Sci. Rep. Kanazawa Univ.
Vol. 41 No. 1 pp, 47~67
July 1996

Mode of occurrence of plagioclase-rich segregation in the Horoman peridotite

Kyoko MATSUKAGE and Shoji ARAI

Department of Earth Sciences, Faculty of Science, Kanazawa University, Kakuma, Kanazawa 920-11, Japan

Abstract : The Horoman peridotite complex, which crops out in the Hidaka belt, northern Japan, is divided into two zone, the Upper and Lower Zones, according to the difference of compositional layering style which is made up of plagioclase lherzolite, spinel lherzolite, harzburgite, dunite gabbro, and a small amount of pyroxenite. Plagioclase-rich segregations which crosscut the foliation and compositional layering of the rock are only present in the Upper Zone. Petrography and mineral chemistry indicate that the degree of depletion of plagioclase lherzolite is larger in the Upper Zone than in the Lower Zone, and that the segregation was a melt pocket formed by indigenous low-pressure partial melting of the Upper Zone peridotite. The peridotites in the Upper Zone are restites, after the low-pressure partial melting at plagioclase-lherzolite stability field. The temperature for the Upper Zone was higher than that for the Lower Zone, but was lower than the dry solidus of lherzolite. The most possible explanation for the selective melting was possible due to lowering of solidus by addition of volatile components only for the Upper Zone which was higher in temperature than the Lower Zone.

1. Introduction

Plagioclase-rich segregations in mantle-derived peridotites, frequently oblique to their deformation structures, were due to the latest melting event of the mantle material. Their origin will provide us direct information of mechanisms of melt formation and segregation in the upper mantle. Peridotites from the Main Zone of the Hidaka belt, Hokkaido, sometimes have such plagioclase-rich segregations (e. g. Niida, 1984 ; Takahashi, 1988, 1995 ; Matsukage and Arai, 1994, 1995). Their post-deformation nature means that they were produced after the main stage of the formation of the layered structure (e. g., Nagasaki, 1966 ; Niida, 1984 ; Obata and Nagahara, 1987 ; Takahashi, 1992). Tagiri et al. (1989) found a partially melted amphibolite block enclosed by peridotite of Nikanbetsu complex, which means that the peridotite was enough hot and plastic to capture and partially melt the crustal material when the mantle material was intruded into the crust. Ozawa and Takahashi (1995) demonstrated that the Horoman peridotite was a hot mantle diapir which could cause the Hidaka metamorphism and acid magmatism.

The plagioclase-rich segregations, which only occur in the Upper Zone (Komatsu and Nochi, 1966 ; Niida, 1984) and sometimes crosscut the layered structure and foliation of surrounding peridotite, were described by Niida (1984) as frozen residual liquid after crystal accumulation which caused the main layering. Takahashi and Ozawa (1994), Matsukage and Arai (1994, 1995), Takahashi (1995) and Ozawa and Takahashi (1995) considered that the segregation was due to small amount of indigenous melt in the mantle peridotite. The purpose of this article is to describe and characterize the plagioclase-rich segregation and related peridotite, and to advance an understanding of the origin of difference between the Upper Zone and the Lower Zone of the Horoman peridotite complex.

2. Geological background

The Horoman peridotite complex is located at the southwestern end of the Hidaka belt, Hokkaido, northern Japan. The Hidaka belt extends about 140 km from north to south with a width of 10 to 20 km and characterized by felsic to mafic magmatism (e. g. Maeda et al., 1986) and low-pressure / high-temperature type metamorphism (Miyashiro, 1961). The Hidaka belt consists of two zones, the Main Zone and the Western Zone. The Main Zone consists of various metamorphic rocks and igneous intrusive rocks (e. g., Maeda, 1989 ; Osanai et al., 1992). The grade of metamorphism in the Main Zone increases westward and attains to granulite facies. Part of metamorphic rocks are anatexites (Ikeda, 1984 ; Osanai et al., 1989 ; Tagiri et al., 1989). The Western Zone consists of ophiolitic rocks (Miyashita, 1983). The boundary between the two zones is a large fault zone (= the Hidaka Main Thrust : HMT), several hundred meters to two kilometers in width.

Several peridotite complexes are exposed along the HMT (e. g. Murota and Arai, 1988). The Horoman peridotite complex, which belongs to the lowest part of the Main Zone, is exposed around Mt. Apoi (810.6m), Mt. Pinneshiri (958.2m) and adjacent areas along the Horoman river. The Horoman peridotite complex is approximately 8×10km in size and is more than 3000m in thickness (Niida, 1984). The Horoman peridotite is in fault contact with surrounding various metamorphic rocks, gabbroic rock and non-metamorphosed sedimentary rocks of Hidaka Super Group (Niida, 1984). The evidence of contact metamorphism has not been found around the complex (Niida, 1984). The Horoman peridotite complex is the largest of all peridotite masses in the Hidaka belt (e. g. Niida, 1984 ; Murota and Arai, 1988).

A lithological map of the southern part of the Horoman peridotite complex by Takahashi (1992) is shown in Fig. 1. The Horoman peridotite complex consists of plagioclase lherzolite, spinel lherzolite, harzburgite, dunite, gabbro, and a small amount of pyroxenites, which make a well-developed compositional layering (Niida, 1984 ; Obata and Nagahara, 1987 ; Takahashi, 1991).

The Horoman complex is divided into two zone, the Upper Zone and the Lower Zone, according to the difference of layering style (Komatsu and Nochi, 1966 ; Niida, 1984). The Lower Zone (2000m in thickness) crops out along the Horoman river and in the northern part of the complex. This zone consists of compositionally layered mass of plagioclase lherzolite, spinel lherzolite, harzburgite and dunite (Niida, 1984 ; Obata and Nagahara, 1987 ; Takahashi, 1991ab, 1992). The Lower Zone has a regular layered sequence with gradual lithological boundaries ; plagioclase lherzolite→lherzolite→harzburgite→lherzolite→plagioclase lherzolite. This sequence repeats at least four times from the base to the top of the Lower Zone (Niida, 1984). Dunite is present in the center of the harzburgite layer without exceptions (Takahashi, 1991ab, 1992). Wave length of the repetition is from several tens to a few hundred meters. Gabbro is scarcely found. On the other hand, the Upper Zone (1000m in thickness) exposes in western and northern ridges of Mt. Apoi, Mt. Pinneshiri and Mt. Bozu-yama. Layering of the Upper Zone is conspicuous. The individual layered structure consists of plagioclase lherzolite, spinel lherzolite, harzburgite, dunite and gabbro (Niida, 1984). Thickness of the individual layers is far smaller than that in the Lower Zone, a several millimeters to several meters. This zone is characterized by frequent presence of gabbro bands and predominance of plagioclase lherzolite. Boundary of each rock type is comparatively sharp.

Takahashi (1991ab, 1992) identified three distinct groups of peridotite in terms of petrological characteristics. They are Main Harzburgite-Lherzolite suite (=MHLS), Spinel-rich Dunite-Wehrlite suite (=SDWS) and Banded Dunite-Harzburgite suite (=BDHS). The Main Harzburgite-Lherzolite suite comprizes the main layered mass. Takahashi (1991) concluded that peridotite of the MHLS is of residual origin due to various degrees of partial melting and melt extraction. The SDWS, mainly composed of dunite with a local wehrlitic portion, occurs as continuous concordant layers within the MHLS harzburgite layers. The contact with the MHLS harzburgite is generally sharp. Peridotites of the SDWS are cumulates from the magma segregated from the MHLS peridotites. The Banded Dunite-Harzburgite suite is composed of refractory dunite, orthopyroxene-rich harzburgite and olivine orthopyroxenite. This suite is characterized by a conspicuous modal layering with sharp boundaries. It only occurs in the Upper Zone as small discontinuous bodies. Peridotites of the BDHS are considered as exotic fragments of pre-existing cumulus lithospheric mantle captured by upwelling MHLS.

In this paper, we mainly describe peridotites of MHLS of Takahashi (1991a). As mentioned below, the plagioclase-rich segregations occur in plagioclase lherzolite of the Upper Zone.

3. Descriptions of peridotites and plagioclase-rich segregations

3.1 Macroscopic observations

Peridotite layered sequence

Plagioclase lherzolite is characterized by existence of plagioclase-bearing seam (Plate I-1, 2). The plagioclase-rich seam is composed of fine-grained minerals; plagioclase and subordinate amounts of chromian spinel and olivine. The seam is gray to pale gray in hand specimens (Plate I-1). The plagioclase-rich seam is approximately a few centimeters in length and a few millimeters in thickness. This plagioclase-rich seam is simply called "seam" hereafter. Adjacent to spinel lherzolite, the seam becomes coarser-grained and smaller in volume. Plagioclase in the seam also decreases in amount towards spinel lherzolite. Plagioclase-free spinel lherzolite usually occurs between plagioclase lherzolite and harzburgite (Takahashi, 1991a). In such spinel lherzolite, fine-grained spinel-orthopyroxene aggregate and / or two-pyroxene spinel symplectite-bearing aggregate (Plate I-5 ; e. g., Tazaki et. al., 1972 ; Takahashi and Arai, 1989 ; Morishita et al., 1995) are found instead of the seam. The symplectite-bearing aggregate is purplish brown in color in hand specimens (Plate I-5). In the Lower Zone, the symplectite-bearing aggregate occurs in fertile spinel lherzolite near plagioclase lherzolite without exception (Takahashi and Arai, 1989), and the symplectite-bearing peridotite layer is relatively thick. In the Upper Zone, the symplectite-bearing aggregate rarely occurs in fertile spinel lherzolite (Plate II-5), and the symplectite-bearing spinel lherzolite layer is, if any, very thin, approximately a few centimeters in thickness. The almost absence of symplectite in the Upper Zone is one of the important keys to solve both the origin of difference between the Upper Zone and the Lower Zone and the origin of plagioclase-rich segregation. In the spinel lherzolite layer, the grain size of spinel gradually grows larger as the peridotite becomes more depleted toward harzburgite. The size of spinel in harzburgite is larger than in other rock types, plagioclase lherzolite and spinel lherzolite. Dunite or gabbro which belong to the SDWS of Takahashi (1991b) is certainly present in the center of harzburgite layer with sharp boundaries (Takahashi, 1991ab, 1992). Foliation plane is easily recognized by an elongation of seams and aggregates with symplectite. Both types of compositional layering are parallel to the foliation.

The plagioclase-rich segregations

Besides the seams, another important occurrence of plagioclase in peridotites is plagioclase-rich segregation which is free of chromian spinel (Plate III-2, see below). The plagioclase-rich segregation only occurs as lens or schlieren of 1 to 20 cm in length and 5 mm to 2 cm in thickness in peridotites in the Upper Zone, especially near the gabbro bands and in plagioclase lherzolite (Plate II-1). The plagioclase-rich segregation in plagioclase lherzolite usually has a depletion aureole of spinel lherzolite (Plate III-1, 2). The individual plagioclase-rich segregations crosscut the foliation (Plate III-1) and sometimes merge as a network, but the segregation-rich zone as a whole is comparatively parallel to the foliation (Plate II-1). Plagioclase lherzolite in the Lower Zone is characterized by absence of the segregation and by nearly absence of gabbro bands.

3.2 Microscopic observations

Plagioclase lherzolite

Plagioclase lherzolite is composed of olivine, orthopyroxene, clinopyroxene, plagioclase, spinel, and a small amount of pargasite. The plagioclase lherzolite is weakly deformed, and has porphyroclastic textures. The grain size of olivine is remarkably variable within a thin section. In most cases, the olivine porphyroclast is 0.4 to 3 cm across, and clinopyroxene is generally smaller in size than olivine. Orthopyroxene is larger than both olivine and clinopyroxene. In the Lower Zone, porphyroclasts of orthopyroxene and olivine are sometimes elongated : the long axis often exceeds 10 mm, and is parallel to the foliation plnae. In the Upper Zone, the minerals are more equant and slightly coarser than those of the Lower Zone. Wavy extinction and kink band are commonly recognized in the minerals, especially in the Lower-Zone peridotites.

Plagioclase occurs as the fine-grained seam which is composed of plagioclase, chromian spinel and olivine (Plate I-3 ; II-2). Small amount of orthopyroxene, clinopyroxene and pargasite rarely occur in the seam (Plate I-4). In the Lower Zone, a "finer"-grained mineral aggregate, a possible remnant of the symplectite, often occurs in the center of the seam (Plate I-3). The finer-grained part is composed of plagioclase, chromian spinel, orthopyroxine and subordinate amount of olivine. In the Upper Zone, the finer-grained part is not observed in the seam, and the grain size of minerals in the seam is larger than that of the Lower Zone (Plate I-3 ; II-2). Plagioclase in the seam sometimes shows wavy extinction. In the Upper Zone, plagioclase also rarely occurs as tiny grain at boundaries between orthopyroxene exsolution lamella and its host of clinopyroxene porphyroclast (plate II-3).

Spinel also occurs as "coarse discrete grains in plagioclase lherzolite in addition to the fine spinel in the seam described above. The coarse spinel appears not to be related to seam and is generally surrounded by olivine. The coarse spinel is considerably rare and irregular in shape.

Pargasite often occurs in grain boundaries of other minerals, especially of clinopyroxene. Pargasite rarely replaces a part of clinopyroxene (Plate II-4) and appears between orthopyroxene lamella and its clinopyroxene host (Plate II-6).

Spinel lherzolite and harzburgite

Olivine, orthopyroxene, clinopyroxene, spinel constitute the spinel lherzolite and harzburgite. The spinel lherzolite and harzburgite have the porphyroclastic texture and minerals are xenomorphic. Orthopyroxene porphyroclast which is 0.5 to 4 mm across is larger than olivine and clinopyroxene. In the spinel lherzolite, fine-grained spinel trails and / or fine-grained spinel-orthopyroxene aggregates are found (Plate I-5 ; II-5). Discrete spinel of the harzburgite is larger in grain size (<2.5mm) than that of the spinel lherzolite. As in the plagioclase lherzolite, the minerals of the spinel lherzolite and harzburgite from the Upper Zone are more equant than those from the lower Zone, and the minerals show wavy extinction and kink band.

The spinel lherzolite is characterized by existence of symplectite (Plate I-5, 7 ; II-7). The symplectite is an ellipsoidal aggregate of vermicular crystals of chromian spinel, orthopyroxene and clinopyroxene (Takahashi and Arai, 1989). Pyroxenes are optically single crystals within individual symplectites although very complicated in shape (Plate I-8 ; II-8). In the spinel lherzolite near the plagioclase lherzolite, chromian spinel in the symplectites is rarely mantled by very thin plagioclase film (Plate I-6 ; Takahashi and Arai, 1989). The shape of symplectite is more simple in the Upper Zone than in the Lower Zone (Plate I-7 ; II-7). The symplectite is usually surrounded with a coarser-grained aggregate of the minerals same as symplectite constituents (Plate I-7 ; Takahashi and Arai, 1989 ; Takahashi, 1991a). The symplectite-bearing aggregate occurs as lens, 1 to 6 cm in length and 1 to 4 mm in thickness. In the symplectite-bearing spinel lherzolite, fine-grained spinel-orthopyroxene aggregates (or spinel trails) without symplectite coexist with the symplectite-bearing aggregates. Detailed petrographical descriptions of the symplectite are available from Takahashi and Arai (1989) and Morishita et al. (1995). The symplectite-bearing spinel lherzolite is rare in the Upper Zone as described above.

The plagioclase-rich segregations

The plagioclase-rich segregations are mostly composed of plagioclase (Plate III-2, 3, 4) with subordinate amount of orthopyroxene and small amounts of olivine and clinopyroxene (Plate III-2). Some of the segregations include pargasite with or without phlogopite (Plate III-3).

In the plagioclase lherzolite, pargasite in the plagioclase-rich segregations occurs as a coarse xenomorphic grain (Plate IV-1) and as a film incompletely lining the segregation (Plate III-5, 6). Furthermore, pargasite is frequently observed within peridotite around the segregations, as isolated coarse grains (same as olivine in grain size), xenomorphic interstitial grains, fine grains replacing clinopyroxene and a film around spinel of the seam (Plate IV-3, 4). Phlogopite is only found in the coarse pargasite (5 mm in size)-bearing segregations, as a grain partly replacing pargasite (Plate IV-2), a film between pargasite film and plagioclase at the marginal part of the segregation (Plate III-5, 6), and subhedral rectangular grains at the marginal part of the segregation (Plate III-7, 8). In the spinel lherzolite aureole around the segregation, fine-grained spinel trails, which are free of plagioclase and have pargasite (Plate IV-5), are found instead of the seam. Spinel is larger in size in the trails than in the seam. Orthopyroxene adjacent to the segregation is sometimes weakly colored (pale brown) and pleochroic. The plagioclase-rich segregations are free of phlogopite and rarely have pargasite in spinel lherzolite and harzburgite. Wavy extinction is occasionally recognized in the both plagioclase and pargasite from the plagioclase-rich segregation.

A unique plagioclase-bearing harzburgite was found at the Horoman river area of the Upper Zone. Plagioclase has a unique mode of occurrence in this harzburgite : it is xenomorphic and makes a kind of clot, which is interstitial to olivine and orthopyroxene (Plate IV-7, 8). Plagioclase sometimes fills the fracture of orthopyroxene, and rarely intrudes into olivine in shape of droplet (Plate IV-6).

4. Mineral chemistry

Minerals were analyzed by a SEM (Akashi alpha 30A)-EDAX system with an energy dispersive spectrometer at Kanazawa University.

We classify the plagioclase lherzolite into four groups by their "stratigraphical" horizon for convenience of comparison between the Lower Zone and the Upper Zone. They are ; lower zone 1 (=LZ1), lower zone 2 (=LZ2), upper zone 1 (=UZ1) and upper zone 2 (=UZ2) upwards from the lower part of the complex (Fig.1). Mineral chemistry will be reported elsewhere, and will be described briefly here.

4.1 Peridotite

plagioclase lherzolite

Fo content of porphyroclast olivine in plagioclase lherzolite ranges from 89.2 to 90.4 in the Lower Zone (LZ1 and LZ2), 89 to 91 in the UZ1, 89.5 to 92 in the UZ2 (Fig. 2a). The Fo content of olivine increases from LZ1 to UZ2 through LZ2 and UZ1 on average.

Cr# (=Cr/(Cr+Al) atomic ratio) of a coarse discrete spinel in the Lower Zone is low, from 0.08 to 0.192 (Fig. 2a ; Takahashi, 1991a). In the Upper Zone, the "coarse" discrete spinel has not been discovered. The Cr# of discrete spinel in the Upper Zone ranges from 0.2 to 0.4 (Fig. 2a). TiO_2 content and $Fe^{3}+/(Al+Cr+Fe^{3+})$ atomic ratio in the coarse discrete spinel are low, from almost nil to 0.2 wt%, and <0.08, respectively.

Core of porphyroclast orthopyroxene is magnesian, with the Mg# (=Mg/(Mg+Fe) atomic ratio) around 0.90. The Al_2O_3 content of orthopyroxene core in the Lower Zone ranges from 3.0 to 4.5 wt% in LZ1, and 2.5 to 5.0 wt% in LZ2. Orthopyroxene in the Upper Zone is more aluminous, with the Al_2O_3 content from 3.5 to 5.0 wt% in UZ1 and 3.0 to 6.0 wt% in UZ2.

Seam in plagioclase lherzolite

Fo content of olivine in the seam ranges from 89.2 to 92.0. No difference in the Fo content of olivine can be observed between porphyroclast and neoblast in the seam.

Spinel in the seam is higher both in Cr# and in TiO_2 content than coarse discrete spinel (Fig. 2a). The Cr# and the TiO_2 content in the seam spinel range from 0.2 to 0.35 and from almost nil to 0.55 wt%, respectively, in the Lower Zone, and from 0.3 to 0.4 wt% and from 0.15 to 0.95 wt%, respectively, in the Upper Zone. It is noteworthy that these values are higher in the Upper Zone than in the Lower Zone. The spinel chemistry of the seam in plagioclase lherzolite generally varies, depending on the stratigraphical position, from LZ1 to UZ2 through LZ2 and UZ1 (Fig. 2). Spinel tends to become monotonously more Cr- and Ti-enriched from LZ1 (lower part of the Lower Zone) to in UZ2 (upper part of the Upper Zone).

Plagioclase in the seam is highly variable in chemistry. In the Lower Zone, the Ca/(Ca+Na) atomic ratio of plagioclase in seam ranges from 0.60 to 0.78, although the Fo content of coexisting olivine is rather constant (Fig. 3). In the Upper Zone, the Ca/(Ca+Na) atomic ratio of plagioclase ranges from 0.60 to 0.90 (mostly around 0.75 ; Fig. 3), higher than in the Lower Zone, and has a weak positive correlation with Fo of olivine, especially in UZ2 (Fig. 3).

Spinel lherzolite and harzburgite

In the Upper Zone, the Fo content of olivine ranges from 91.2 to 92.5 (Fig. 2b). The Cr# of discrete spinel widely varies according to the lithofacies, from 0.27 (lherzolite) to 0.60 (harzburgite). The Cr# of discrete spinel rapidly increases with an increase of the Fo content of coexisting olivine (Fig. 2b). $Fe^{3+}/(Al+Cr+Fe^{3+})$ atomic ratio of spinel is low, less than 0.07. The TiO_2 content is also low, from nil to 0.25. The Mg# of clinopyroxene ranges from 0.92 to 0.93 and TiO_2wt% is less than 0.25.

Mineral chemistry of spinel lherzolite and harzburgite in the Lower Zone was described in detail by Takahashi (1991ab). In the Lower Zone, the Fo content of olivine ranges from 90.0 to 92.8 and the Cr# of discrete spinel ranges from 0.18 to 0.68 (Fig. 2b). The Cr# of discrete spinel in the Lower Zone also systematically increases with a slight increase of the Fo content of olivine (Takahashi, 1991ab). The $Fe^{3+}/(Al+Cr+Fe^{3+})$ atomic ratio and the TiO_2 content of the discrete spinel are low, <0.08 and <0.3, respectively.

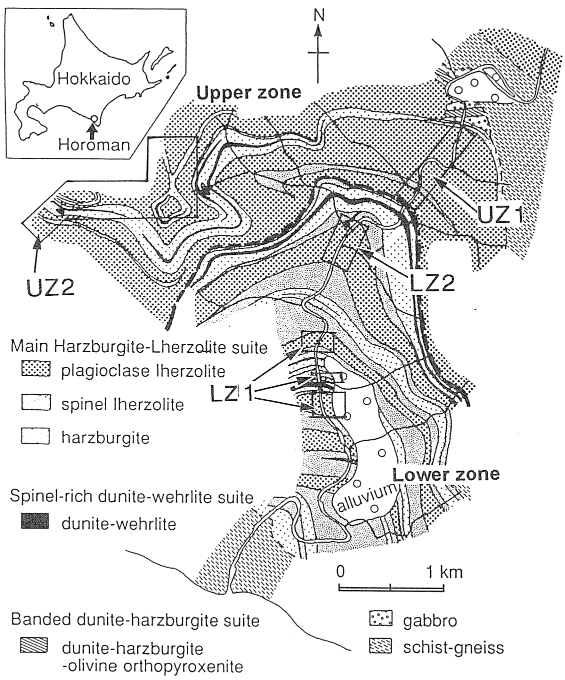


Fig. 1. Locations of four zones (LZ1, LZ2, UZ1 and UZ2) examined on a lithological map of the Horoman peridotite complex (modified after Takahashi, 1992). Broken line indicates the boundary between the Upper and Lower Zones (Niida, 1984).

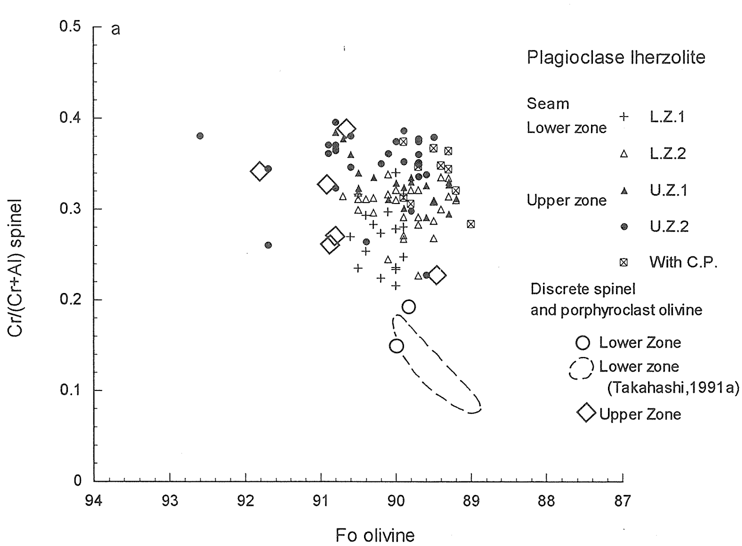
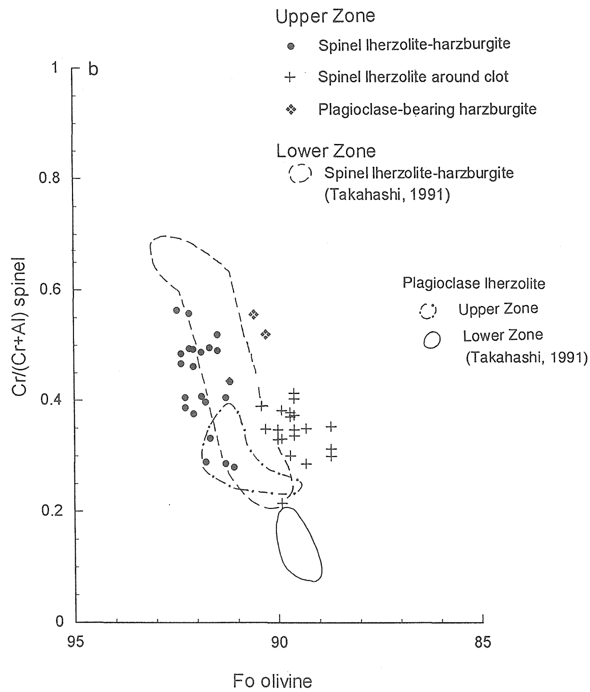


Fig. 2. Relationship between Fo content of olivine and Cr / (Cr+Al) atomic ratio of coexisting chromian spinel in the Horoman peridotites. Part of the Lower Zone data are after Takahashi (1991a).

a. Plagioclase lherzolite. C. P. means plagioclase-rich segregation. b. Spinel lherzolite and harzburgite.



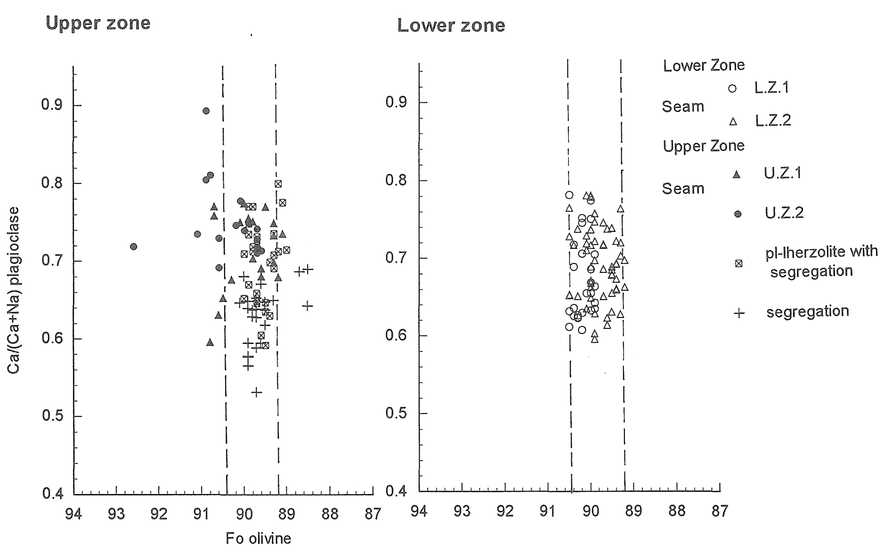


Fig. 3. Relationship between Fo content of olivine and Ca / (Ca+Na) atomic ratio of coexisting plagioclase in both the seam and the plagioclase-rich segregation. Note that chemical variety of minerals of the seam is larger in the Upper Zone than in the Lower Zone.

Comparison between the Upper Zone and the Lower Zone

The olivine-discrete spinel pairs from plagioclase lherzolite and spinel peridotites in the Upper Zone make a linear positive trend (Fig. 2b), as in the Lower Zone (Takahashi, 1991a). The trend for the Upper Zone peridotite deviates toward Mg-rich direction from that for the Lower Zone peridotite compared at a fixed Cr# of spinel (Fig. 2b). The Cr# of discrete spinel of plagioclase lherzolite in the Upper Zone is comparable to a more depleted lithofacies in the Lower Zone.

Minerals in plagioclase lherzolite from the Upper Zone are wider in chemical range toward refractory ends than those from in the Lower Zone, except Al_2O_3 contents of orthopyroxene (Ozawa and Takahashi, 1995) and TiO_2 contents of spinel and clinopyroxene. This chemical signature gradually changes from lower part of the Lower Zone to upper part of the Upper Zone.

4.2 Plagioclase-rich segregations and surrounding peridotite

The Fo content of olivine in plagioclase lherzolite with plagioclase-rich segregations ranges from 89.0 to 89.9 (Fig. 2a). The Ca/(Ca+Na) atomic ratio of plagioclase in the seam range from 0.59 to 0.8 (Fig. 3). Plagioclase in the seam is more calcic than that within segregation.

As shown in Fig. 2b, the Fo content of olivine of spinel lherzolite around the segregations ranges from 88.8 to 90.5 and the Cr# of spinel ranges from 0.28 to 0.41. Olivine in the spinel lherzolite around the segregation is Fe-richer than that in the spinel peridotite without segregation of the Upper and Lower Zones compared at a fixed Cr# of spinel.

The Ca/(Ca+Na) atomic ratio of plagioclase of segregation is comparatively low, ranging from 0.52 to 0.68 (Fig. 3). The Fo content of olivine in contact with the segregation ranges from 88.4 to 90.0 (Fig. 3). Both the Ca/(Ca+Na) atomic ratio of plagioclase and the Fo content of olivine are lower than those of the seam.

Plagioclase in the plagioclase-bearing harzburgite (sample No. HO94100404) is characterized by a low-Ca character, from An22.4 to An33.2. Both the TiO2 content of spinel and the Fo content of olivine in this harzburgite are noteworthy. At a fixed Cr# of spinel (0.519 to 0.612), FeO content of olivine (Fo=90.6) and TiO_2 content of spinel (0.33 to 0.70 wt%) is higher than those of ordinary harzburgite without plagioclase of the MHLS (Fig. 2b).

5. Discussion

5.1 Origin of the plagioclase-rich segregations

The textual and chemical characteristics indicate that the plagioclase-rich segregation is a frozen melt pocket due to melting of peridotite of the Upper Zone, and that the plagioclase lherzolite in the Upper Zone is a residue after this partial melting. The melting occurred at low pressures (plagioclase lherzolite stability field) after the main stage of deformation, as discussed below. As described above, olivine and clinopyroxene show an increase in Mg# from the Lower Zone to the Upper Zone. Ca/(Ca+Na) ratio of plagioclase in the seam increases upwards from the Lower Zone to the Upper Zone, and has a weak positive correlation with Fo content of surrounding olivine (Fig. 3). These observations for the seam in the Upper Zone can not be explained solely by the subsolidus reaction, pyroxenes + Al-rich spinel→plagioclase + olivine + Cr,Ti-rich spinel ± Ti-rich pyroxenes, although the plagioclase-bearing seam had been originally formed by the reaction (Takahashi, 1992), but indicate that the melting and melt extraction process were also responsible for the mineral chemical characteristics of the seam in plagioclase lherzolite of the Upper Zone because the enrichment of compatible elements, e.g., Mg and Ca, are associated with the depletion of incompatible elements. On the other hand, Ca content of plagioclase is clearly lower in the plagioclase-rich segregations than in the seam of both the Lower and Upper Zones, and Fo content of olivine (from Fo88.4 to Fo90.1) in contact with the segregations is the lowest of all olivines in the plagioclase lherzolite, spinel lherzolite and harzburgite. The chemical characteristics of the plagioclase-rich segregation, i. e. enrichment of incompatible elements, combined with the association of depletion aureole of spinel lherzolite, suggest that the plagioclase-rich segregation is a melt pocket formed by incipient partial melting of plagioclase peridotite. Plagioclase in the plagioclase-bearing harzburgite also formed by the partial melt discussed above. The plagioclase in the harzburgite was crystallized from some fractionated partial melt because its An content is lower than in the segregation in plagioclase lherzolite.

Olivine of spinel lherzolite around the segregations is too Fe-enriched to be ordinary olivine in the spinel lherzolite restite formed in spinel or garnet lherzolite stability field from the fertile lherzolite like the plagioclase lherzolite from the Lower Zone (Takahashi, 1992). Furthermore, if the partial melting occurred in spinel lherzolite stability field for the Upper Zone, the symplectite should have been commonly found in the Upper Zone as in the Lower Zone. The "Fe-enrichment" in olivine of spinel lherzolite aureole around the segregations and the almost absence of symplectite in the Upper Zone suggest that the partial melting occurred at lower pressures, i.e., in plagioclase lherzolite stability field after the symplectite had been formed. The low-pressures partial melting is reflected in occurrence of plagioclase-rich segregation which crosscut the deformation structures. Any lines of evidence for the partial melting at low pressures have not been discovered in the Lower Zone. Plagioclase lherzolite in the Upper Zone may be formed by partial melting of a more fertile lherzolite similar to plagioclase lherzolite in the Lower Zone. Some of the difference of plagioclase lherzolite between the two zones is caused by some selective partial melting of the Upper Zone.

5.2 Melting condition of the Upper Zone

The selective melting of the Upper Zone was due to selective addition of volatile components to the Upper Zone and / or to thermal difference between the Upper Zone and the Lower Zone (Ozawa and Takahashi, 1995). The selective addition of volatiles can not be mainly responsible for the selective melting. The volatile components were probably added to the two zones because secondary amphibole and phlogopite, main storage of volatiles in the upper mantle, occur both in the Upper Zone and in the Lower Zone of the Horoman complex (Takahashi et al., 1989). It is thus necessary that peridotite in the Upper Zone was higher in temperature than that in the Lower Zone for selective melting of the former. Ozawa and Takahashi (1995) estimated a P-T path of plagioclase lherzolite by Al and Ca contents in orthopyroxene, and indicated that the temperature is higher in the Upper Zone than in the Lower Zone. They suggested that the Horoman peridotite complex represents a hot diapir that started to ascend from a depth more than 60 km. The P-T trajectories of Ozawa and Takahashi (1995) do not exceed 1000℃ at low pressures (about 8kb). A decrease of Al content of spinel and an increase of Al content of orthopyroxene from the Lower Zone to the Upper Zone are due to an upward increase of temperature. But the estimated temperature of the Upper Zone is thus below the dry solidus (about 1200℃ ; Takahashi and Kushiro, 1983). It is most probable that the low-pressure (approximately 8 kb) partial melting of the Upper Zone took place by addition of small amount of volatile components (for example H2O) at higher temperatures (1000 to 1100℃) than the Lower Zone.

The main layered sequence of plagioclase lherzolite, spinel lherzolite and harzburgite in both the Upper Zone and Lower Zone are restites which were formed by various degrees of partial melting of a primitive mantle peridotite (now plagioclase lherzolite) at comparatively high-pressures ($>$10 kb) (Takahashi, 1992). The differences in mineral chemistry and lithological features of plagioclase lherzolite, spinel lherzolite and harzburgite between the two zones can be explained by the remelting at low pressures (plagioclase lherzolite stability field) of various peridotites in the Upper Zone, which had once experienced partially melting at higher pressures.

6. Conclusions

1. The Upper Zone and Lower Zone of the Horoman peridotite complex also have different mineral chemical and textural characteristics. Minerals in plagioclase lherzolite from the Upper Zone are wider in chemical range toward refractory ends than those from the Lower Zone. The structural and chemical signatures gradually change from lower part of the Lower Zone to upper part of the Upper Zone.

2. Peridotites in the Upper Zone are characterized by presence of plagioclase-rich segregations and almost absence of two-pyroxene spinel symplectite. The segregation in

plagioclase lherzolite is frequently oblique to deformation structures and commonly has a "spinel lherzolite aureole" which indicates a depletion around the segregation. The segregation of plagioclase is a melt pocket formed by indigenous partial melting at low pressures after the main deformation stage. The peridotite of the Upper Zone are restites, formed at plagioclase-lherzolite stability field (approximately 8 kb). This low-pressure partial melting took place only in the Upper Zone by addition of small amount of volatile components at higher temperatures (1000 to 1100℃) than the Lower Zone.

Acknowledgements

We are grateful to Dr. A. Ishiwatari and Dr. A. Toramaru for their discussions and suggestions. Suggestions by Dr. K. Ozawa were greatly helpful to proceed this study. We would like to thank Mr. T. Morishita, Mr. K. Kadoshima, Mr. K. Akutagawa, Mr. A. Ninomiya and Mr. T. Sawaguchi for their collaborations in the field.

References

Ikeda, Y. (1984). Trace-element contents of granitic rocks in the Hidaka belt, Hokkaido, Japan. *Magma*, v. 70, p. 9-14. (in Japanese)

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.*, v. 20, p. 21-29 (in Japanese with English abstract)

Maeda, J. (1989). Formation of the Hidaka magmatic zone: possible reactivation of a paleo-ocean ridge on an overriding plate due to subduction of an mid-ocean ridge. *Chikyu Monthly*, v. 11, p. 265-270. (in Japanese)

Maeda, J., Suetake, S., Ikeda, Y., Tomura, S., Motoyoshi, Y. and Okamoto, Y. (1986). Tertiary plutonic rocks in the axial zone of Hokkaido -distribution, age, major element chemistry, and tectonics-. *Monograph Assoc. Geol. Collab. Japan*, v. 31, p. 223-246. (in Japanese with English abstract)

Matsukage, K. and Arai, S. (1994). Variable melting processes imposed on the Horoman peridotites ; A comparison between upper-zone and lower-zone peridotites. *Abst., Japan Earth Planet. Sci. joint meeting*, Sendai, p. 74. (in Japanese)

Matsukage, K. and Arai, S. (1995). Two contrasting melting processes in the Horoman peridotite complex : remelting of Upper Zone at low pressure. *Abst., Japan Earth Planet. Sci. joint meeting*, Tokyo, p. 324. (in Japanese)

Miyashiro, A. (1961). Evolution of metamorphic belts. *Jour. Petr.*, v. 2, p. 277-311.

Miyashita, S. (1983). Reconstruction of the ohiolite succession in the western zone of the Hidaka Metamorphic Belt, Hokkaido. *Jour. Geol. Soc. Japan*, v. 89, p. 69-86.

Morishita, T., Arai, S. and Takahashi, N. (1995). Partial melting process in the upper mantle deduced from morphological and chemical variations of the chromian spinel two-pyroxene symplectite due to progressive partial melting of the Horoman peridotite, Hokkaido, Japan. *Jour. Min. Petr. Econ. Geol* ., v. 90, p. 93-102. (in Japanese with English abstract)

Murota, Y. and Arai, S. (1988). Petrographical notes on deep-seated and related rocks (6). Petrological characteristics of primary peridotites from the Uenzaru complex, the Hidaka belt Hokkaido, Japan. *Ann. Rep., Inst. Geosci., Univ. Tsukuba*, v. 14, p. 64-68.

Nagasaki, H. (1966). A layered ultrabasic complex at Horoman, Hokkaido, Japan. *Jour. Fac. Sci., Tokyo Univ*., v. 16, p. 313-346.

Niida, K. (1984). Petrology of the Horoman ultramafic rocks in the Hidaka metamorphic belt, Hokkaido, Japan. *Jour. Fac. Sci. Hokkaido Univ*., Ser. IV, v. 21, p. 197-250.

Obata, M and Nagahara, N. (1987). Layering of alpine-type peridotite and the segregation of partial melt in the upper mantle. *Jour. Geophys. Res*. v. 92, p. 3467-3474.

Osanai, Y., Komatsu, M., and Owada, M. (1989). *Chikyu Monthly*, v. 11, p. 245-251. (in Japanese)

Osanai, Y., Owada, M., and Kawasaki, T. (1992). Tertiary deep crustal ultrametamorphism in the Hidaka metamorphic belt, northern Japan. *Jour. metamorphic Geol*., v. 10, p. 401-414.

Ozawa, K. and Takahashi, N. (1995). P-T history of mantle diapir : the Horoman peridotite complex, Hokkaido, northern Japan. *Contrib. Mineral. Petrol*., v. 120, p. 223-248.

Tagiri, M., Shiba, M. and Onuki, H. (1989). Anatexis and chemical evolution of pelitic rocks during metamorphism and migmatization in the Hidaka metamorphic belt, Hokkaido. *Geochem. Jour*., v. 23, p. 321-337.

Takahashi, E. and Kushiro, I. (1983). Melting of a dry peridotite at high pressures and basalt magma genesis. *American Mineralogist*, v. 68, p. 859- 879.

Takahashi, N. (1988). The Horoman peridotite mass, the Hidaka belt, Hokkaido, northern Japan ; A complex of three kinds of peridotite suites. Unpublished thesis, Univ. Tsukuba, 134p.

Takahashi, N. (1991a). Origin of three peridotite suites from Horoman peridotite complex, Hokkaido, Japan; melting, melt segregation and solidification processes in the upper mantle. *Jour. Min. Petr. Econ. Geol*. v. 86, p. 199-215.

Takahashi, N. (1991b). Evolutional history of the uppermost mantle of an arc system : Petrology of the Horoman peridotite massif, Japan. In Ophiolite Genesis and Evolution of Oceanic Lithosphere (Peters, Tj. et al. Eds), Kluwer, Dordrecht, p. 197-208.

Takahashi, N. (1992). Evidence for melt segregation towards fractures in the Horoman mantle peridotite complex. *Nature*, v. 359, p. 52-55.

Takahashi, N. (1995). Incipient melting observed in the Horoman complex. *Abst., Japan Earth Planet. Sci. joint meeting,* Tokyo, p. 324. (in Japanese)

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, v. 10, p. 45-55.

Takahashi, N. and Ozawa, K. (1994). P-T history of the Horoman complex and its constraints on partial melting and melt segregation process in the upper mantle. *The 101st annual meeting of the Geol. Soc. Japan*, p23

Takahashi, N., Arai, S. and Murota, Y. (1989). Alkali metasomatism in peridotite complexes from the Hidaka belt, Hokkaido, northern Japan. *Jour. Geol. Soc. Japan*. v. 95, p. 311-329. (in Japanese with English abstract)

Tazaki, K., Ito, E. and Komatsu, M. (1972). Experimental study on pyroxene-spinel symplectite of high pressures and temperature. *Jour. Geol. Soc. Japan*, v. 72, p. 347-354.

Captions for Plates

Scale bars denote 0.5 mm for photomicrographs.

Plate I Plagioclase lherzolite and symplectite-bearing spinel lherzolite in the Lower Zone

(1) Plagioclase lherzolite on the outcrop. Plagioclase-bearing seam is gray to pale gray in color. Orthopyroxene is dark brown in color. The pen has a length of 14 cm.

(2) Photograph of a thin section of plagioclase lherzolite. Brown and green spots are orthopyroxene and clinopyroxene respectively. Note the strong foliation. Seams are visible by trails of spinel (black dots).

(3) Photomicrograph of the plagioclase-bearing seams. Note the finer-grained mineral aggregate in the center of the seam. Plane-polarized light.

(4) Photomicrograph of the plagioclase-bearing seam with pargasite (light brown). Plane-polarized light.

(5) Photograph of a thin section of symplectite-bearing spinel lherzolite. Arrow indicates a symplectite.

(6) Photomicrograph of symplectite in spinel lherzolite near plagioclase lherzolite. Chromian spinel in the symplectite is mantled by very thin plagioclase film (light color). Crossed-polarized light.

(7) Photomicrograph of symplectite and symplectite-bearing aggregate in spinel lherzolite. The Symplectite is composed of vermicular crystals of chromian spinel, orthopyroxene and clinopyroxene. Plane-polarized light.

(8) Crossed-polarized light.

Plate II Plagioclase lherzolite and symplectite-bearing spinel lherzolite in the Upper Zone

(1) Plagioclase lherzolite with plagioclase-rich segregations and gabbro bands. Note the segregation-rich zone (arrow) which is parallel to the foliation. The yellow scale bar is 1m.

(2) Photomicrograph of the plagioclase-bearing seam. The grain size of minerals in the seam is larger than that of the Lower Zone (e. g., Plate I-3). Plane-polarized light.

(3) Photomicrograph of plagioclase (arrow) at the boundary between an orthopyroxene bleb and its host clinopyroxene porphyroclast in plagioclase lherzolite. Crossed-polarized light.

(4) Photomicrograph of pargasite (brown) replacing a part of clinopyroxene porphyroclast in plagioclase lherzolite. Plane-polarized light.

(5) Photograph of a thin section of symplectite-bearing spinel lherzolite.

(6) -a Photomicrograph of pargasite between a thick orthopyroxene lamella and its clinopyroxene host.

(6) -b Crossed-polarized light.

(7) Photomicrograph of symplectite in spinel lherzolite. Note the less complicated shape of symplectite compared to that the Lower Zone. Plane-polarized light.

(8) Crossed-polarized light.

Plate III Plagioclase-rich segregation in the Upper Zone

(1) Plagioclase-rich segregations in plagioclase lherzolite. The segregations usually have a "spinel lherzolite aureole". The individual segregations crosscut the foliation. The hammer has a length of 36 cm.

(2) Photograph of a thin section of a plagioclase-rich segregation in plagioclase lherzolite. Note the spinel lherzolite aureole, which was altered to brown, around the segregation.

(3) Photomicrograph of a plagioclase-rich segregation in plagioclase lherzolite. Plane-polarized light. Note thin film of hydrous minerals (brown) partly lining the segregation.

(4) Crossed-polarized light.

(5) A close-up of the left rim of the plagioclase-rich segregation of (3). The pargasite (darker brown, pa) occurs as a film incompletely lining the segregation. The phlogopite (lighter brown, ph) appears as a film between the pargasite film and plagioclase at the marginal part of the segregation. Plane-polarized light.

(6) Crossed-polarized light.

(7) Photomicrograph of a marginal part of the plagioclase-rich segregation with phlogopite. Note the subhedral rectangular grains of phlogopite (light brown, arrow).

(8) Crossed-polarized light.

Plate IV (continued from Plate III)

(1) Photomicrograph of coarse xenomorphic pargasite in the plagioclase-rich segregation. Plane-polarized light.

(2) Photomicrograph of phlogopite (lighter brown) partly replacing pargasite (darker brown) in the plagioclase-rich segregation. Plane-polarized light.

(3) Photomicrograph of pargasite as a film around spinel of the seam in plagioclase lherzolite with the plagioclase-rich segregations. Plane-polarized light.

(4) Crossed-polarized light.

(5) Photomicrograph of fine-grained spinel trail in the spinel lherzolite aureole around the plagioclase-rich segregation. Note the absence of plagioclase and existence of pargasite. Plane-polarized light.

(6) Photomicrograph of plagioclase-bearing harzburgite. Plagioclase (arrow) fills the fracture of orthopyroxene and intrude into olivine in shape of droplet. Crossed-polarized light.

(7) Photomicrograph of plagioclase in the plagioclase-bearing harzburgite. Plagioclase makes a kind of clot, interstitial to olivine and orthopyroxene. Note the small size of plagioclase, which is low in An component. Plane-polarized light.

(8) Crossed-polarized light.

Plate 1

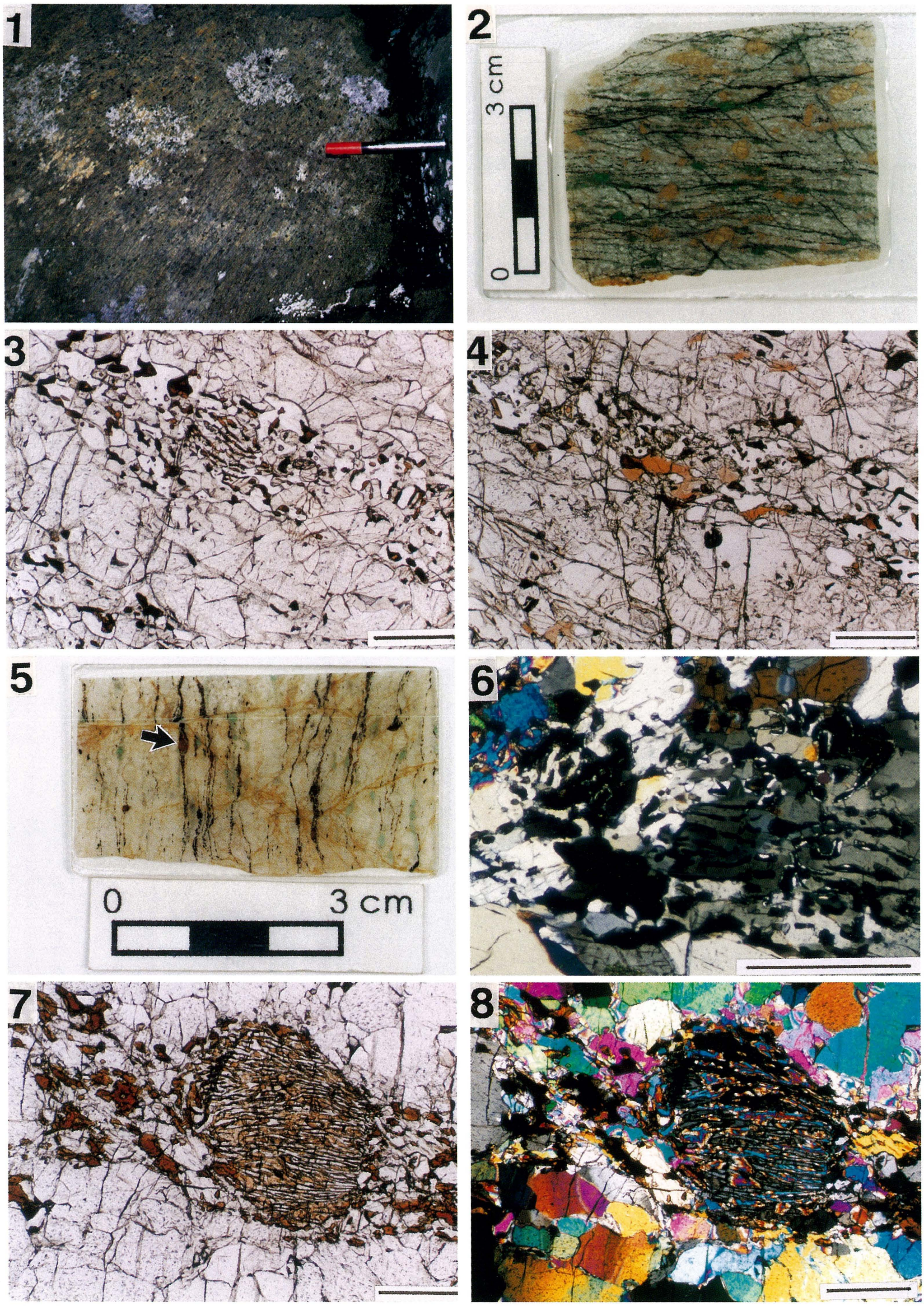


Plate 2

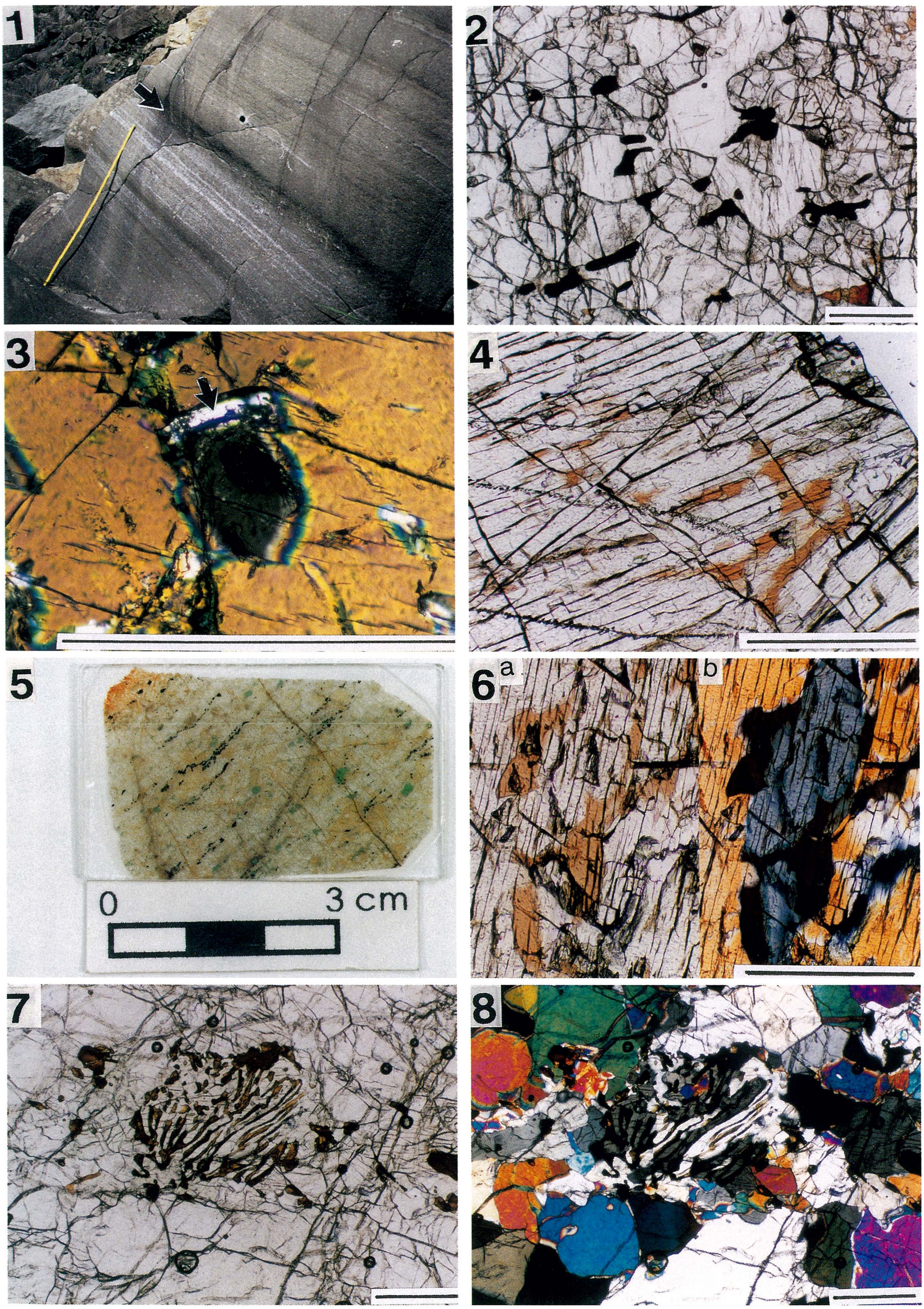


Plate 3

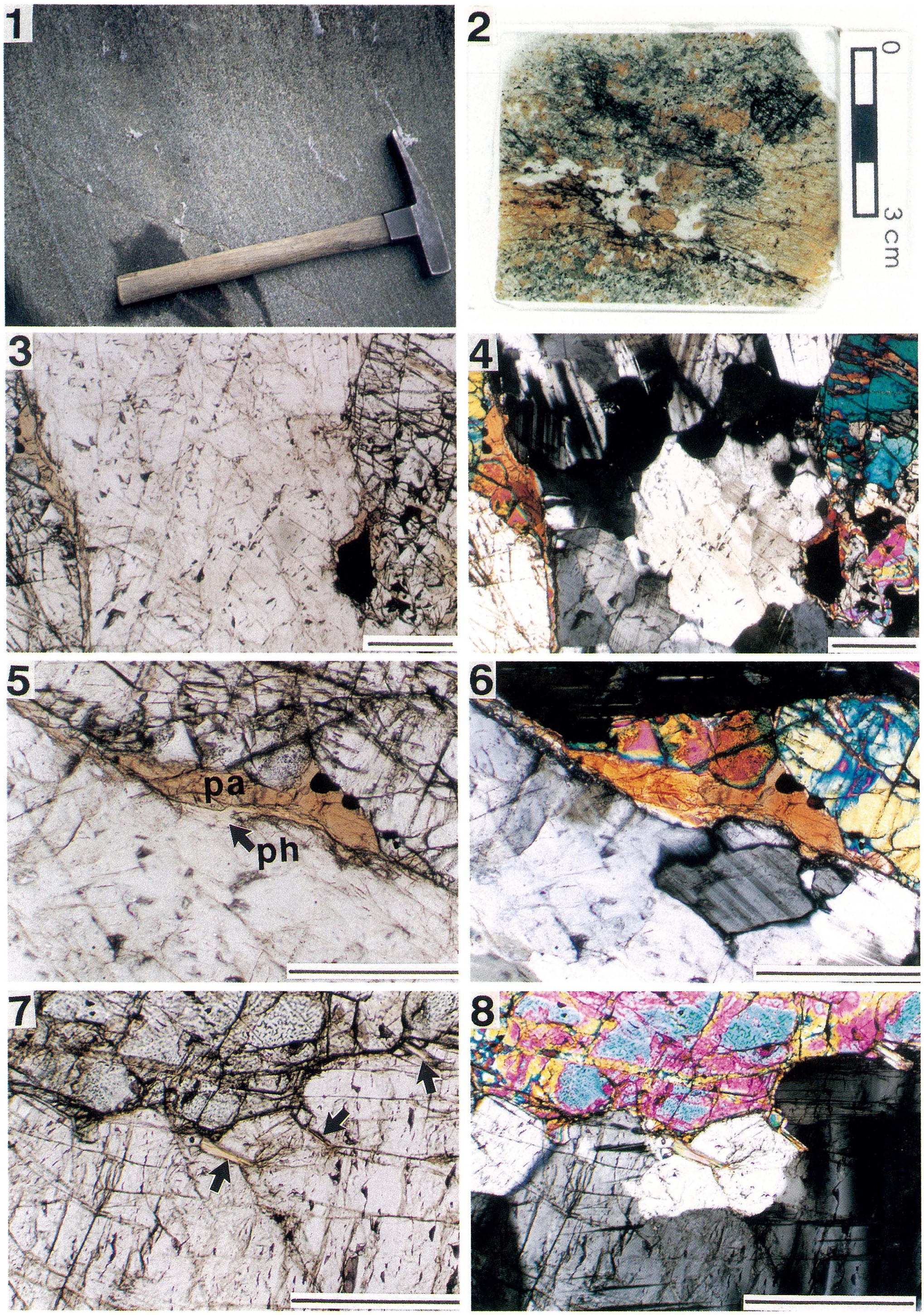


Plate 4