Incipient melting of mantle peridotites observed in the Horoman and Nikanbetsu Peridotite Complexes, Hokkaido, northern Japan

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Plagioclase lherzolite from the Horoman complex, Hokkaido, Japan, contains four types of plagioclase, seam type, inclusion type, isolated type and vein type, with different mode of occurrence and texture. The occurrence of each type is systematically related to the lithostratigraphy of the complex, most typically represented by the contrast between the Lower and Upper Zone, and is mostly due to the continuous spatial change in P-T history suggesting a diapiric structure for the complex. The seam type plagioclase commonly occurs as one of minerals forming seam-like fine-grained aggregates that are divided into two sub-types: clinopyroxene-free seam and clinopyroxene-bearing seam. Clinopyroxene-free seams are common in the Lower Zone (cooler marginal zone of the diapir) and are inferred to have been formed by the subsolidus reaction among spinel and pyroxenes, which were originated from garnet and olivine. The bleb-like inclusions of sodic plagioclase associated with quartz, orthopyroxene, and Ti-pargasite only occur in the middle of the Lower Zone, and are inferred to represent an incipient partial melt formed and trapped in clinopyroxene. Seams containing a certain amount of clinopyroxene, isolated plagioclase grains, and sodic plagioclase-rich veins fringed by orthopyroxene are commonly occur in the Upper Zone (hotter central zone of the diapir). They indicate that a significant extent of partial melting took place in this zone. The veins may correspond to fractures, toward which incipient partial melt was segregated and crystallized. The contrasts between the two zones demonstrate that partial melting of plagioclase lherzolite was extensive to permit segregation of the partial melt into fractures in the Upper Zone, but that the melting and segregation was fairly limited in the Lower Zone. In the Nikanbetsu complex, segregation veins are frequently observed forming a network, which is interpreted to be a more advanced stage of partial melting associated with melt segregation than that presumed for the Upper Zone of the Horoman complex.

Keywords : Incipient melting, Peridotite, Mantle, Diapir, Horoman, Nikanbetsu

I. Introduction

Different upwelling histories have been reported for peridotite complexes in orogenic belts. Some complexes (e.g., the Lanzo complex; Boudier and Nicolas, 1977; Bodinier, 1988) are interpreted to be mantle materials that experienced extensive melting during the final ascent stage on the basis of the common presence of plagioclase-rich lenses and veins with depletion zone in the surrounding per-

idotites. On the other hand, some complexes, such as the Kinabalu complex (Imai and Ozawa, 1991), are thought to have been uplifted from the mantle by a tectonic force without cutting the dry solidus. The Erro-Tabbiro complex is considered to be a mantle material ascended along the P-T trajectory below the dry solidus but above its hydrous solidus causing melting during the ascent of the complex with addition of water-rich fluid (Vissers *et al.*, 1991).

Ozawa and Takahashi (1995) revealed a

diapir structure in the Horoman peridotite complex from detailed investigation on P-T history of plagioclase lherzolite samples from the bottom to the top of the complex. They described petrological, mineralogical, and textural variations from the Lower Zone to the Upper Zone, whose division was first proposed by Komatsu and Nochi (1966) and later clearly defined by Niida (1974, 1984), and concluded that the essential differences of the two zones were caused by difference in P-T upwelling history from the garnet stability field. The Lower Zone is inferred to have taken a lower temperature trajectory, probably corresponding to the outer part of the diapir and the Upper Zone to have taken the higher temperature trajectory, corresponding to the inner part of the diapir. Nearly adiabatic decompression path for the Upper Zone could lead to a melting if the peridotites were not completely dry. We, therefore, expect that an incipient melting may have occurred in the Upper Zone of the Horoman complex.

The Nikanbetsu complex, located 9 km to the east of the Horoman complex, has been regarded as a part of the Upper Zone of the Horoman complex (Niida and Katoh, 1978; Komatsu *et al.*, 1982). Mineralogical and textural data for the Nikanbetsu complex suggest that the complex experienced a similar P-T history to that of the Upper Zone of the Horoman complex. Therefore, the complex may also have had a good chance to experience melting event during its ascent.

In this paper, evidences for incipient melting in plagioclase lherzolite from the Horoman and Nikanbetsu complexes are presented. The mode of occurrence and chemical compositions of plagioclase in plagioclase lherzolite and plagioclase-rich veins are described in detail, because they give fruitful information on distribution of the incipient partial melt in the complexes as well as its redistribution processes,

such as segregation into fractures. On the basis of these observations, conditions required for an incipient melting, factors controlling spatial variability of the extent of the melting, and mechanism of smaller-scale melt segregation are discussed.

II. Geological background

The Horoman and Nikanbetsu peridotite complexes are located at the southern end of the Hidaka belt, which is characterized by a low-P and high-T type metamorphism in the Paleogene to early Miocene ages (e.g., Saeki *et al.*, 1991; Arita *et al.*, 1993). The Hidaka belt consists of two zones: Western Zone, which is a metamorphosed ophiolitic sequence, and Main Zone, which is supposed to be an arc crust-mantle sequence with thick crustal section (Komatsu *et al.*, 1986, 1989). They are in contact with the Hidaka Main Thrust. The Horoman and Nikanbetsu complexes belong to the Main Zone and occupy the lowest mantle sequence (Komatsu *et al.*, 1986).

1. Geologic outline of the Horoman complex

The Horoman complex is approximately 8×10 km in size and is in fault contact with surrounding mylonitic granite, gneiss, and gabbro (Komatsu *et al.*, 1983; Niida, 1984; Komatsu *et al.*, 1992). The total thickness of the complex is estimated to be up to 3,000 m (Niida, 1984). Niida (1974, 1984) divided the complex into Lower Zone and Upper Zone, on the basis of the amount of gabbroic rocks and some structural features. Gabbroic layers are much more abundant in the Upper Zone, and frequently alternate with thinner peridotites with sharp boundaries as compared with the Lower Zone. Ultramafic rocks in the Lower Zone, except for dunite of the Spinel-rich Dunite-Wehrlite suite (Takahashi, 1991a, b; 1992), mostly occur as thick layers with gradational boundaries.

Ozawa and Takahashi (1995) pointed out that plagioclase lherzolite from the Upper Zone is locally cut by plagioclase-rich, 0.3~3.0 centimeters thick and up to 10 centimeters long segregation veins, which are oriented parallel to the lineation but oblique to the foliation. In three dimensions, they typically have a flattened lens shape. Such plagioclase-rich veins have never been observed in the Lower Zone.

Monomineralic plagioclase lenses (a few centimeters in size) are also observed in the olivine-rich portion in the upper part of the Upper Zone (Figs. 1a and 1c). The veins and lenses often occur in a depletion zone surrounding thin gabbroic layers (Figs. 1a and 1c). A community of plagioclase-rich veins also occurs in plagioclase lherzolite that is far away from any gabbroic layers and extends for several to a few tens of meters along the direction of the lineation. Such zone is several centimeters in thickness.

Another characteristic textural feature of the Upper Zone is that fine grained plagioclase-rich lens-like aggregates are very common in peridotites occurring between plagioclase lherzolite and harzburgite, where symplectite-bearing spinel lherzolite is present in the Lower Zone.

2. Geology of the Nikanbetsu complex

The Nikanbetsu complex is approximately 2×1 km in size and is in fault contact with the surrounding gneiss, schist, and gabbro (Fig. 2). The complex is composed mainly of plagioclase lherzolite with subordinate amounts of lherzolite, harzburgite, gabbro, clinopyroxenite, and pegmatitic two pyroxene gabbro (Niida and Katoh, 1978; Takahashi *et al.*, 1989), showing many similar features to the upper part of the Horoman complex (Niida and Katoh, 1978; Komatsu *et al.*, 1982). In addition to these rocks, minor plagioclase-bearing websterite

Fig. 1. Photograph of lens-like plagioclase-rich bodies in the Horoman complex, occurring in the vicinity of a thin gabbro layer (a), and plagioclase-rich veins (arrows) in the Nikanbetsu complex (b), which are oblique to the foliation (F) and parallel to the lineation (L). Note that in (a) the vein is mantled by orthopyroxene. Sketch of photograph-(a) in (c).

lens occurs in plagioclase lherzolite, and orthopyroxenite between gabbro layers and the host peridotite. Plagioclase-rich veins are observed in plagioclase lherzolite and always have more than a few centimeter thick zone in which plagioclase is absent on the both sides (deple-

Fig. 2. Index map of the Horoman and the Nikanbetsu complex, after Komatsu *et al.*, (1986) (a), and lithological map of the Nikanbetsu complex, showing localities of studied peridotite specimens (b).

tion zone; Fig. 1b).

The structure is almost consistent within the complex (Fig. 2). The foliation strikes $N70^{\circ}E \sim N86^{\circ}W$ and dips $78^{\circ}N \sim 86^{\circ}N$, except for the northern part, where it dips to the south. Harzburgite and lherzolite layers alternate with gabbroic layers in the central part (Niida and Katoh, 1978), and the layering is nearly parallel to the foliation. Plagioclase-rich veins strike $N78^{\circ}E \sim N88^{\circ}W$ and dip $48^{\circ}N \sim 62^{\circ}N$. The veins are always parallel to the lineation and oblique to the foliation with $23 \sim 34^{\circ}$ angles (Fig. 1b).

Many plagioclase-rich veins occur in the central part of the complex (Figs. 1b and 2).

The vein-rich zone is up to 180 m in total thickness. The size of each vein is much larger than that of the Horoman complex, up to several tens centimeters in length and 1 centimeter in thickness. Sometimes, they connect with each other and make a network structure, size of which varies from several tens centimeters to a few meters. In the central part, gabbro dikes (several tens centimeters in thickness) are observed, which have irregular outline and the same mineral assemblage of plagioclase-rich veins nearby. Plagioclase-rich veins are locally associated with plagioclase-bearing websterite lens with irregular shape (10 centimeters long and 5 centimeters wide).

III. Textural variations of plagioclase lherzolite in the Horoman complex

1. General texture variation

Plagioclase lherzolite from the Lower Zone is typically characterized by mylonitic to porphyroclastic textures with large orthopyroxene and clinopyroxene grains as porphyroclasts (Fig. 3a). Obvious plagioclase-rich seam, which is parallel to the lineation, occurs in plagioclase lherzolite from the Lower Zone (Fig. 3a) (Niida, 1984; Ozawa and Takahashi,

1995). By contrast, plagioclase lherzolite from the Upper Zone is typically characterized by tabular equigranular to equigranular texture with minor smaller porphyroclastic grains of orthopyroxene and clinopyroxene (Fig. 3b). There is a transitional zone between the Upper and Lower Zones in terms of texture as well as of P-T histories (Ozawa and Takahashi, 1995).

Grain size of minerals in plagioclase-rich seams is almost constant or slightly increases upwards in the Lower Zone and significantly increases from the bottom of the Upper Zone

Fig. 3. Distributions of orthopyroxene, clinopyroxene, and plagioclase in plagioclase lherzolite samples from the Horoman and Nikanbetsu complexes. Plagioclase lherzolite from the Lower Zone is shown in (a), from the Upper Zone of the Horoman complex in (b), from Nikanbetsu in (c), and from the vicinity of plagioclase-rich vein of the Nikanbetsu complex in (d). The distributions were obtained from 2-dimensional elemental mappings, in which Na, Ca, K, Mg, Fe, Al, Cr and Si were measured. Black part is plagioclase, dark gray is clinopyroxene, light gray is orthopyroxene and white is other minerals, mainly olivine with minor spinel. Note that scales are the same in (a)~(d).

toward the top of the complex (Fig. 4). By contrast, aspect ratio of the minerals tends to decrease from the bottom to the top of the complex (Ozawa and Takahashi, 1995). The grain size of minerals in plagioclase-rich seams is smaller than that of minerals occurring outside the seam in the Lower Zone. The shape of plagioclase-rich seam is, therefore, clear and sharp in the Lower Zone (Fig. 3a), because of the significantly smaller grain size in addition to the peculiar modal composition. Plagioclase-rich seams are stretched and thinned by deformation and alternate with olivine-rich bands. These thin layers are fairly well defined in spite of the strong deformations and

are not mixed with some exceptions (Fig. 3a). By contrast, the grain size of seam minerals is as large as those occurring outside the seam and often it is difficult to recognize primary minerals from seam minerals in terms of grain size in the Upper Zone (Fig. 3b).

The aspect ratio of the seam in sections vertical to the foliation and parallel to the lineation (XZ section) changes from 30 in the lower part of the Lower Zone to 8 in the upper part of the Lower Zone. In the lower part of the Upper Zone, some seams still keep the lens shape, but most of them have diffused outline, around which isolated plagioclase grains are scattered (Fig. 3b). Near the top of the Upper Zone, we can barely recognize lens-like plagioclase-rich aggregates, and isolated interstitial plagioclase grains become common along grain boundaries of olivine and pyroxenes.

Fig. 4. Grain size of minerals in fine-grained aggregates in plagioclase lherzolite from the Horoman complex, plotted against distance from the base of the complex. The data is average of measurement on 100 grains.

2. Mode of occurrences of four types of plagioclase

Plagioclase in plagioclase lherzolite from the Horoman complex is classified into four types. These are seam type, inclusion type, isolated type, and vein type by its mode of occurrence (Fig. 5).

(1) seam type

Plagioclase of the seam type occurs as one of minerals forming a seam-like fine-grained aggregate (Figs. 3a, 5a and 5b). It is at least partly a product of the decompression reaction

Fig. 5. Photomicrographs showing mode of occurrence of plagioclase in plagioclase lherzolite from the Horoman complex. a : plagioclase-rich seam from the Lower Zone (seam type), open nicol ; b : plagioclase-rich aggregate in peridotite surrounding plagioclase-rich veins from the Upper Zone (intermediate between seam and vein types), with isolated plagioclase grains near the aggregate, open nicol ; c : plagioclase, Ti-pargasite, and orthopyroxene blebs in a clinopyroxene porphyroclast from the lowest part of the Upper Zone (inclusion type), open nicol ; d : isolated plagioclase along grain boundaries of pyroxenes from the Upper Zone (isolated type), open nicol ; e : Clinopyroxene porphyroclast with albite, quartz, Ti-pargasite, and orthopyroxene inclusions from the Lower Zone (inclusion type). Open nicol ; f : crossed nicols of (e) ; g : isolated plagioclase in olivine-rich part in plagioclase lherzolite from the Upper Zone (isolated type), open nicol ; h : isolated plagioclase rimmed by orthopyroxene (isolated type), crossed nicols. Abbreviations are ; pl, plagioclase ; sp, spinel ; cpx, clinopyroxene ; opx, orthopyroxene ; amph, amphibole ; ol : olivine.

among two pyroxenes and spinel which were derived from the reaction between garnet and olivine (Takahashi and Arai, 1989; Takahashi, 1991b; 1992) (Fig. 5a). Thus, the seam can be regarded as a deformed pseudomorph of garnet with possible modification by incipient melting and late-stage metasomatism. In the Lower Zone, plagioclase-bearing seams usually do not contain clinopyroxene (Fig. 6). Very small amount of clinopyroxene is rarely present in the aggregate as a film along grain boundaries of the other minerals. Plagioclase film rimming spinel grains in symplectitic aggregate occurring in the center of seams can be observed in the Lower Zone. The important feature of seam-type plagioclase of the Upper Zone is the general association of clinopyroxene, whose modal composition is up to 11 vol-

ume present in a seam (Fig. 6).

(2) inclusion type

Plagioclase of the inclusion type occurs as inclusions in clinopyroxene porphyroclasts, always coexisting with orthopyroxene blebs and sometimes with Ti-pargasite that partly replaces clinopyroxene (Fig. 5c). The grain size of this type of plagioclase is up to 70 μm and smaller than the other types. Clinopyroxene with many inclusions exhibits patchy appearance under the microscope (Fig. 5c). This type of plagioclase commonly occurs in the Upper Zone and the upper part of the Lower Zone, and very rarely in the middle part of the Lower Zone associated with Ti-pargasite. Tiny sodic plagioclase (17~20 μm in size) occurring in the core area of clinopyroxene porphyroclasts from the middle part of the Lower

Fig. 6. Modal composition of plagioclase-rich aggregates and veins from the Horoman and Nikanbetsu complexes. For the sample localities in the Horoman complex, see Ozawa and Takahashi (1995). Sample localities in the Nikanbetsu complex are shown in Fig. 2. Height from the bottom of the Horoman complex is shown in the right of the sample name.

Zone, coexists with quartz, Ti-pargasite, orthopyroxene and fine aggregates of albite and quartz and makes the clinopyroxene porphyroclasts dusty under the microscope (Figs. 5e and 5f). The dusty area is mantled by clear clinopyroxene margin, where the Na₂O content decreases drastically toward the rim (Ozawa and Takahashi, 1995). Such type of clinopyroxene porphyroclast has never been observed in the lower part of the Lower Zone and in the Upper Zone.

(3) isolated type

Plagioclase of the isolated type occurs outside plagioclase-rich seams as an isolated grain with size ranging from 0.20 to 0.57 mm (Figs. 5d, 5g and 5f). It occurs in olivine-rich zones between flattened seams in XZ sections. Some isolated grains occurring closer to plagioclase-rich seam may have been derived from the seam due to deformation. The isolated type is commonly observed in the Upper Zone, where isolated plagioclase is often mantled by orthopyroxene film (Fig. 5h). We rarely observe isolated plagioclase in contact with pyroxenes porphyroclasts in the upper part of the Lower Zone. Isolated plagioclase in less deformed plagioclase lherzolite shows clear albite twin (Fig. 5h), although it shows deformation twin in strongly deformed peridotites characterized by porphyroclastic texture (Nicolas, 1989).

(4) vein type

Plagioclase of the vein type occurs as a main constituent mineral in veins cutting the host plagioclase lherzolite (Takahashi, 1988; 1991b). Such veins are oriented oblique to the foliation at 25~35° angle and parallel to the lineation (Ozawa and Takahashi, 1995) and locally form a three dimensional network (Fig. 1). This type of plagioclase is observed only in the Upper Zone (Ozawa and Takahashi, 1995) and has never been observed in the Lower Zone, and in the lowest portion of the Upper Zone (up

to 120 m above the boundary with the Lower Zone).

Plagioclase veins are locally fringed by thin orthopyroxenite, and have several to several tens millimeter thick depletion zones where plagioclase is very minor in abundance (Fig. 3d). In the surrounding host peridotite, plagioclase-rich aggregates are locally present, which are associated with spinel, olivine, and clinopyroxene.

IV. Textural variations of plagioclase lherzolite in the Nikanbetsu complex

Peridotites from the margins of the Nikanbetsu complex show mylonitic or porphyroclastic textures, and those far away from the contacts with surrounding metamorphic rocks show protogranular texture (Mercier and Nicolas, 1975). The grain size is usually coarser than that of peridotites from the top of the Upper Zone of the Horoman complex.

Plagioclase lherzolite from the southern margin of the complex exhibits features similar to the Horoman complex, such as the occurrence of rounded two pyroxenes and spinel symplectite, plagioclase-rich seam, plagioclase rimming isolated spinel grains, and presence of interstitial plagioclase grains (Fig. 3c). The occurrence of interstitial isolated plagioclase in the pyroxene-rich part is, however, more common than that in the Horoman Upper Zone. Rare spinel grains in plagioclase-rich seams are mantled by Ti-pargasite film. In the central part of the complex, all plagioclase grains are interstitial to pyroxene and olivine (Komatsu *et al.*, 1982). Such interstitial plagioclase grains locally connect with each other forming a network structure, which is responsible for the heterogeneous distribution of plagioclase on a centimeter scale.

Plagioclase-rich veins, which are more common in the Nikanbetsu complex than in the Horoman complex, are composed mainly of

plagioclase (ranging from 0.27 to 3.43 mm in grain size and 1.12 mm in average) and coarse orthopyroxene (3.2 mm in grain size), olivine, $\pm$ Ti-pargasite, and $\pm$ phlogopite.

V. Mineral chemistry in the Horoman and the Nikanbetsu complexes

Minerals were analyzed with electron microprobe analyzers, JEOL JCMS 733 MkII at the Geological Institute of the University of Tokyo and JEOL JXA-8900 at the Chemical Analysis Center of Chiba University. Analytical procedures are the same as described by Nakamura and Kushiro (1970) with correction procedures after Bence and Albee (1968). The NiO content in olivine was analyzed under the 25 kV acceleratory voltage and with correction procedure of ZAF. The detection limit of the NiO content is 0.002 wt%.

1. Plagioclase

Plagioclase of the seam type exhibits Na-Ca zoning typically increasing An (100*Ca/

(Ca + Na) of plagioclase) content from the core to the rim (Ozawa and Takahashi, 1995) (Fig. 7). The minimum An content at the core increases gradually from the bottom to the top of the Lower Zone (An_{56-58}) and significantly from the lower part of the Upper Zone (An_{62-64}) to the upper part ($\sim An_{78}$) (Fig. 7).

The elongation of plagioclase is almost parallel to the lineation, and the rims situated in this direction have Ca-enrichment towards the rim (Fig. 7). Some elongated plagioclase grains in plagioclase-rich seams show Na enrichment toward the rims that situated perpendicular to the lineation (Fig. 8). Thus, the An zoning profile exhibits M-shape in the perpendicular direction (Fig. 8a). The An content increases from 60-62 at the core to 74-80 toward the margin and then decreases steeply up to ~ 40 at the rim without any increase at all (Fig. 8). This type of zoning is frequently observed in the Lower Zone, and rarely in the Upper Zone of the Horoman complex, and has never been observed in the Nikanbetsu com-

Fig. 7. Sodium-Calcium zoning of plagioclase grains in seams from both of the Lower and Upper Zones of the Horoman complex. Height from the bottom of the complex is shown in the lower right corner.

Fig. 8. Sodium-Calcium zoning of plagioclase grains showing Na enrichment toward the rim in the direction perpendicular to the lineation. Sketches based on mapping analysis show the location of analysis lines and location of the enrichment and coexisting Ca enrichment toward the rim in the direction parallel to the lineation. The samples are from the Lower Zone of the Horoman complex. Line profile, parallel to the direction of lineation of the same grain (b) is shown in Fig. 9a of Ozawa and Takahashi (1995). Note that in (a), plagioclase-1 includes a small spinel grain beneath the surface of the section, and the An content in the vicinity of the spinel is high.

plex.

Anorthite content of plagioclase of the isolated type shows a systematic variation depending on their occurrences (Fig. 9). The core composition is fairly similar to that of seam type plagioclase (cf. Fig. 7c and Figs. 9a and 9b; Fig. 7e and Fig. 9e). Plagioclase grains forming an aggregate (a few centimeters in size) and transitional type between the isolated and vein types, are systematically An-poor ($< \text{An}_{60}$) than completely isolated plagioclase grains, even if they are in the same thin section (cf. Figs. 9c and 9d). Isolated plagioclase

occurring closer to plagioclase-rich veins also has An-poor core ($\sim \text{An}_{56}$) (Fig. 9f), which is similar to that of plagioclase from the veins as will be described below.

Plagioclase inclusions in clinopyroxene (inclusion type) have homogenized core with $\sim \text{An}_{70}$, regardless of horizon in the Horoman complex. Some grains have slight Ca-enrichment toward the rim.

Plagioclase from the Nikanbetsu complex shows also Na-Ca zoning similar to the Horoman complex (Fig. 10). It has An-poor core, (An_{61-66}) and An-rich rim (up to An_{90}). The

Isolated plagioclase from the Upper Zone

Fig. 9. Sodium-Calcium zoning of isolated plagioclase grains far away from plagioclase-rich veins (a-e) and those occurring near such veins (f) from the Upper Zone of the Horoman complex. Height from the bottom of the complex is shown in the lower right corner.

Plagioclase from the Nikanbetsu complex

Fig. 10. Compositional zoning of plagioclase grains in seams (a-d) and of an isolated grain (e) from the Nikanbetsu complex.

Fig. 11. Line profile of An mol% (100 Ca/(Ca + Na + K)) of plagioclase and Fo mol% of olivine, Mg# (100* Mg/(Mg + Fe)) of orthopyroxene from a plagioclase-rich vein and the surrounding peridotite. Compositional variations crossing a vein from the Upper Zone of the Horoman complex is shown in (a), variations of An mol% crossing two grains of plagioclase near irregular spinel grains from the relatively marginal part in (b), and plagioclase grains from the central part of vein-(a) in (c). Compositional variations of plagioclase and orthopyroxene crossing a small vein mantled by orthopyroxene grains from the Nikanbetsu complex are also shown in (d). Arrows in (a) and (d) indicate grain boundaries of plagioclase grains in the veins.

An content of plagioclase of the seam type ranges from 62 to 68, whose values are similar to that of the Upper Zone of the Horoman complex. Large isolated plagioclase grains from the Nikanbetsu complex show a W-shaped Na-Ca zoning pattern (Figs. 10a and 10e); in the core region the An content slightly decreases from 70 to 65 followed by an increase up to An₈₅ at the rim (Fig. 10e).

All plagioclase grains from plagioclase-rich veins in plagioclase lherzolite from the

Horoman and Nikanbetsu complexes have also compositional zoning similar to the other types. The An content increases from the core of each grain to the rim (Fig. 11b). Some plagioclase from the center of a thick vein, rarely shows a W-shaped zoning pattern (Fig. 11c). There is also a systematic variation within a vein (Figs. 11a and 11d). Core of plagioclase from the margin of veins is relatively An-rich (An₇₀₋₇₂), whose value is similar to that of plagioclase grains of seams in the surrounding peridotite.

Fig. 12. Relationship between TiO_2 wt% at the core of clinopyroxene porphyroclasts and average Fo contents of coexisting olivine from the Horoman complex. Data for Spinel-rich Dunite-Wehrlite suits (SDW) and Main Harzburgite-Lherzolite suite (MHL) are after Takahashi (1991a, b; 1992).

The core of plagioclase from the center of the vein is An-poor (An_{52}). This large scale variation of the An content in the veins is most remarkable at the tips of the veins. Plagioclase in contact with irregular spinel grains in the vein shows remarkable enrichment of An content toward the contact with the spinel, up to more than 80.

2. Pyroxenes

Clinopyroxene from the Nikanbetsu complex shows chemical zoning similar to that from the Upper Zone of the Horoman complex (Ozawa and Takahashi, 1995). Al content of the clinopyroxene grains from the Nikanbetsu complex is homogeneous in the core and its content decreases monotonously to the rim. The Na_2O content slightly decreases from the core to the rim. The TiO_2 content consistent-

Fig. 13. Relationship between Fo and NiO contents in olivine from peridotites of the Horoman and the Nikanbetsu complex. Lines connect olivine in a plagioclase-rich seam and that occurring in the host peridotite.

SDW, Spinel-rich Dunite-Wehrlite suits; MHL, Main Harzburgite-Lherzolite suite.

ly increases from the core to the rim in all plagioclase lherzolite from the Horoman and Nikanbetsu complexes, although the range of the zoning is much less in the Upper Zone of the Horoman complex and the Nikanbetsu complex than that from the Lower Zone of the Horoman complex. Clinopyroxene occurring at the margin of plagioclase-rich veins is more Ti-rich, as compared with that far away from such veins (Fig. 12).

Orthopyroxene from the Nikanbetsu complex shows chemical zoning similar to that from the Upper Zone of the Horoman complex (Ozawa and Takahashi, 1995). The Wo content at the core ranges from 2.8 to 3.2.

3. Olivine

Olivine occurring in the vicinity of plagioclase-rich veins has Fo ($100 \times \text{Mg}/(\text{Mg} + \text{Fe})$)-poor and Ni-poor characters as compared with olivine far away from the veins (Fig. 13). They are not plotted on the linear Fe-rich extension of the trend of the Horoman peridotites (mantle olivine array after Takahashi *et al.* (1987) on the Fo-NiO diagram), and the data clusters are shifted to the lower Ni-poor side. At the contact with the vein, the NiO content of olivine is 0.34 wt%. As the distance from the vein increases, the content first decreases to ~ 0.30 wt% followed by an increase up to more than 0.34 wt% within 1 m from the vein. Olivine compositions of plagioclase lherzolite about 2 m away from the veins are plotted within the Horoman peridotites trend. Olivine occurring in plagioclase-rich seams has similar Fo content, but is poor in Ni as compared with those of olivine away from the seams (Fig. 13). Some polygonal olivine grains which are in contact with plagioclase-rich seam from the Horoman complex also show the low-Ni character. Olivine in plagioclase lherzolite from the Nikanbetsu complex is mostly plotted in the Horoman trend, however, olivine from the

area where abundant plagioclase-rich veins occur (NK13; Fig. 2), shows low-Ni content regardless of its mode of occurrence (Fig. 13). Olivine from wall of plagioclase-rich veins from the Nikanbetsu complex also has Fo-poor and Ni-poor characters (reversed triangles in Fig. 13).

VI. Discussion

Ozawa and Takahashi (1995) revealed that Na-Ca zoning of plagioclase in the plagioclase-rich seam, which is characterized by the systematic increase in An content toward the rim, was formed by a continuous reaction among two pyroxenes and spinel driven by decompression through the boundary of the spinel and plagioclase peridotite facies. They also clarified the systematic increase in homogeneity of Cr and Al distribution in spinel grains and An content in plagioclase grains from the bottom to the top of the Horoman complex and inferred that the continuously increasing temperature of the decompressional P-T path from the base to the top is responsible for the observed variation of the homogeneities. On the basis of the inferred P-T histories of the Horoman complex, origin of the textural and mineralogical features described above are discussed to reveal melting and melt segregation process in the Horoman and Nikanbetsu complexes.

1. Origin of inclusion type plagioclase in clinopyroxene porphyroclasts from the Lower Zone and the lowest part of the Upper Zone of the Horoman complex

Plagioclase inclusions associated with orthopyroxene and Ti-pargasite in clinopyroxene porphyroclasts (Fig. 5c) may be explained by crystallization from a small amount of incipient melt formed inside clinopyroxene (Schiano *et al.*, 1992). The appearance of pargasite suggests that the addition of hydrous fluid or already existed hydrous phases may have en-

hanced the melting. The presence of albite and quartz grains with orthopyroxene and par-gastic amphibole in clinopyroxene porphyro-clasts from the middle of the Lower Zone, whose initial temperature is estimated to be about 990°C from the core compositions of two pyroxenes, indicates that in the lower temperature condition, an incipient melting produced fairly SiO₂-rich melt. If this melting system was open to have been in equilibrium with surrounding olivine, an H₂O saturated condition was required for such SiO₂-rich melt (Kushiro, 1990). These incipient melt formed in clinopyroxene might have isolated from olivine during cooling of the complex and crystallized as inclusion minerals.

2. Origin of isolated plagioclase and plagioclase-rich veins from the Upper Zone of the Horoman complex

Ozawa and Takahashi (1995) suggested that plagioclase-rich veins, which are restricted in the Upper Zone, were crystallized from an interstitial melt segregated into fractures from the surrounding partially molten peridotites (segregation vein). They also suggested that isolated plagioclase grains were crystallized from a small amount of the interstitial partial melt.

Commonly observed less marked Ca-enrichment towards the rim of isolated plagioclase in plagioclase lherzolite from the Upper Zone than that observed in seam type plagioclase from the Lower Zone (cf., Figs. 7 and 9) (Ozawa and Takahashi, 1995) indicates that the isolated type also recorded decompression processes to a certain extent but in a manner much closer to equilibrium than the seam type plagioclase. There is a possibility that some isolated plagioclase grains were formed by a subsolidus nucleation and recrystallization of seam type plagioclase outside of seams, because isolated grains tend to occur close to

the seams (Fig. 5b). However, some grains are rimmed by filmy orthopyroxene along the grain boundary with olivine, which has never been observed in the Lower Zone (Fig. 5h). This texture suggests that orthopyroxene was crystallized by a reaction between olivine and silicate melt, which also crystallized plagioclase.

Plagioclase occurring in a small lens-shaped plagioclase-rich aggregate that is fringed by orthopyroxene shows more Ab-rich nature (Fig. 8d) than isolated plagioclase and plagioclase in seams, which are at least partly originated from subsolidus reaction. Some plagioclase grains cut orthopyroxene porphyroclast exhibiting interstitial texture. These observations are consistent with an idea that the plagioclase was crystallized from a small amount of interstitial melt.

The texture of isolated type of plagioclase interstitial to pyroxenes grains (Fig. 5d) suggests that it was crystallized from a very small amount of partial melt formed in the vicinity of clinopyroxene and orthopyroxene porphyroclasts. The chemical composition is, however, similar to that of plagioclase in seams. This may be due to its fine grain size, which makes the plagioclase composition more susceptible to subsolidus P-T change due to the ascent of the complex.

Plagioclase-rich veins cut the foliation of plagioclase lherzolite at 25~35° (Fig. 1) but are parallel to the lineation, indicating that the veins were formed during or after the deformation of the host peridotite. If the vein formation was predated the shear deformation of the Horoman complex, veins had to become oblique to the lineation, which is not the case. The observed vein wall free of plagioclase suggests that a crack sucks partial melt from the surrounding partially molten peridotite (Boudier and Nicolas, 1977; Nicolas and Jackson, 1982; Nicolas, 1989). The Fe-rich and NiO-poor

nature of the surrounding olivine (Fig. 13) indicates that the melt was not simply extracted from the host peridotite, because the simple melt extraction will cause Mg and Ni enrichment. The sharply decreasing trend for Ni content of the olivine in the surrounding zone of the veins can be explained by crystallization from a melt in equilibrium with the plagioclase lherzolite host away from the veins. This mechanism is similar to that for the origin of the Spinel-rich Dunite-Wehrlite suite, which is supposed to have formed by fractional crystallization from a magma in equilibrium with harzburgite (Takahashi, 1991a,b; 1992). Olivine is thought to have been crystallized on the vein wall from the segregated melt. There may have been a modification by a reaction with an evolved melt derived by olivine fractionation from the segregated melt. This process results in a trend convex upwards on the Fo-NiO diagram as investigated by Ozawa (1994). This mechanism, however, requires some extent of olivine fractionation to produce less magnesian melt, which also requires olivine crystallization on the vein wall.

The variation of the core composition of plagioclase within plagioclase-rich veins featuring Ca enrichment toward the vein wall (Fig. 11) indicates that plagioclase was crystallized on the vein wall at first, followed by filling up the center of the vein, because plagioclase at the center is more sodic. This is consistent with the model of olivine crystallization on the vein wall as discussed above, and with Ti-rich nature of clinopyroxene in the wall peridotite (Fig. 12). The variation of plagioclase composition in the vein can be explained by the crystallization of sodic plagioclase followed by preferential growth of subsolidus calcic plagioclase along the margin of the veins derived from the decompression reaction among spinel and pyroxenes. However, the presence of abundant sodic plagioclase in the veins, W-

shaped zoning profile of the plagioclase (Fig. 11c), and the presence of Ni-poor olivine, and Ti-rich clinopyroxene in the surrounding peridotite demonstrate that the veins were filled by melt during decompression of the Horoman and Nikanbetsu complexes. The chemical zoning of some plagioclase grains in veins is typically represented by a W-shaped variation of An content. The W-shape zoning indicates that the decompression proceeded either during or after the crystallization of plagioclase, because production of the more Ca-plagioclase can be attributed to the subsolidus reaction among pyroxenes and spinel.

3. Origin of fine-grained aggregate from the Upper Zone of the Horoman complex

Fine-grained aggregates forming seams in plagioclase lherzolite from the Lower Zone are interpreted to be subsolidus reaction products among pyroxenes and spinel, which were derived from the earlier decompression reaction between garnet and olivine (Ozawa and Takahashi, 1995).

Plagioclase in seams from the Upper Zone of the Horoman complex shows Na-Ca zoning similar to that of the Lower Zone (Fig. 7). Therefore, such seams from the Upper Zone may have been derived from garnet as in the case for the Lower Zone. This inference is also supported by the observation that the seams rarely contain symplectitic aggregates and are very poor in clinopyroxene. Fine-grained aggregates from the Upper Zone, however, commonly contain a significant amount of clinopyroxene (Fig. 6), which cannot be explained by only subsolidus processes in a closed system. This is because clinopyroxene is completely consumed up if the aggregates were derived from garnet and olivine. Actually, the modal compositions of seams from the Lower Zone indicate that the subsolidus reaction consumed all clinopyroxene to produce olivine and

plagioclase (Fig. 6). Furthermore, the Upper Zone took much higher P-T path than that of the Lower Zone, requiring the more advanced decompression reaction (Ozawa and Takahashi, 1995). If the aggregates from the Upper Zone were totally of subsolidus origin, therefore, they have to contain no clinopyroxene.

The feature of low NiO content of olivine in fine-grained aggregates from the Lower Zone (Fig. 13) is consistent with their subsolidus origin, because two pyroxene and spinel contain lesser amount of Ni. During the reaction to produce two pyroxenes and spinel from olivine and garnet, Ni may be diffused out from the seam into the surrounding olivine, because of higher temperature in the early stage of the decompression. Moreover, garnet contains minor amount of Ni (Canil, 1994). Olivine in some fine-grained aggregates of the Upper Zone has significantly lower NiO and Fo content than that from the Lower Zone (Fig. 13). The olivine composition is much closer to that of olivine in plagioclase-rich vein. Moreover, some plagioclase grains in seams from the Upper Zone and the Nikanbetsu complex are rimmed by filmy orthopyroxene. These observations indicate that at least some plagioclase in these seams are of magmatic origin. Magmatic plagioclase and clinopyroxene may have crystallized from a small amount of partial melt, which was locally segregated into the seams. The plagioclase composition may have been modified during the decompression of the complex above and below the solidus condition. After this event, subsolidus equilibrium process progressed, and the compositions became more closer to the subsolidus one.

4. Origin of Na-rich rim of plagioclase

Na-enrichment towards the rim of plagioclase is mainly observed in the Lower Zone of the Horoman complex. The enrichment is usually observed towards the rim in the direc-

tion perpendicular to the foliation (Fig. 8). Two possible formation mechanisms are considered in this section.

The first possibility is that the Na-rich rim was derived from a very small amount of partial melt, as proposed for albitic plagioclase inclusions in clinopyroxene from the Lower Zone. Fine grained aggregates from the Lower Zone are thought to be subsolidus reaction products among pyroxenes and spinel, but the aggregate could be the preferable site for the first incipient melting because of their fertile character. The partial melt could have been precipitated as Na-rich plagioclase rim. This idea does not, however, explain the orientation-controlled occurrence of the Na-rich rim, unless the overgrowth of Na-rich rim is restricted in the most compressed direction by some mechanism. Precipitation of dissolved mineral components in a fluid typically takes place in the least compressed direction in metamorphic rocks (e.g., Nicolas, 1987).

The second possibility is that the Na-rich rim is formed during subsolidus deformation process associated with a reaction among pyroxenes and spinel to produce plagioclase and olivine. Because of the elongated feature of seams and the constituent minerals, fine-grained aggregates from the Lower Zone of the Horoman complex definitely experienced strong deformation associated with decompression reactions during the ascent from the garnet peridotite facies into the plagioclase peridotite facies. The inter-diffusion of CaAl and NaSi in plagioclase is very slow (Grove *et al.*, 1984). This is supported by the preservation of very steep Na-Ca zoning in many plagioclase grains from the Horoman Lower Zone. Stress induced diffusive mass transport (Cobble creep) was advocated by Ozawa (1989) for the orientation-controlled Cr-Al zoning in chromite spinel. This mechanism is not applicable for the Na-rich rim, because of the very slow Na-Ca

diffusivity in plagioclase, which reject the possibility of Cobble creep. The large compositional contrast between the rims in the directions perpendicular and parallel to the lineation may indicate that plagioclase component generated during the latest stage of the decompression was distributed to the Ca-rich and Na-rich rims by grain boundary diffusion responding differential stress applied on the surface of each grain. Coexistence of the sharp increase of the An content all the way up to the rim in the direction of lineation (Ozawa and Takahashi, 1995) and the sharp decrease in the direction vertical to the lineation (Fig. 8b) requires stress to keep the composition contrast along the grain surface.

5. Origin of plagioclase in plagioclase lherzolite from the Nikanbetsu complex

Komatsu *et al.* (1982) concluded that plagioclase in plagioclase lherzolite of the Nikanbetsu complex was crystallized from a partial melt on the basis of its interstitial occurrence. Detailed textural and mineralogical observation presented above principally support their idea as discussed below.

Plagioclase lherzolite from the southern part of the Nikanbetsu complex contains a round symplectitic aggregate, which is composed of spinel and two pyroxenes *without plagioclase and olivine*. This symplectite is mantled by coarser-grained aggregate of two pyroxenes and spinel as observed in the Horoman complex. In the same sample, a plagioclase-rich seam presents and also contains a round symplectitic aggregate composed of *plagioclase*, olivine, spinel, and orthopyroxene. These observations indicate that the Nikanbetsu complex also started to ascend from the garnet stability field as advocated for the Horoman complex (Ozawa and Takahashi, 1995). Plagioclase grains in the seams typically show Na-Ca zoning, which varies from An₆₄ at the

core to An₈₇ at the rim, similar range for the Horoman complex. Calculated temperature for core-core pairs of coarse pyroxenes according to Wells (1977) indicates more than 1100 ~1170°C, which is similar to the highest value for the Upper Zone of the Horoman complex.

A large isolated plagioclase crystal from the Nikanbetsu complex has outward Na enrichment in the core area, which is followed by Ca enrichment toward the rim (Fig. 10). The zoning pattern has never been observed in the Horoman complex except for plagioclase-rich veins in the Upper Zone. The W-shaped pattern suggests that a rapid decompression, which caused the marginal Ca enrichment under above or below solidus conditions, took place after the partial crystallization of a trapped partial melt.

The crystallization from melt is also supported by the more common occurrence of this type of plagioclase in veins. Such plagioclase-rich veins have depletion zone less than a few meter scale, suggesting segregation took place near fractures, toward which melt was segregated to form oblique plagioclase-rich vein. Excepting the depletion zone, partial melt was not effectively segregated but was mostly trapped in the peridotite and crystallized interstitial plagioclase. The minimum estimation of volume percentage of the partial melt is 6 to 9, which was estimated by total volume of plagioclase and associated interstitial minerals.

6. P-T conditions of the Horoman and Nikanbetsu complexes

Plagioclase lherzolite from the Upper Zone of the Horoman complex took nearly adiabatic P-T path with initial temperature slightly higher than 1100–1150°C and the initial depth greater than ~60 km (Ozawa and Takahashi, 1995). The upper part of the Upper Zone, which experienced the highest temperature tra-

jectory within the Horoman complex, had undergone a decompression just below the dry solidus of a fertile lherzolite after Takahashi and Kushiro (1986) and far above solidus of H_2O -bearing peridotite system at 7~8 kb condition (Kushiro *et al.*, 1968; Green, 1973; Millhollen *et al.*, 1974). If the initial temperature was a little higher, or if the peridotite system had a small amount of H_2O , the P-T trajectory could have cut the solidus. The fact that the common occurrence of isolated plagioclase grains and plagioclase-rich segregation veins associated with rare hydrous minerals in the middle and upper part of the Upper Zone suggests that an incipient melting might have happened and a certain amount of partial melt was formed and segregated into fractures under almost dry condition. Ozawa and Takahashi (1995) and Ozawa (1997) attributed the higher Wo content near the rim of orthopyroxene porphyroclasts than that of the core to a heating even near the boundary of the spinel and plagioclase peridotite facies during the ascent of the Horoman complex. According to this idea, it is also quite probable for the upper part

of the Upper Zone to have cut the dry solidus during the ascent of the complex.

Plagioclase lherzolite from the middle part of the Lower Zone to the lower part of the Upper Zone, which took relatively lower temperature P-T path than that of the upper part of the Upper Zone. It could have experienced an incipient melting in a wet condition. Segregation veins have never been observed in this horizon of the Horoman complex, but isolated plagioclase and plagioclase inclusion in clinopyroxene porphyroclast that coexist with Ti-pargasite are observed. This is consistent with the inferred thermal history for this horizon and suggests that a small amount of incipient melt was formed under the wet condition but that the melting degree was not high enough to afford sufficient melt connectivity for melt segregation.

The Al and Ca zoning of pyroxenes from Nikanbetsu plagioclase lherzolite is similar to that of the Upper Zone of the Horoman complex, but the average Wo content at the core of orthopyroxene is a little higher than that of the Upper Zone. The nearly isothermal P-T tra-

Fig. 14. Schematic model for the Horoman diapir, which has partial melting zone at the core. The Lower Zone of the Horoman complex corresponds to the marginal zone, the Upper Zone to the relatively inner zone, and the Nikanbetsu complex to the central zone where partial melting was fairly extensive.

jectory of the Nikanbetsu complex is, therefore, inferred to have been slightly higher than that of the Horoman complex, with the initial temperature ranging from 1100 to 1170°C. The texture and chemical compositions also suggest that the Nikanbetsu complex experienced higher temperature conditions, which may have lead to the higher degree of partial melting than the Upper Zone of the Horoman complex.

The Nikanbetsu complex may represent a much hotter part of a mantle diapir proposed by Ozawa and Takahashi (1995) for the Horoman complex (Fig. 14). However, the grain size of plagioclase of the Nikanbetsu complex is still smaller than that for some definitely partially molten plagioclase peridotites on the way to their emplacement into the crust, such as the Lanzo complex (Boudier and Nicolas, 1977). This is consistent with the fact that the maximum calculated two pyroxene temperatures for the Horoman complex is much lower than those for the Lanzo complex (up to 1275°C; Bodinier *et al.*, 1986). There are two explanations for the difference between the Lanzo and the Horoman-Nikanbetsu complexes; the first is that the Horoman diapir may have been a cooler mantle diapir than that for the Lanzo complex, and the second is that both the Upper Zone of Horoman and the Nikanbetsu complex do not represent the hottest portion, where partial melting was extensive, but marginal cooler portion of the diapir. If the latter explanation is the case, there is a possibility that the hotter portion may crop out somewhere in the Hidaka belt.

The thermal structure of the Horoman diapir is illustrated schematically in Fig. 14. The Lower Zone of the Horoman complex represents the relatively marginal part of the diapir, and the Upper Zone the relatively hotter part. An incipient partial melting took place in this hotter portion. The Nikanbetsu complex represents the much hotter part near the

central partial melting zone of the diapir, where significant melting followed by segregation of the partial melt into fractures took place. The melt segregation process selectively progressed only in the vicinity of fractures, although the host peridotite may have attained up to ~10% degree of melting.

The timing of the first incipient melting at the hotter portion of the diapir cannot be correctly estimated, but we can suggest that the first incipient melting may have happened at depth deeper than 7–8 kb, probably in the spinel stability field. When the diapir reached the boundary of spinel and plagioclase peridotite facies in the CFMAS system (7–8 kb; Gasparik, 1987), the marginal part started to cool rapidly to a subsolidus condition, which may have been caused by a contact with the colder crustal materials. During this cooling stage, the magmatic compositions of plagioclase were modified to various extents depending on the cooling rate and the maximum degree of melting.

VII. Conclusions

Four types of plagioclase with different mode of occurrence and texture are recognized in plagioclase lherzolite of the Horoman and the Nikanbetsu complexes. They are seam type, inclusion type, isolated type and vein type. The occurrence of each type is governed by the inferred thermal history of the host peridotite, which indicates that the Horoman complex is at least a part of a diapir (Horoman diapir). The seam type containing no or very rare clinopyroxene occurs in the Lower Zone of the Horoman complex, which took subsolidus P-T path. The clinopyroxene-free and plagioclase-rich seam was formed by subsolidus reaction among two pyroxenes and aluminous spinel which were originated from garnet and olivine. The inclusion type associated with quartz, orthopyroxene and pargasitic horn-

blende only occurs in the middle of the Lower Zone, where about 1000°C initial temperature followed by nearly adiabatic ascent P-T path is presented. This peculiar mineral assemblage may have crystallized from a small amount of incipient melt under H₂O-rich condition and trapped in clinopyroxene. Plagioclase-rich seams containing clinopyroxene, up to 11 modal %, plagioclase-rich veins and isolated plagioclase occur mostly in the Upper Zone of the Horoman complex and in the Nikanbetsu complex, which experienced a thermal history with 1100~1170°C initial temperature, much higher than the Lower Zone. Isolated plagioclase and such seams and veins were crystallized from partial melt in almost dry condition. The Nikanbetsu complex may represent a much hotter portion of the Horoman mantle diapir, where significant melting enabled segregation of the partial melt into fractures that were sealed later to form plagioclase veins.

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References

- Arita, K., Shingu, H. and Itaya, T. (1993), K-Ar geochronological constraints on tectonics and exhumation of the Hidaka metamorphic belt, Hokkaido, northern Japan. *J. Min. Petr. Econ. Geol.*, **88**, 101-113.
- Bence, A.E. and Albee, A.L. (1968), Empirical correction factors for the electron microanalysis of silicates and oxides. *J. Geol.*, **76**, 382-403.
- Bodinier, J.L. (1988), Geochemistry and petrogenesis of the Lanzo peridotite body, western Alps. *Tectonophysics*, **149**, 67-88.
- Bodinier, J.L., Guiraud, M., Dupuy, C. and Dostal, J. (1986), Geochemistry of basic dikes in the Lanzo massif (Western Alps): petrogenetic and geodynamic implications. *Tectonophysics*, **128**, 77-95.
- Boudier, F. and Nicolas, A. (1977), Structural controls on partial melting in the Lanzo peridotite. In Oregon Dept. Geol. Mineral. Ind. (Dick, H.J.B. Ed.), **96**, 63-78.
- Canil, D. (1994), An experimental calibration of the "Nickel in Garnet" geothermometer with applications. *Contrib. Mineral. Petrol.*, **117**, 410-420.
- Gasparik, T. (1987), Orthopyroxene thermobarometry in simple and complex system. *Contrib. Mineral. Petrol.*, **96**, 357-370.
- Green, D.H. (1973), Experimental melting studies on a model upper mantle composition at high pressure under water-saturated and water-undersaturated condition. *Earth Planet. Sci. Lett.*, **19**, 37-53.
- Grove, T.L., Baker, M.B. and Kinzer R.J. (1984), Coupled CaAl-NaSi diffusion in plagioclase feldspar: Experiments and applications to cooling rate speedometry. *Geochim. Cosmochim. Acta.*, **48**, 2113-2121.
- Imai, A. and Ozawa, K. (1991), Tectonic implications of the hydrated garnet peridotites near Mt. Kinabalu, Sabah, East Malaysia. *J. Southeast Asian Earth Sci.*, **6**, 431-445.
- Komatsu, M. and Nochi, M. (1966), Ultrabasic rocks in Hidaka metamorphic belt, Hokkaido, Japan. I. Mode of occurrence of the Horoman ultrabasic rocks. *Earth Sci.*, **20**, 99-108. (in Japanese with English abstract)
- Komatsu, M., Miyashita, S. and Arita, I. (1986), Composition and structure of the Hidaka metamorphic belt, Hokkaido: historical reviews and present status. *Mongraph. Assoc. Geol. Collab. Japan*, **31**, 189-203. (in Japanese with English abstract)
- Komatsu, M., Osanai, Y., Toyoshima, T. and Miyashita, S. (1989), Evolution of the Hidaka metamorphic belt, northern Japan. In Evolution of metamorphic belt (Daly, J.S., Cliff, R.A. and Yardley, B.W.D. Eds.). *Geol. Soc. Spec. Pub.*, No. 43, 487-498.
- Komatsu, M., Miyashita, S., Maeda, J. Osanai, Y. and Toyoshima, T. (1983), Disclosure of a deepest section of continental-type crust up-

- thrust as the final event of collision of arcs in Hokkaido, northsen Japan. *In* Accretion Tectonics in the Circum-Pacific Regions (Hashimoto, M. and Uyeda, S. Eds.). Terra Sci. Pub., Tokyo, 149-165.
- Komatsu, M., Shibakusa, H., Miyashita, S., Ishizuka, H., Osanai, Y. and Sakakibara, M. (1992), Subduction and collision related high and low P/T metamorphic belts in Hokkaido. *29th International Geological Congress Field Trip CO1 guide book* 55.
- Komatsu, M., Miyashita, S., Maeda, J., Osanai, Y., Toyoshima, T., Motoyoshi, Y. and Arita, K. (1982), Petrological constitution of the continental type crust upthrust in the Hidaka belt, Hokkaido. *Spec. Issue J. Min. Petr. Econ. Geol.*, 229-238. (in Japanese with English abstract)
- Kushiro, I. (1990), Partial melting of mantle wedge and evolution of island arc crust. *J. Geophys. Res.*, **95**, 15929-15939.
- Kushiro, I., Syono, Y. and Akimoto, S. (1968), Melting of a peridotite nodule at high pressures and high water pressures. *J. Geophys. Res.*, **73**, 6023-6029.
- Mercier, J.C. and Nicolas, A. (1975), Textures and fabrics of upper mantle peridotites as illustrated by basalt xenoliths. *J. Petrol.*, **16**, 454-487.
- Millhollen, G.L., Irving, A.J. and Wyllie, P.J. (1974), Melting interval of peridotite with 5.7 percent water to 30 kilobars. *J. Geol.*, **82**, 575-587.
- Nakamura, Y. and Kushiro, I. (1970), Compositional relations of coexisting orthopyroxene, pigeonite and augite in a tholeiitic andesite from Hakone volcano. *Contrib. Mineral. Petrol.*, **26**, 265-275.
- Nicolas, A. (1987), Principles of rock deformation. pp.208, D.Reidel Publishing Company, Dordrecht.
- Nicolas, A. (1989), Structures of ophiolites and dynamics of oceanic lithosphere. pp.367, Kluwer Acadmic Publishers, Dordrecht.
- Nicolas, A. and Jackson M. (1982), High temperature dikes in peridotites: Origin byhydraulic fracturing. *J. Petrol.*, **23**, 568-582.
- Niida, K. (1974), Structure of the Horoman ultramafic massif of the Hidaka metamorphic belt in Hokkaido, Japan. *J. Geol. Soc. Japan*, **80**, 31-44.
- Niida, K. (1984), Petrology of the Horoman ultramafic rocks in the Hidaka metamorphic belt, Hokkaido, Japan. *J. Fac. Sci. Hokkaido Univ. Ser. IV*, **21**, 185-194.
- Niida, K. and Katoh, T. (1978), Ultramafic rocks in Hokkaido, Monog. *Assoc. Geol. Col. Jpn*, **21**, 61-81. (in Japanese with English abstract)
- Ozawa, K. (1989), Stress-induced Al-Cr zoning of spinel in deformed peridotites. *Nature*, **338**, 141-144.
- Ozawa, K. (1994), Melting and melt segregation in the mantle wedge above a subduction zone: evidence from the chromite-bearing peridotites of the Miyamori ophiolite complex, northeastern Japan, *J. Petrol.*, **35**, 647-678.
- Ozawa, K. (1997), Ascending hot diapir and thermal disturbance of related magma generation. *Memo. Geol. Soc. Japan*, **47**, (in press)
- Ozawa, K. and Takahashi, N. (1995), P-T History of a mantle diapir: the Horoman peridotite complex, Hokkaido, northern Japan. *Contrib. Mineral. Petrol.*, **120**, 223-248.
- Saeki, K., Shiba, M. and Itaya, T. (1991), K-Ar ages of metamorphic and igneous rocks from the southern Hidaka metamorphic belt. *J. Min. Petr. Econ. Geol.*, **86**, 177-178.
- Schiano, P., Clocchiatti, R. and Joron, J.L. (1992), Melt and fluid inclusions in basalts and xenoliths from Tahaa Island, Society archipelago: evidence for a metasomatized upper mantle. *Earth Planet. Sci. Lett.*, **111**, 69-82.
- Takahashi, E and Kushiro, I (1986), Melting of a dry peridotite at high pressure and basalt magma genesis. *Amer. Mineral.*, **68**, 859-879.
- Takahashi, E., Uto, K. and Schilling, J.G. (1987), Primary magma compositions and Mg/Fe ratios of their mantle residues along Mid Atlantic Ridges 29°N to 73°N. *Tech. Rep. ISEI. Okayama Univ.*, A-9, 1-12.
- Takahashi, N. (1988), The Horoman peridotite complex, the Hidaka belt, northern Japan; A complex of three kinds of peridotite suites, *M. Sc. Thesis, Univ. Tsukuba*, 134 pp.
- Takahashi, N. (1991a), Evolutional history of the uppermost mantle of an arc system: petrology of the Horoman peridotite massif, Japan. *In* Ophiolite Genesis and Evolution of the Oceanic Lithosphere (Peters, T., Nicolas, A. and Coleman, R.G. Eds.). Kluwer Academic Publishers, Dordrecht, 195-205.
- Takahashi, N. (1991b), Origin of three peridotite suites from Horoman peridotite complex, Hokkaido, Japan; Melting, melt segregation and solidification processes in the upper mantle. *J. Min. Petrol. Econ. Geol.*, **86**, 199-215.
- Takahashi, N. (1992), Evidence for melt segregation towards fractures in the Horoman mantle peridotite complex. *Nature*, **359**, 52-55.

- Takahashi, N. and Arai, S. (1989), Textural and chemical features of chromian spinel pyroxene symplectites in the Horoman peridotites, Hokkaido, Japan. *Sci. Rep. Inst. Geosci. Univ. Tsukuba*, Sec. B, **10**, 45-55.
- Takahashi, N., Arai, S. and Murota, U. (1989), Alkali metasomatism in peridotite complexes from the Hidaka belt, Hokkaido, northern Japan. *J. Geol. Soc. Japan*, **95**, 311-329. (in Japanese with English abstract)
- Visser, R.L.M., Drury, M.R., E.H.H. Strating, E.H. and Wal, D.V.D. (1991), Shear zones in the upper mantle: A case study in an Alpine lherzolite massif. *Geology*, **19**, 990-993.
- Wells, P.R.A., (1977), Pyroxene thermometry in simple and complex systems. *Contrib. Mineral. Petrol.*, **62**, 129-139.

北海道幌満岩体とニカンベツ岩体のかんらん岩中に観察される初期メルト発生過程

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北海道、日高帯南部に位置する幌満岩体とニカンベツ岩体に産するメルト成分に枯渇していないレールゾライトには大別して4つのタイプの斜長石が出現する。産状、化学組成、また、岩石の温度履歴の解析から、それらの成因は低温の履歴をたどったため形成されたザクロ石を起源とするサブソリダスでの分解反応生成物と様々な条件下でのソリダスを切ったため生じた初期発生メルトから晶出したものである。すべてはサブソリダスの再平衡化を被っており、程度は異なるがその化学組成を変化させている。また、より高温の履歴を示すかんらん岩では小規模な割れ目にメルトが濃集したものやそれらが連結してネットワーク構造をつくっているものが観察され、その周囲ではメルト成分が枯渇しており、割れ目の周囲で効果的にメルトの分離が起こったことを示唆している。両岩体は同一マントルダイアピル起源で、冷たい周囲から熱い中心部にかけての断片であると考えられる。