DUNITES AND SERPENTINITES IN THE SANBAGAWA METAMORPHIC BELT, CENTRAL SHIKOKU AND KII PENINSULA, JAPAN

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Large dunite-serpentinite masses of the Sanbagawa metamorphic belt occur in the axial zone of large scale recumbent fold. The texture and chemistry of olivines from the Higashi-Akaishi and Shiraga bodies (central Shikoku) and the Ryumon body (Kii peninsula) demonstrate the two types of dunite to be present in this belt. Dunites of the Higashi-Akaishi body had experienced two stages of metamorphism, resulting in slight compositional change of their olivines, but the dunites remained dunite, whereas those of the Shiraga and Ryumon bodies consist of olivines newly formed by the metamorphism of serpentinite. The newly formed olivines contain the minerals of serpentinite, such as magnetite, antigorite, chlorite, brucite and magnesite, as inclusions, and some of them have a positive correlation between \( X_{Fe} \) and \( NiO \) content being the reverse to the compositional trend formed by igneous crystallization. The presence of olivine + antigorite in the Shiraga and Ryumon bodies is in harmony with the thermal structure of the Sanbagawa terrain. This harmony and the widespread occurrence of newly formed olivine indicate that this type of dunite was formed by the metamorphism of serpentinite during the Sanbagawa metamorphism. From the viewpoint of thermal history, not all the peridotites in the Sanbagawa metamorphic belt are simple dismembered masses of the Higashi-Akaishi-type peridotite.

INTRODUCTION

Recently, attention has been paid on olivine formed by the metamorphism of serpentinite (Trommsdorff and Evans, 1972, 1974; Springer, 1974; Arai, 1975; Vance and Dungun, 1977; Pincent and Hirst, 1977). Overgrowth of olivine on relic minerals of serpentinite (Trommsdorff and Evans, 1974; Arai, 1975) and the turbid appearance and chemical heterogeneity are some of useful criteria to identify the metamorphic olivines.

In the Sanbagawa metamorphic belt, many ultramafic intrusions are situated along the axial zone of large scale recumbent fold. They are mainly dunite or its serpentinized equivalents, but they are accompanied by a variety of ultramafic and mafic rocks, namely, the Higashi-Akaishi and Fujiwara bodies are parts of metamorphosed gabbro-peridotite complex, the Higashi-Akaishi body accompanies garnet-clinopyroxenite (Mori and Banno, 1973), the Fujiwara body omphacite rocks (Onuki et al., 1978), and the Shiraga and Ryumon bodies are serpentinite with olivine newly formed from serpentinite.

To clarify the similarities and differences of the petrology of ultramafic bodies in the high-pressure metamorphic belt, a comparative study of the mineralogy of dunite

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and serpentinite was undertaken with the emphasis on the mineralogy of olivine. In this paper, the mode of occurrence, chemistry and texture of olivines from the Higashi-Akaishi and Shiraga bodies in central Shikoku and the Ryumon body in Kii peninsula will be described along with the discussion on their genesis, especially on the thermal history of the ultramafic bodies.

**GEOLOGICAL SETTING**

Three ultramafic bodies, the Higashi-Akaishi and Shiraga bodies in central Shikoku and the Ryumon body in Kii peninsula, are chosen for comparative study. Their locations are shown in Fig. 1. The Higashi-Akaishi and Shiraga bodies are located in the Upper member of the Minawa formation in the sense of Kojima et al. (1956) and the Ryumon body in the Ryumon formation in the sense of Kamiyama et al. (1964). These two formations are named differently, as their distributions are separated by Kii channel, but they probably represent the same geological unit, as they consist of the alternation of pelitic and psammitic rocks associated by chert and metabasite, their metamorphic grade is of the albite-epidote amphibolite facies as well as they distribute in the area of intense large scale recumbent fold.

1) **The Higashi-Akaishi body**: This body occurs in the albite-epidote amphibolite facies area (the biotite zone of Higashino, 1975) as a lenticular and concordant body, and is a part of metagabbro-peridotite complex (Banno et al., 1976). It is composed mainly of dunite with subordinate amount of wehrlite, clinopyroxenite, garnet-clinopyroxenite and chromitite. Yoshino (1961, 1964) distinguished two types of dunite, massive and foliated, and found that the direction of lattice orientation of olivine is in general concordant with the schistosity of the country rocks. In the upper part of the body (the Gongen part), which is well observed in the Gongen valley, rhythmic alternation of dunite, wehrlite, clinopyroxenite, garnet clinopyroxenite and chromitite of several millimeters to meters in thickness is conspicuous, giving foliation. The petrology of the body has been studied by Mori and Banno (1973) and Yokoyama and Mori (1975) by means of geothermometrical approach. They recognized two stages of metamorphism, the spinel-pyroxenite (earlier metamorphism) and garnet-pyroxenite (later metamorphism) stages corresponding to the granulite and albite-epidote amphibolite facies, respectively.

2) **The Shiraga body**: The body occurs in the Upper member of the Minawa formation as does the Higashi-Akaishi body and measures about 1.5 × 1 km² on the surface. The country rocks are pelitic and basic schists of the garnet zone of Higashino (1975). The body consists of serpentinite in which newly formed metamorphic olivine occurs. Chromite seam accompanying uvarovite, about 1 cm thick, was recognized by Yokoyama (1977).

3) **The Ryumon body**: The Ryumon body is situated in the Ryumon formation that
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is a stratigraphical equivalent to the Upper member of the Minawa formation in Shikoku (Kamiyama et al., 1964). The body occurs as a lenticular and concordant body at the axis of the Iimori recumbent syncline (Kamiyama et al., 1964) and measures about 2.5 x 1.5 km² on the surface. The metamorphic grade of the surrounding schists of the Ryumon body is probably the biotite zone (Kamiyama et al., 1964; Kanekira, 1967). The body is composed of dunite and serpentinite, the latter tends to occur in the marginal part. There are two types of dunite, brownish orange and dark brownish types. The former brownish orange type occurs only in the western part of the body, and the dark brownish type is the predominant type over the entire body. No chromite segregation has been recognized, though chromite is dispersed in many of dunite.

PETROGRAPHY AND MINERAL CHEMISTRY

1) The Higashi-Akaishi body: The body is divided into two parts, the main part and the Gongen part, in terms of the texture of dunite as follows.

**Main Part:** The dunite of the main part is predominantly porphyroclastic. Even though Mori and Banno (1973) have noticed the porphyroclastic nature of dunite, they did not study its details, and Toriumi (1978) was the first to emphasize the porphyroclastic nature of dunite. Porphyroclastic olivine measures about 2 mm in diameter and often shows wavy extinction, and is surrounded by fine-grained (0.05-0.3 mm) equant and strain-free olivines with mosaic texture. The porphyroclastic olivines often contain subhedral chromite, but never contain dusty magnetite. The porphyroclast has higher Fe/(Fe+Mg), X_Fe, than the mosaic olivine or it is zoned with higher X_Fe at the rim (Toriumi, 1978). Acicular antigorite sometimes replaces olivine, being aligned to form foliation. It postdated the metamorphism of the garnet pyroxenite stage, because of the fact that the dislocation structure of olivine develops across serpentine (Toriumi, 1978). When situated in serpentine, chromite is usually zoned with ferritchromit rim, but is not coated with magnetite (Kunugiza in prep.).

Some dunite of the main part remain less deformed and have granular texture. The dunite is composed of equigranular strain-free olivine, with diameter of 2 mm in average, and accompanies accessory chromite. The dunite of this rock-type is less serpentinized than the porphyroclastic dunite, and constituent chromite is seldom zoned. Olivine with wavy extinction and polygonization also occurs suggesting the transition to prophyroclastic dunite.

**Gogen Part:** At the Gongen valley, dunite is interlayered with sheared and serpentinized dunite, giving a strong foliation. In contrast to the main part, the dunite with equigranular or tabular mosaic texture in the sense of Mercier and Nicolas (1975) is common. Constituent olivines are equant and fine-grained (0.1 mm) and show little sign of wavy extinction and serpentinization. Yoshino (1961, 1964) and Mori and Banno (1973) called the dunite at this locality “mylonitized dunite”, but their characterization does not seem adequate, as the dunite was completely recrystallized. Subhedral chromite occurs at the triple junctions of olivines, and are not converted to ferritchromit at the rim.

Except the porphyroclastic olivine, the olivines of the Higashi-Akaishi body are usually homogeneous within each thin
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2) The Shiraga body: The serpentinite of this body consists of serpentine, olivine, magnetite and chromite and, in some rocks, uvarovite and chlorite. X-ray diffraction pattern indicates that serpentine is predominantly antigorite. Antigorite is rectangular (0.05 mm), showing the bladed mat texture of Maltman (1978). Lizardite pseudomorph after olivine was not found.

Mangetite occurs as dense aggregate (0.3 mm) or as dusty grains, and occupies up to 5 per cent of serpentinite. It is rich in NiO (about 0.7 wt %). Chromite is subhedral (0.2 mm) and is usually coated with magnetite. At the boundary between chromite and magnetite, thin ferritchromit is detected by means of reflected microscopy and electron-probe microanalyzer. Magnetite and chromite are often included in porphyroblastic olivine. Uvarovite and chlorite are occasional constituents; the former forms aggregate consisting of several grains, and develops only around chromite seam, where it envelopes chromite and magnetite on the one hand, and is included porphyroblastic olivine on the other.

Olivine occurs both as porphyroblast and as fine-grained matrix constituent. Its mode ranges from 0 to 60 per cent, being maximum in the rock with chromite seam. The porphyroblastic olivine is medium-grained (up to 1 mm) and anhedral, and in places its aggregation forms olivine-clot where olivines have zigzag grain boundaries (Fig. 3a). It is strongly turbid under the open nicol and has ragged rim (Fig. 3b). Porphyroblastic olivine commonly includes chromite, magnetite, antigorite and uvarovite.

Fine-grained matrix olivine (0.01 to 0.05 mm) is usually discrete, prismatic and free from dusty inclusions (Fig. 3c), but in places it forms aggregate consisting of several grains, the texture of which resembles to that of the ragged rim of the porphyroblast. It is noted that a few tens of olivine grains neighbouring to each other sometimes exhibit dimensional parallelism and nearly simultaneous extinction (Fig. 3d). This texture is also reported from the Saltan-Durrington ultramafic complex (Dungun, 1977) and found in the dehydration experi-

Fig. 2. $X_{Fe}$-NiO relation of olivines of the Higashi-Akaishi body.

![Graphical representation of the XFe-NiO relation of olivines.](image-url)
Fig. 3 Photomicrographs of serpentinite of the Shiraga body.

a) Olivine-clot in antigorite matrix. Olivines envelope a magnetite-chromite zoned grain (left center). Closed nicols.
b) Ragged rim of prophyroblastic olivine. Open nicol.
c) Discrete fine-grained prismatic olivines. Note abundant magnetites. Partly closed nicols.
d) Fine-grained prismatic olivines showing dimentional parallelism. Open nicol.

ment of serpentinite (Raleigh and Paterson, 1965).

Olivine of this body is characterized by its low $X_{Fe}$ and NiO content, and shows a limited range of solid solution from $X_{Fe} = 0.02$ to 0.05. As seen in Fig. 4, olivines represent a positive correlation of $X_{Fe}$ and NiO content. This extremely low $X_{Fe}$ and NiO content can be explained if olivine was formed from serpentine, leaving magnetite intact. The chemistry of olivine and the fact that all the inclusions in olivine are the minerals of the serpentinite indicate that olivine was formed by the metamorphism of serpentinite.

3) The Ryumon body: The dark brownish
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Fig. 5 Photomicrograph of dunite of the Ryumon body.

a) Lineation in granoblastic olivines. Opaque minerals (black) consist of both discrete magnetite and zoned spinel phase (see text). Open nicol.

b) Coexisting granoblastic olivines and mosaic olivines in dark brownish dunite. Closed nicols.

cent) with small amount of antigorite, chlorite, brucite, magnesite, magnetite and chromite. In some rocks, fine-grained diopside occurs in association with chlorite. Antigorite occurs interstitial to granoblastic olivines; the boundary between olivine and antigorite is diffused by gradational change of olivine to antigorite ratio. This texture resembles to that of olivine-rich serpentinite of the Shiraga body. Chlorite, brucite and magnesite are also interstitial constituents. Chlorite contains significant amount of chromium, up to 1.5 wt %. Antigorite, chlorite, brucite and magnesite occur also as inclusion in olivine. Magnetite and chromite are dispersed through dunite, occurring mostly as inclusions in olivine. Aside from discrete magnetite, they are always zoned like that found in the Shiraga body, but the former have wider intermediate zone of ferrichromite than the latter.

Olivine (granoblastic olivine) is coarse-grained (up to 3 mm) and anhedral. Similar to the porphyroblastic olivine of the Shiraga body, it is also turbid under the open nicol and contains inclusions of magnetite, chromite, antigorite, chlorite, brucite and magnesite, suggesting that olivine of this body was also formed from serpentine. Magnetite and chromite inclusions sometimes exhibit subparallel arrangement through granoblastic olivines, defining a lineation of the rock (Fig. 5a). This texture is evidently attributed to deformation at the serpentinite stage thereby opaque minerals were re-arranged. In places, granoblastic olivines are surrounded by fine-grained (0.02 mm) equant olivines (mosaic olivine) (Fig. 5b). The ratio of granoblastic olivine to mosaic one varies from a specimen to another. The mosaic olivine is free from dusty inclusions; opaque minerals occur at the triple junctions of olivines. The olivines are heterogeneous in composition from a grain to another. Typically, adjacent two olivines of both 0.02 mm in diameter have a compositional difference of $X_{Fe}=0.03$.

The brownish orange dunite almost consists of fine-grained equant olivines with mosaic texture and is scarce of hydrous
silicates and magnesite except for chlorite. The amount of magnetite is less than that in the dark brownish dunite, but zoned spinel phase, having chromite at the core, ferritchromit at the intermediate zone and magnetite at the rim, is common. The olivine is usually, but not always, free from dusty inclusions, and shows compositional heterogeneity grain by grain. Hence, that is the mosaic olivine described previously.

The olivine of this body is relatively iron-rich, their $X_{Fe}$ and NiO content ranging from 0.08 and 0.5 wt % to 0.16 and 0.2 wt %, respectively. The olivines are chemically heterogeneous in a thin section and their compositional range encountered reaches up to $X_{Fe}=0.05$ (see Fig. 6). As deformation hardly affect the olivine composition, such a wide compositional variation has to be attributed to the metamorphism of serpentinite. There are two trends in $X_{Fe}$-NiO relation; the $X_{Fe}$ of olivines in the dark brownish dunite increases with decreasing NiO content, whereas olivines from the brownish orange dunite show simultaneous increase in $X_{Fe}$ and NiO content. The latter compositional trend is evidently the reverse to well known trend of olivine formed by igneous crystallization.

**DISCUSSION**

1) **Genesis of Olivine** The Higashi-Akaishi body, which was originally cumulate from basaltic magma, had experienced at least two stages of metamorphism (Mori and Banno, 1973; Yokoyama and Mori, 1975; Banno et al., 1976), the spinel-pyroxenite and garnet-pyroxenite stages, the latter the anhydrous equivalent of the albite-epidote amphibolite facies metamorphism of the Sanbagawa belt. It could have experienced low temperature environment between these two stages, at which serpentinite could have been stable, but we have as yet not found any texture indicative of the olivine formation from serpentinite. Antigorite is common in serpenitized peridotite of the Higashi-Akaishi body, but the mineral we observe now always replaces olivine and never predated it. From the time of its formation as the cumulate, the olivine of this body has experienced the element re-distribution owing to changing physical conditions and the recrystallization accompanied by granulation, but the peridotite remained peridotite. Thus, except the olivines in chromitite and wehrlite, in which olivine is not the predominant mineral, olivine essentially retained its primary chemistry, as exemplified by the simple $X_{Fe}$-NiO relation mentioned previously.

On the contrary, the olivines from the Shiraga and Ryumon bodies were all formed from serpentinite. They contain the minerals of serpentinite, such as antigorite, magnetcite, brucite, chlorite and magnesite, as inclusions. The amount of olivine formed by the metamorphism of serpentinite differs in different bodies. It is less than 60 per cent in the Shiraga body, but ranges from 70 to nearly 100 per cent in the Ryumon body. Thus, some...
the Ryumon body consist almost exclusively of olivine, but the mineral has following features that suggest its origin different from that in the Higashi-Akaishi body: olivine contains magnetite and antigorite as inclusions, discrete Cr-rich chlorite coexists with olivine and chromite is always rimmed by magnetite with intermediate zone of ferritchromit. Further, the olivine in the Ryumon body is very often chemically heterogeneous, even if the dunite consists of almost solely olivine. The chemical heterogeneity of olivine does also exist in dunite of the Higashi-Akaishi body, but only the rocks containing both porphyroclastic and mosaic olivines. Local chemical heterogeneity of olivine in metamorphosed serpentinite can be explained by the difference of the degree of consumption of magnetite during dehydration, which varies considerably even in the size of thin section. The fact that the $X_{Fe}$-NiO relation of the dunite and serpentinite of the Shiraga and Ryumon bodies have different trend from what is expected for the cumulate olivine can be also related to the degree of consumption of magnetite. As magnetite favors Fe and Ni more than serpentine minerals and olivine do, the more magnetite is consumed, the more Fe and Ni enters olivine giving rise the trend previously mentioned.

2) Temperature of Equilibration Toriumi (1978) recognized two types of olivine, prophyroclastic and mosaic, in porphyroclastic dunite of the Higashi-Akaishi body, and correlated them to the spinel-pyroxenite and garnet-pyroxenite stages, respectively. The partition of Fe and Mg between olivine and chromite is more or less consistent with his recognition. The details of the consideration of this geothermometer will be discussed elsewhere and only its conclusions are quoted below. As seen in Fig. 7, the olivine-chromite pairs in the porphyroclastic dunite of the main part give slightly higher temperature than the pairs in the mosaic dunite of both the main and Gongen parts. By applying the new evaluation of olivine-chromite geothermometer carried out by Roeder et al. (1979) gives a temperature of 550°C, the garnet-pyroxenite stage, for the mosaic olivine.

On the contrary, newly formed olivine in the Shiraga and Ryumon bodies is not in equilibrium with chromite, because their Fe-Mg partition gives a nominal temperature range of up to 300°C, even in a thin section. It is evident, however, that the dunite and serpentinite of these bodies are in the temperature range of the stability field of antigorite. The assemblage of olivine+antigorite appears in the zone III of the Western Sierra Nevada (Springer, 1974) and in the zone I of the Tari-Misaka ultramafic complex (Arai, 1975) and corresponds to the green schists to epidote amphibolite facies (Evans and Frost, 1975).

3) Stage of Olivine Formation The garnet-pyroxenite stage, at which the Higashi-Akaishi peridotite had equilibrated, is the
anhydrous equivalent of the albite-epidote amphibolite facies metamorphism. Further, the Shiraga and Ryumon bodies had suffered the green schists to the epidote amphibolite facies metamorphism; the common appearance of dunite in the latter body might be in part due to the higher temperature of metamorphism than that of the former. Though we can not as yet make direct comparison of the temperatures of the ultramafic bodies and their surrounding schists, it is nevertheless pointed out that the thermal structure of the ultramafic bodies is in good harmony with that of the Sanbagawa terrain. This harmony suggests that the ultramafic bodies were regionally metamorphosed. Thus, the formation of newly formed olivine of the Shiraga and Ryumon bodies had taken place during the Sanbagawa metamorphism. Their widespread occurrence, in central Shikoku and Kii peninsula, had hardly been induced by tertiary granitic intrusives (cf. Ishibashi et al., 1977).

4) Dunites and Dunites in the Sanbagawa Terrain It has been pointed out by many authors that peridotites in the Sanbagawa terrain in the strict sense, i.e. terrain of schists north of the so-called Mikabu green rocks, are all dunite and wehrlite or their serpentinized equivalents. However, recent studies, including this study, of these peridotites have shown that they don't have a common origin and thermal history even though they intruded into more or less the same stratigraphic position, the Upper member of the Minawa formation and the Ryumon formation. Namely, the Higashi-Akaishi peridotite, which was originally cumulate, had experienced at least two stages of metamorphism, but the peridotite remained peridotite, being never much serpentinized. The Nikubuchi peridotite, which is also a part of the Higashi-Akaishi metagabbro-periodotite complex (Banno et al., 1976), consists mainly of dunite with granular texture. Yokoyama (1977 and in prep.) demonstrated that the peridotite was originally cumulate as was the Higashi-Akaishi body, but the majority of the Nikubuchi body had equilibrated at the spinel-pyroxenite stage, the earlier metamorphism of this metagabbro-peridotite complex. The Shiraga and Ryumon bodies are now olivine-bearing serpentinite and dunite, respectively. However, they are not serpentinized dunite but metamorphosed serpentinite. Thus, not all the peridotites in the Sanbagawa terrain are simple dismembered masses of the Higashi-Akaishi-type peridotite.

To recapitulate, from the view point of thermal history, there are dunites and dunites in the Sanbagawa terrain. Despite of this, however, the notion that the Sanbagawa terrain is characterized by dunite-wehrlite series (Research group of peridotite intrusion, 1968) is valid. After the formation of dunite-wehrlite by the crystallization of basaltic magma, some of them had passed through low temperature and near surface environment where the Higashi-Akaishi body could have suffered serpentinization. This fact gives a constraint in reconstructing the geological history of this high-pressure metamorphic belt.

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