density strongly depends on initial dislocation density and annealing temperature. Annealing time necessary to produce a slight change in the dislocation density is one day for initial density of 10^{11}cm^{-2} and one year for 10^8cm^{-2} both at 1,100° C. If observed dislocation density is much less than these values and annealing time at the magmatic temperature of 1,100° C is less than 1 year, the density and structure of dislocation will remain unchanged and the state of the creep deformation within the upper mantle will be preserved. Inasmuch as the observed dislocation density is in the range of 10^6 – 10^8cm^{-2} , and the annealing time during the ascent of peridotite xenoliths from the upper mantle in basaltic magma is much less than 1 year (Toriumi and Karato, 1978), the observed dislocation density and structure in the studied olivine grains from the peridotite xenoliths should have maintained the state of creep deformation within the upper mantle.

The dislocation structure of olivine grains in dunite of the Mt. Higashi Akaishi and in peridotites of the Kamogawa continues across the cracks filled with serpentine and magnetite (Fig. 1d). This suggests that the dislocation structure was not affected by late stage deformation and consequent formation of secondary minerals during ascent of peridotites.

Relation Between Subgrain Size and Dislocation Density Within Subgrains

Both the diameter of subgrains and dislocation density within subgrains vary even in a single rock sample. Frequency distributions of subgrain diameter and dislocation density in a representative sample are shown in Fig. 3. The figures indicate a simple mode of their distributions. In Table 1, mean sizes of subgrain and mean dislocation densities within subgrains are listed. The linear relation in the full-logarithmic diagram is clearly shown in Fig. 4. From this, the empirical relation between the dislocation density, ρ , and the subgrain size, d , becomes,

$$d = K' / \sqrt{\rho}, \quad (1)$$

where nondimensional constant K' is 15 obtained from the least square fitting in Fig. 4. On the other hand, Kohlstedt and Goetze (1974) concluded that the differential stress is proportional to square root of the dislocation density in the steady state as follows;

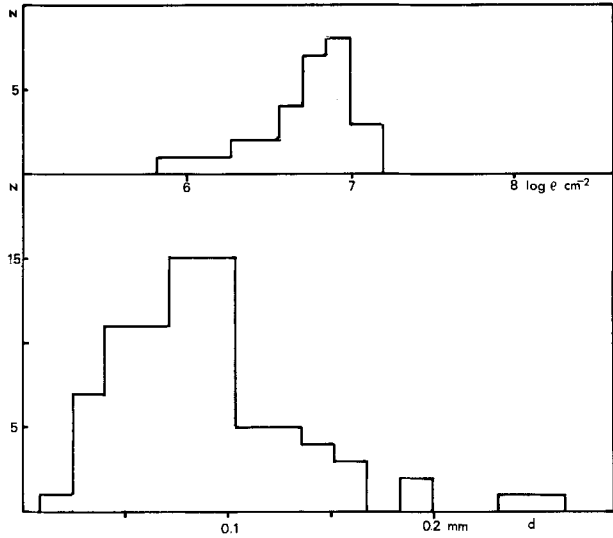


Fig. 3. Frequency distributions of the dislocation density within subgrains (upper) and subgrain diameter (bottom) of olivine grains in sample of Tak-1

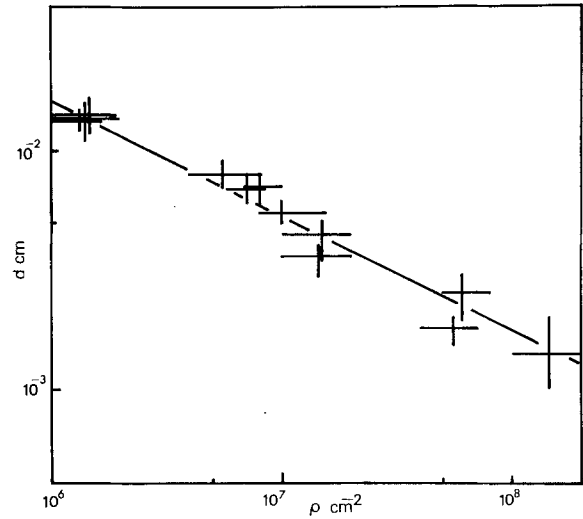


Fig. 4. Relation between the subgrain diameter (d) and the dislocation density of subgrain interiors (ρ)

Table 1. Mean subgrain diameters and dislocation densities of subgrain interiors for various samples

Sample	subgrain diameter (micron)	dislocation density (cm^{-2})
Ichinomegata		
Ich-7	40-50	$1-2 \times 10^7$
Ich-26	50-60	$0.8-1.5 \times 10^7$
Takashima		
Tak-3	120-160	$1-2 \times 10^6$
Tak-1	60- 80	$0.7-1 \times 10^7$
Tak-2	30- 40	$1-2 \times 10^7$
Oki-Dogo		
Oki-13	130-150	$1-2 \times 10^6$
Salt Lake	70-90	$4-8 \times 10^6$
San Carlos	130-170	$1-2 \times 10^6$
Dreiser Weiher	60- 80	$5-8 \times 10^6$
Mt. Higashi Akaishi		
HA-30	20- 30	$5-7 \times 10^7$
HA-5	10- 20	$1-2 \times 10^8$
Kamogawa		
Ka-5	15- 20	$4-7 \times 10^7$

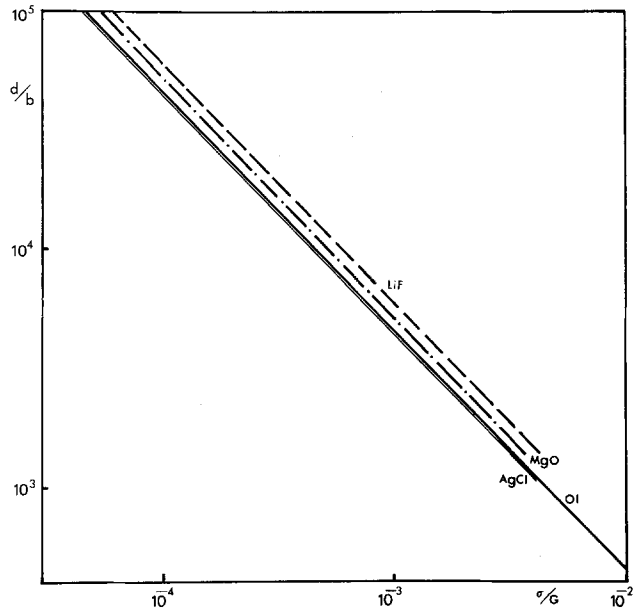


Fig. 5. Relation between the subgrain diameter and stress (σ) normalized by the magnitude of the Burger's vector and rigidity, respectively. Data of MgO, LiF, and AgCl are cited from Nicolas and Poirier (1976)

$$\sigma = K'' Gb \sqrt{\rho}, \quad (2)$$

in which ρ , G and b are the differential stress, the rigidity ($0.65 \times 10^6 \text{ bar}$) and the magnitude of the Burger's vector ($5 \times 10^{-8} \text{ cm}$) of olivine respectively. The nondimensional constant K'' is 3.

So far as the dislocation density within subgrains in most olivines studied here represents the value at

the time of the formation of subgrains (Toriumi and Karato, 1978), the dislocation density can be eliminated by combining Eq. (1) with Eq. (2). The relation between the dislocation density and subgrain size can be, therefore, converted into the relation between the differential stress and the subgrain size as

$$d = K Gb/\rho, \quad (3)$$

where nondimensional constant K is about 45, being quite close to those in metal (100), halides (60–44), and a simple oxide (MgO, 50) (Nicolas and Poirier, 1976) as shown in Fig. 5.

Discussion

Raleigh and Kirby (1970) proposed a simple relation between the subgrain size and the stress. Their relation is not consistent with result studied here. The discrepancy seems to have resulted from a different methods for measuring the subgrain diameter. In most cases, the subgrains can be identified only by etching, decoration, and TEM methods by which dislocations can be observed, because small-angle subboundaries are made by simple dislocation walls. The relation obtained here is quite similar to the apparently universal relationship mentioned above. Recently, Durham et al. (1977) have proposed a relation between the distance of (100) subboundaries and stress. The spacings between (100) subboundaries are nearly equal to the spacings between (001) and (010) subboundaries in the studied olivine grains. Therefore, the subgrain surrounded by these subboundaries appears equant and their diameter is quite similar to the spacings between (100) subboundaries.

The subboundaries are probably stable during static annealing (Nicolas and Poirier, 1976), but not against additional stress (Durham et al., 1977). High dislocation density inside the subgrains is relatively unstable during static annealing, in comparison with low dislocation density (Toriumi and Karato, 1978). If the subboundaries are stable, we can deduce the internal relation between the subgrain diameter and dislocation density for olivine grains annealed in static conditions for different annealing times, using the annealing experiments by Toriumi and Karato (1978). The general scheme to be predicted is shown in Fig. 6. It is suggested that the subgrain diameter-dislocation density relation in annealed samples is composed of two segments at a given set of temperature and annealing time: one is $d \propto 1/\sqrt{\rho}$, and another is $d = \text{constant}$. A point of meeting the two segments depends strongly on annealing time and temperature. Annihilation experiments by Toriumi and Karato (1978) give the relation as

$$\rho = \exp(-E_c/RT)/10^2 t_{\text{an}} \text{ (sec)},$$

E_c and ρ are the annealing time, the activation energy for the annihilation process, and dislocation density, respectively. This relation is useful for deducing the duration of static annealing of peridotites both in magmatic chamber and in the upper mantle, but it

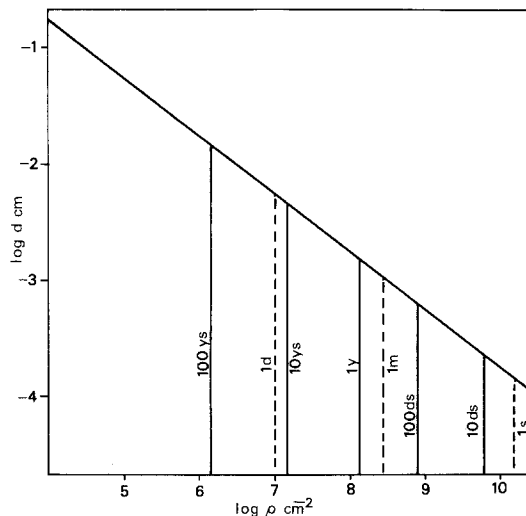


Fig. 6. Inferred relations between dislocation density and subgrain diameter of olivine for various annealing times at 1,100 (full lines) and 1400° C (broken lines). Annealing times are shown by the numbers

does not apply to the case in which dislocations with one sign is far more abundant than those with opposite sign, because of the lack of dislocation annihilation. However, as pairs of dislocations with opposite signs must be emitted from the Frank-Read source within subgrains or from subboundaries as described in the previous section, number of dislocations with one sign should be nearly equal to that with opposite sign in most subgrains.

Formation of dislocation wall has been discussed by several authors (Holt, 1970; Reppich and Hüther, 1974). Holt (1970) gave a theoretical relation between the dislocation density and the distance of dislocation walls. His simple model was based on the interaction of one dimensional screw dislocations without multiplication and annihilation of dislocations. On the other hand, Reppich and Hüther (1974) discussed the formation mechanism of simple dislocation walls such as tilt and twist boundaries by pinning and climbing of dislocations emitted from Frank-Read source inside the subgrains. As this contains the multiplication and annihilation of dislocations, it is important for wall-formation in the steady state creep, but it does not give a relation between subgrain size and dislocation density within a subgrain.

The observations about dislocation substructure in subgrains and dislocation walls in this paper, however, suggest that the dislocation multiplication and annihilation take place at subboundaries. This is important when the model of the steady state creep is considered. The above suggestion demands the role of the dislocation walls as the sink and source of dislocations. Thus, the flow is governed by dislocation

climb at dislocation walls but not by glide process within subgrains. This constraint is quite similar to the Weertman's model (Nicolas and Poirier, 1976).

Conclusions

The relations between subgrain size d and dislocation density ρ of subgrain interiors obtained from naturally deformed olivine grains is represented as,

$$d = 15/\sqrt{\rho} \text{ (cm)}.$$

Combining with the empirical relation between the differential stress and dislocation density proposed by Kohlstedt and Goetze (1974), the relation between the subgrain size and the differential stress σ becomes

$$d = 45 \text{ Gb}/\sigma \text{ (bar)} \text{ (cm)}.$$

The nondimensional constant in this equation for olivine is very close to those for a simple oxide (MgO), halides (LiF, NaCl) and metals.

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