DISLOCATION STRUCTURE OF OLIVINE IN THE MT. HIGASHI
AKAISHI DUNITE MASS IN THE SAMBAGAWA
METAMORPHIC TERRANE OF JAPAN

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Abstract Dislocation density and structure were studied in olivines of the Mt. Higashi
Akaishi dunite mass in the Sambagawa metamorphic terrane. Many rocks of the mass
show porphyroclastic texture, in which porphyroclastic olivines show the cellular dislocation
structure with dislocation density of cell interior of \(5 \times 10^7 - 2 \times 10^8\) cm\(^{-2}\). In matrix olivines,
the dislocation density varies markedly in the range from \(10^5\) to \(10^8\) cm\(^{-2}\) even in a
section, and the dislocation structure is composed of tangled dislocations and bundled
dislocation dipoles without dislocation cell walls. The cellular structure of porphyroclastic
olivine probably formed in the steady state creep, while dislocation structure of matrix olivine
formed in transient creep.

The dislocation structure formed before the uplift of the mass, judging from the facts that
it continues across the cracks filled with serpentine and magnetite. The differential stress
is estimated to be about 1 kb from the dislocation density of porphyroclastic olivines using
the experimental relations between the stress and the dislocation density (KOHLS TEDT &
GOETZE, 1974). The strain rate can be deduced from above stress condition, metamorphic
temperature of about 550°C, and pressure of 7–13 kb (MORI & BANNO, 1973) as \(10^{-25}\) sec\(^{-1}\),
suggesting that the mass behaved as rigid body during the Sambagawa metamorphism.

Introduction

There are two types of different tectonic origin in peridotite. The alpine-type massive
peridotite has been believed to be emplaced into the crust from the upper mantle near
the plate margin (COLEMAN, 1971), while peridotite xenolith in basalt is brought from the
upper mantle within the plate. Some different textural types of peridotite can be also recognized;
porphyroclastic peridotite is common in the alpine-type peridotite, and protogranular and equigranular peridotites are
common in peridotite xenolith (MERCIER & NICOLAS, 1975).

Dislocation density of olivines in various peridotites has been measured by many auth-
ors using the TEM and decoration methods (BOLAND et al., 1971; GREEN & RADCLIFFE,
1972a, b; PHAKEY et al., 1972; GOETZE & KOHLSTEDT, 1973; KIRBY & RALEIGH, 1973;
BUISKOOOL TOXOPEUS & BOLAND, 1976; BOLAND, 1977; GUEGUEN, 1977; TORIUMI & KA-
RATO, 1978). Their results show that the dislocation density of most olivines in the alpine-type peridotite ranges from \(10^8\) to \(10^9\)
\(\) cm\(^{-2}\), and that in the peridotite xenolith does from \(10^6\) to \(10^7\) cm\(^{-2}\). Referring the relations
between the dislocation density and the differential stress given by KOHLSTEDT & GOETZE
(1974), the differential stress in the alpine-type peridotite mass is more intensive than
that in the peridotite xenolith by a factor of 10. This does not indicate strikingly the differ-
ence of the flow stress within the upper mantle near the plate margin and within the
plate as suggested by CARTER (1976) and NICOLAS (1976), for the dislocation structure and
density of olivines in the alpine-type peridotites probably form during their emplacement from
the upper mantle to the crust. In order to discuss the differential stress within the uppermost mantle and/or the lowermost crust near the plate margin, we must study the dislocation density and structure of olivines which deformed in the uppermost mantle near the plate margin.

In this paper, the author intends to describe the dislocation structure of olivine in the dunite mass of the Mt. Higashi Akaishi of central Shikoku, Japan, which is suffered from high pressure type regional metamorphism (the Sambagawa metamorphism) which probably occurred in the uppermost mantle and/or lowermost crust near the plate margin (MIYASHIRO, 1961). The author also discusses the flow stress of the Mt. Higashi Akaishi dunite mass during the Sambagawa metamorphism. This study also gives important data on an origin of porphyroclastic texture.

**Geological Setting**

The dunite mass studied here occurs in the epidote-amphibolite facies area of the Sambagawa metamorphic terrane in central Shikoku (Fig. 1). Geology of the mass has been studied by BAMBA (1953), YOSHINO (1961, 1964) and MORI & BANNO (1973). The mass occurs as a large lenticular mass elongated in the E-W direction, and it contacts with the mass of epidote amphibolite on the north, and on the south and west it is in contact with pelitic and basic schists.

The mass consists mainly of dunite and rarely of wherlite, pyroxenite, chromite and eclogite. Chromite bands and seams occur commonly in the massive dunite. Eclogite and pyroxenite are found as boudines surrounded by mylonitic dunite.

The mass has been studied petrologically in detail by MORI & BANNO (1973) and YOKOYAMA & MORI (1975). They have recognized two stages of recrystallization in the mass; the spinel-pyroxenite and the garnet-pyroxenite stage (YOKOYAMA & MORI, 1975). The temperature of the earlier stage (spinel-pyroxenite stage) has been inferred to be in the condition of the granulite facies (YOKOYAMA & MORI, 1975), and that of the later stage (garnet-pyroxenite stage) to be about 500—600°C (MORI & BANNO, 1973). The pressure condition estimated from garnet-orthopyrox-
Fig. 2 Photographs showing occurrence of matrix olivine and porphyroclastic olivine in porphyroclastic dunite. A; matrix olivine around chromian spinel. B; matrix olivine around porphyroclastic olivine. P; porphyroclastic olivine. M; matrix olivine. S; chromian spinel.

The compositional difference between porphyroclastic and matrix olivine has resulted from the two stages of recrystallization of olivine mentioned in the previous section. The main constituents in the dunite mass are chromian spinel and olivine, so that the change of iron content in olivine is governed by partitioning of Fe and Mg between spinel and olivine and by modal composition of spinel. Partition coefficient of Fe and Mg between them decreases markedly with decreasing temperature. Consequently, FeO-content in olivine, which was in equilibrium with chromian spinel in the high temperature condition, turns into a lower level in the lower temperature (Arai, 1975). Two stages of recrystallization in the Mt. Higashi Akaishi mass are recognized (Yokoyama & Mori, 1975); temperature of the earlier stage is of the granulite facies, and that of the later stage is about 550°C, which is lower than that of the earlier stage. Therefore, it is suggested that porphyroclastic olivine formed during the earlier stage, and matrix olivine recrystallized in the later stage. Chemical zoning in the outer part of porphyroclastic olivine grain may be due to diffusion of Fe and Mg induced by repartitioning of them between olivine and spinel during the later stage. This may lead to the conclusion that porphyroclastic olivine had been suffered from deformation of all over the Sambagawa metamorphism but matrix olivine was done during some periods in its later stage.
Dislocation Structure

a) Experimental procedures

Dislocations in olivine were observed by the oxidation-decoration method (Kohlstedt & Vander Sande, 1975) under optical microscope, and by 100 kV transmission electron microscope. There are scarce disturbance on dislocation structure by cutting with diamond saw and heating for decoration in a furnace at 900°C during one hour. The small dot in the decorated thin section was identified as the small dislocation loop less than 1 micron radius by comparison of optical feature with the electron microscopic image of ion-bombarded thin section.

The samples studied here were collected from the Mt. Higashi Akaishi dunite mass along a traverse from the top of the Mt. Higashi Akaishi to the south (Fig. 1B). Each of 36 samples was collected about 3 meters apart.

b) Dislocation structure and density

Dislocations show uniform distribution, forming cellular structure in porphyroclastic olivine, and in matrix olivine they usually occur as dense arrays. Dense arrays of dislocations are on the plane or appear as bundle. Most dislocations in dense arrays are extensively elongated half or complete loop. Therefore, a pair of two segments of dislocation loop behaves as dislocation dipole. Groves & Kelly (1962) have shown that closed dislocation dipole in MgO is destroyed into trail of small dislocation loops in annealing experiment. There are many trails of small dislocation loops in matrix olivine which contains dense arrays of dislocation dipoles, suggesting the partial recovery of matrix olivine.

Porphyroclastic olivine

Typical dislocation structures as shown in Plates Ia to If are framed up by twist and tilt boundaries, helical dislocations, and bowing-out dislocations expanding from cell walls. Twist boundaries which are the network of [100] and [001] screw dislocations are parallel to (010) plane (Plate Ib), and tilt boundaries (parallel alignment of edge dislocations) are (100) and (001) planes (Plate Id). This dislocation structure in porphyroclastic olivine, therefore, is to be called as the cellular type described in the previous paper (Toriumi & Karato, 1978).

Some of porphyroclastic olivine, however, show a faint cellular structure as illustrated in Plates Ia and Ie. In this type of olivine, there are abundant tilt boundaries but not common twist ones, and the dislocation density within cell is relatively higher than that of olivine with clear cellular dislocation structure as shown in Plates Ib, Ic and Id.

Dislocation dipoles are sometimes observed, and many of them are partially annihilated to form loops (Plate Ia). Cross-slipped dislocations are abundant within cell, and they occur as rectangular helics.

Cell size ranges from 10 to 30 microns and it decreases with increasing dislocation density.
within cell.

Matrix olivine

Typical dislocation structures are shown in Plates IIa to IIb. In matrix olivine with low dislocation density, dislocations occur as extremely elongated half loop or as bowing-out dislocation expanding from grain boundary (Plates IIa and IIc), and form their bundles (Plate IIb). As is clear in Plate III, bundled dislocations are aligned on (110) plane. Many of matrix olivine with high dislocation density show tangled dislocation structure (Plates IIb and IIc). Bundles of tangled dislocations are aligned parallel to the elongation of helical dislocations. Some of tangled dislocations show double helices, suggesting that tangled structure is produced by interaction of many dislocation dipoles as observed in Plate IIb. It is, therefore, suggested that the tangled dislocation structure is derived from the structure of dense arrays of straight dislocation dipole (Plates IIb and III) with progressive deformation. Network dislocations forming impure twist boundary are rare in matrix and its spacing is relatively wide compared with those in the porphyroclastic olivine.

Dislocation density

The dislocation density in porphyroclastic olivine ranges from $5 \times 10^7$ to $2 \times 10^8$ cm$^{-2}$, and that in matrix olivine varies in a wide range from $10^5$ to $10^8$ cm$^{-2}$, which does not exceed so markedly the density of porphyroclastic olivine in a section. Frequency distribution of the dislocation density varies in rocks as shown in Figs. 4 and 5. In most samples, it shows a peak at the highest dislocation density, but in some samples, for example HA-2, the frequency diagram shows a peak near the middle (Fig. 4). As is clear in Figs. 4 and 5, the dislocation density of porphyroclastic olivine falls in a narrow range compared with that of matrix olivine. As discussed in the preceding section, porphyroclastic olivine is considered to deform under the steady state creep, so that the dislocation density within cell does reflect the flow stress of the dunite mass. The variation of the dislocation density in porphyroclastic olivines along the traverse from the top of the Mt.Higashi Akaishi toward the south is shown in Fig.6. The figure indicates a periodical change of the dislocation density. This regional variation of the dislocation density is over the range of the density in a sample. The density in the highly deformed olivine reaches about $2 \times 10^8$ cm$^{-2}$, and in the weakly deformed one about $5 \times 10^7$ cm$^{-2}$. Periodicity of variation in dislocation density shows the wavelength of about 10 meters.
Discussions

a) Preservation of dislocation structure and density

The dislocation structure and density in olivine may change through annealing. High temperature annealing experiments on olivine have been carried out by Toriumi & Karato (1978). They have confirmed that the annihilation rate of dislocations depends significantly on temperature and initial dislocation density. Following their results, the dislocation density of about $10^8$ cm$^{-2}$ is nearly equal to the initial density in the annealing time of some ten million years at 550°C. On the other hand, the annealing time of the dunite mass during the Sambagawa metamorphism is probably on the order of 1—10 million years, judging from the length of zonal structure of about 100 microns in porphyroclastic olivine and from diffusion constant of about $10^{-15}$ cm$^2$/sec at 550°C estimated from Misener’s experimental data (Misener, 1972). Therefore, the dislocation density and structure of olivine in the Mt. Higashi Akaishi mass did not change during metamorphism even if the late stage of the metamorphism was in the static condition.

The dislocation structure continues across the cracks filled with serpentine and magnetite in a single grain of all samples of the mass (Plates If and IIif). It is most striking that the dislocation structure formed before the formation of serpentine and magnetite. The formation of serpentine and magnetite is considered to have taken place during the uplift of the Sambagawa metamorphic belt after recrystallization of the mass in the later stage. Consequently, the dislocation structure and density of both porphyroclastic
and matrix olivine formed during the Sambagawa metamorphism and they remain until now.

b) Dislocation structure

Streb & Reppich (1973) and Hüther & Reppich (1973) have investigated the change of dislocation structure from transient creep to the steady state creep of MgO and LiF, respectively. They have concluded that the equiaxed-cellular structure of dislocations forms in the steady state creep, but the tangled structure does in transient creep. Their results can be applicable to olivines studied here. The marked difference of the structure between matrix and porphyroclastic olivine is not considered to be due to the difference of grain size, for matrix olivine with different diameters show the same dislocation structure. As shown in the previous section, porphyroclastic olivine has been existing all through the Sambagawa metamorphism, while matrix olivine had formed at a stage in it. It is possible to consider that the deformation during the Sambagawa metamorphism continued through a period long enough for porphyroclastic olivine to approach the steady state creep. On the other hand, matrix olivine with low dislocation density deformed in the early stage of transient creep. Matrix olivine with high dislocation density and tangled dislocation structure probably deformed in the later stage of transient creep, because of appearance of partial annihilation of dislocation dipoles. It is also probable to consider that the frequency distribution pattern of the dislocation density in matrix olivine indicates strikingly the successive recrystallization during the Sambagawa metamorphism. If it is so, it may be also suggested that the bimodal distribution of the dislocation density as seen in Fig. 4 shows a discontinuous recrystallization of matrix grains in the later stage.

c) Flow of the Mt. Higashi Akaishi dunite mass

The dislocation structure in porphyroclastic olivine has formed in the steady state creep, and the dislocation density of porphyroclastic olivine in all samples studied here is in the narrow range. Therefore, it is concluded that the differential stress within the dunite mass ranges from 500 to 10,000 bars, using the experimental relations given by Kohlstedt & Goetze (1974). The Sambagawa metamorphism might have taken place at the subduction zone (Miyashiro, 1961). Then the tectonic stress obtained here has been acting within the uppermost mantle and/or the lowermost crust near the plate margin. The value of the tectonic stress is markedly higher than that in the upper mantle beneath the arc and oceanic island obtained from the dislocation density and subgrain size of olivine in peridotite xenoliths in alkali basalt (Green & Radcliffe, 1972b; Carter, 1976; Gueguen, 1977; Toriumi & Karato, 1978), and it is similar to that in the alpine-type peridotite of other localities and kimberlite xenoliths obtained by Buiskool Toxopeus & Boland (1976), Boland (1977) and Gueguen (1977).

Assuming the steady state creep defor-
formation of the dunite mass governed by Weertman-type creep law, we can deduce the strain rate of the mass. This assumption involves absence of heterogeneous deformation induced by recrystallization of olivine in the mass. Recrystallization-softening discussed by Nicolas & Poirier (1976) may increase the strain rate, but it is considered to take place in transient creep. Equilibrium temperature and pressure are about 550°C and 7—13 kb for the dunite mass of the Mt. Higashi Akaishi, respectively (Mori & Banno, 1973), and they are close to those of the deformation during the Sambagawa metamorphism. The strain rate in dry condition is estimated as 10^{-25} sec^{-1} as shown in Fig.7. In this figure, the strain rate of the upper mantle under the island arc of Northeast Japan is shown, being estimated from the dislocation density of olivine in Ichinomogata peridotite xenoliths (Toriumi & Karato, 1978). It is clear that the strain rate of the Mt.Higashi Akaishi dunite mass is extremely lower than that in the upper mantle under the Northeast Japan Arc. It is suggested that the Mt.Higashi Akaishi dunite mass behaved as a rigid body during the Sambagawa metamorphism.

Conclusion

Two types of olivine in the Mt.Higashi Akaishi dunite mass are recognized; one is porphyroclastic and another is matrix grain. The matrix grains of olivine have recrystallized during the Sambagawa metamorphism, and the porphyroclastic olivines are relic in the metamorphism.

Dislocation structure in porphyroclastic olivine is an equiaxed-cellular network structure of which cell walls are simple (100) and (001) dislocation walls of tilt boundary, and (010) dislocation network of twist boundary. Dislocations in matrix olivine form usually dipole and they are tangled commonly. The cellular dislocation structure probably formed in the steady state creep, but the tangled structure did in transient creep. The dislocation density in porphyroclastic olivine ranges from $5 \times 10^7$ to $2 \times 10^8$ cm$^{-2}$, thereby showing the differential stress of about 500 to 1,000 bars. Inasmuch as the Sambagawa metamorphism had taken place in the upper mantle and/or the lowermost crust near the plate margin, the stress obtained here had been acting within the uppermost mantle near the plate margin. This values of the stress is very higher than the stress within the plate under Island Arc of Japan estimated from the Ichinomogata peridotite xenoliths (Toriumi & Karato, 1978). On the other hand, as the temperature of deformation in the Mt.Higashi Akaishi dunite mass is about 550°C, the strain rate governed by the Weertman-type creep law in the mass is extremely lower than that in the upper mantle under the Island Arc of Japan. This suggests that the Mt.Higashi Akaishi dunite mass behaved as a rigid body during the deformation in the Sambagawa metamorphism.

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References


東赤石山かんらん岩体のかんらん石の転位構造

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（要 旨）

東赤石山かんらん岩体の岩石はしばしばポーフィロクラスタックチュク組織を示している。ポーフィロクラスタックチュクのかんらん石の転位構造は微小角の回転境界と小傾角境界によって作られるセル構造であり、セル内部の転位密度は $5 \times 10^7$ から $2 \times 10^8 \text{cm}^{-2}$ である。一方マトリックスのかんらん石はからみ合う転位と転位双極子の不均質に分布する転位構造を示すか、もしくは転位双極子が(110)面に並んだ構造を示す。このマトリックスのかんらん石の転位密度は $10^6$ から $10^7 \text{cm}^{-2}$ までの広い範囲にわたっている。セル構造を示すかんらん石は定常クリープによって変形した場合と推論される。一方からみ合う転位からなる転位構造は遷移クリープ段階で形成されたものと推論される。

転位構造と密度は岩石の上昇以前、すなわち三波川変成作用に伴う変形運動の結果によるものであり、それから変形運動の応力、および歪速度が推定される。セル構造をもつかんらん石の転位密度（$5 \times 10^7$ から $2 \times 10^8 \text{cm}^{-2}$）から、岩体に加わっていた応力は 500bar から 1 kb と推定される。また岩体の平衡温度は 550℃、平衡圧力 7 ～ 13 kb を用いて、この応力をヤルマンタイプの流動則に適用すると歪速度として約 $10^{-28} \text{sec}^{-1}$ という値が得られる。このことから東赤石山かんらん岩体は三波川変成岩の変形運動の間ほとんど剛体としてあると考えられる。
Plate I

Dislocation structures of porphyroclastic olivine. Each bar represents 10 microns in length. a; rectangular loop on (010) in cell, b; dislocation network on (010) forming twist boundary, c; cellular structure on (001) plane, d; typical cellular structure on (010), e; faint cellular structure of olivine with high dislocation density, f; dislocation structure continuing across crack filled with serpentine(S).
Plate II

Dislocation structures of matrix olivine of a; extremely elongated half loop in olivine with low dislocation density, b; dislocation bundles and trails of dislocation loop on (110), c; bowing-out dislocations expanding from grain boundary, d; tangled dislocations and trails of dislocation loops, e; dislocation structure on (001) of olivine with high dislocation density, f; dislocations aligned on (110) plane and the dislocation structure continuing across crack filled serpentine(S). Each bar represents 10 microns in length.