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Petrology of Peridotite Xenoliths from Arcs as an Insight into Wedge-Mantle Processes

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Abstract- Petrological characteristics of peridotite xenoliths obtained from arcs will provide us direct information about materials and processes of mantle wedge. They include: (1) highly depleted characters both in modal compositions and in major elements with high-Mg (Fo>92) olivine and high-Cr# (>0.7) spinel, (2) formation of secondary amphibole and mica with low Ti contents, and (3) relatively high fO₂. In addition to them, secondary formation of orthopyroxene at the expense of olivine is very important in the mantle wedge via Si-rich melt or fluid released from subducted slab. The secondary orthopyroxene can protect SiO₂-oversaturated melt against consumption through reaction to transport up to the crust (= adakite eruption). The formation of secondary orthopyroxene enriched the mantle wedge with SiO₂.

I Introduction

Mantle-wedge derived xenoliths, represented by peridotite xenoliths captured by arc magmas, are rare relative to those from non-arc settings, that is from oceanic hotspots and continental rift zones (e.g., [1]). This means paucity of xenolith-based direct petrological information about the mantle wedge relative to other tectonic settings. Hence the arc-derived peridotite xenoliths definitely need to be investigated more systematically and in more detail to explore the mantle wedge materials and processes.

Peridotite xenoliths of possible mantle-wedge origin have been described from the Japan island arcs (e.g., [2, 3, 4]), Colorado Plateau (e.g., [5]) the Cascades, USA [6], Mexico [7], Papua New Guinea [8] and the Kamchatka arc [9, 10]. Peridotite xenoliths captured by arc-type magmas are especially important because they are genuinely of mantle-wedge origin. The characteristics of the mantle-wedge peridotites are: (1) highly depleted characters both in modal compositions and in major elements with high-Mg (Fo>92) olivine and high-Cr# (>0.7) spinel, (2) formation of secondary amphibole and mica with low Ti contents, and (3) relatively high fO₂. In this paper we would like to stress an additional point, the addition of silica from slab. We summarize our recent results of petrological studies of peridotites derived from mantle wedge. We especially deal with the process of silica addition to the mantle wedge recorded on peridotite xenoliths from Tallante, Spain and from Avacha volcano, Kamchatka Russia.

II. Petrography and Petrology of Peridotite Xenoliths with Special Reference to Quartz-bearing Tonalite Vein

A. GEOLOGY AND PETROGRAPHY

Ultramafic xenoliths, up to 20 cm across, are abundant in alkali basaltic pyroclastics near the village of Tallante, Spain. The age of alkali basalt is 2.7 Ma. The xenoliths are classified into two, Groups I (peridotites) and II (clinopyroxenites and gabbros). Composite xenoliths, e.g., xenoliths of peridotite cut by clinopyroxenite or gabbro and of clinopyroxenite enclosing peridotite clasts, are common. The peridotite has equigranular to porphyroclastic textures and is mostly spinel lherzolite to harzburgite, containing less than 10 % by volume of clinopyroxene, with or without plagioclase. Peridotites (Group I) are predominant (>80 %) over pyroxenites and gabbros (Group II) by volume. Megacrysts of clinopyroxene and kaersutite are very common.

The peridotite that contains the tonalite veinlets is plagioclase-spinel lherzolite with fine-grained lenticular aggregates composed of chromian spinel and pyroxenes. The aggregates are very similar to those surrounding the spinel-pyroxene symplectite in the Horoman peridotite, Hokkaido, Japan, which has been interpreted as pseudomorphs after pyrope-rich garnet.

B. MINERAL CHEMISTRY AND PETROLOGY OF THE PERIDOTITE HOST

The host lherzolite contains olivine of Fo_{89.9} and relatively Al-rich spinel of Cr# (= Cr/[Cr+Al] atomic ratio) = 0.12. The Tallante peridotite demonstrates systematic mineral chemical variations depending on the presence or absence of plagioclase. Olivine is Fo_{90.5-91.3} in spinel peridotite and Fo_{89.0-91.0} in plagioclase-spinel one. Cr# of chromian spinel mostly ranges from 0.21 to 0.25 for both types, although its TiO₂ content is clearly different, less than 0.04 wt% in spinel peridotite and 0.1-0.3 wt% in plagioclase-spinel peridotite. Al₂O₃ and Cr₂O₃ contents in pyroxenes are also different between the two types: they tend to be higher in spinel peridotite than in plagioclase-spinel peridotite. Na₂O content in clinopyroxene is slightly higher in spinel peridotite than in plagioclase-spinel one. Interstitial plagioclase is mostly An₆₀₋₇₀ but rarely >An₈₀ and is very low in K (<Or₁).

C. PETROGRAPHY AND CHEMISTRY OF THE TONALITE VEINS

White veins (up to 5 mm thick) are common in the Tallante peridotite. They sometimes form a network cutting

the foliation of the rocks. The thicker veins are relatively coarse-grained and are tonalitic in mode. Quartz, up to 1 mm across, is only in the central part of the veins, and orthopyroxene always intervenes along the olivine-rich wall. We found small amounts of hydrous minerals (pargasite and/or phlogopite), zircon, rutile and apatite in tonalite. Clinopyroxene, which is anhedral and coarse (up to 2 mm across), is in contact with quartz and poikilitically encloses plagioclase laths. Plagioclase is slightly zoned, and orthopyroxene is free from lamellae of clinopyroxene. K-feldspars are absent. Hydrous minerals are also distributed in adjacent peridotite wall: phlogopite forms especially around primary chromian spinel. Thinner veins are free from quartz and are mainly composed of plagioclase and orthopyroxene.

Plagioclase in the tonalite veins is slightly less calcic than interstitial one and shows normal zoning, from An₅₄₋₆₁ to An₄₇₋₅₂ from the core outward. The K content in plagioclase is negatively correlated with An, ranging from Or_{1.5} to Or_{4.1}. Orthopyroxene in the veins is as magnesian as but is distinctly lower in CaO (0.6 to 0.2 wt%), Al₂O₃ (2 to 0.8 wt%) and Cr₂O₃ (0.2 wt% to nil) than that in the peridotite. Clinopyroxene in tonalite is diopside with high Mg# (= Mg/(Mg + total Fe) atomic ratio), ca. 0.89, and low contents of TiO₂ (0.1-0.2 wt%), Al₂O₃ (0.7-0.8 wt%) and Cr₂O₃ (<0.1 wt%). Both phlogopite and hornblende are low in TiO₂, <1.8 wt% and <1 wt%, respectively. The olivine wall apparently has no chemical gradient toward the vein: the Fo content is constantly around 90. A chemical gradient, however, does exist within the orthopyroxene selvage; its Mg# decreases from around 0.90 to 0.87 inward over 1 to 2 mm.

The bulk composition of the tonalite has a small amount of normative quartz and large amounts of pyroxenes, especially hypersthene, which may be due to incomplete elimination of orthopyroxene adjacent to olivine wall. It is remarkably low in alkalis (< 1 wt%). The Mg# is very high, 0.893, being equivalent to the peridotite wall. It is highly difficult to determine the composition of the melt, but its initial SiO₂ content probably has exceeded 60 wt% if we assume the normative hypersthene was due to reaction of olivine and melt.

III. Peridotite Xenoliths from Avacha Volcano, Kamchatka, Russia

A. GEOLOGICAL SETTING

Avacha (Avachinsky) volcano is located at 53°15.3'N and 158°49.8'E on the volcanic front of the southern Kamchatka arc. Pacific plate subducts beneath the Kamchatka Peninsula at a rate of 9 cm/year through a trench about 200 km off the coast, and the depth to the slab is about 100 to 120 km beneath Avacha volcano.

The Avacha volcano has been active from the late Pleistocene, and the volcanic activity of Holocene can be divided into two stages, I Av (from 7200 to 3700 years B.P.)

and II Av (3500 years B.P.) [11]. The magma is andesite for I Av and basaltic andesite for II Av.

Several pyroclastic deposits have been found to contain ultramafic xenoliths [11]. The I Av24 deposits are well known to contain abundant xenoliths of harzburgite, clinopyroxenite and hornblende gabbro. Xenoliths were collected with the assistance of V.M. Okrugin and the future study will be proceeded with his collaboration.

B. PRIMARY PERIDOTITE

Harzburgite is coarse-grained, and usually exhibits protogranular to porphyroclastic textures with coarse olivine and orthopyroxene grains up to 1 cm across in some samples. Olivine and orthopyroxene with exsolution lamellae of clinopyroxene are commonly kinked. Clinopyroxene is smaller in size and is closely associated with orthopyroxene even if it occurs as discrete grains. Chromian spinel is subhedral to anhedral and exhibits black to reddish brown color under the microscope. Chromian spinel commonly occurs as thin lamellae in coarse olivine grains. Olivine and orthopyroxene are 54 to 88 % and 40 to 10 %, respectively, in volume. As described below, secondary orthopyroxene and other metasomatic minerals are contained in various amounts in harzburgite.

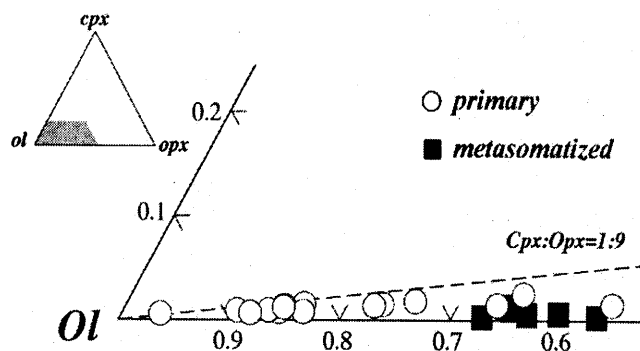


Fig. 1. Modal amounts of olivine, orthopyroxene and clinopyroxene in peridotite xenoliths from Avacha. Note that the metasomatized peridotite is richer in orthopyroxene than the primary peridotite. After [9].

IV. Silica Addition to the Mantle Wedge

A. TALLANTE PERIDOTITE: MELT ADDITION

The mode of occurrence of the Tallante tonalitic veins strongly suggests that the silica-oversaturated melt changes its composition basically by a reaction, olivine digestion combined with orthopyroxene precipitation. It can preserve its original character (e.g., silica oversaturation and low Cr) to some extent only if continuously armored by the reaction product, orthopyroxene, from ambient peridotite. Larger melt/olivine ratio and fissure flow mechanism are favorable for preservation of the original character. This means that the Tallante tonalitic melt has left larger amount of orthopyroxenite at the expense of olivine below, because the

host peridotite was derived from the shallowest part of the upper mantle of plagioclase-lherzolite stability field, at < 1 GPa [13]. The melt which produced the tonalite veins had been in equilibrium with peridotite wall through orthopyroxene lining in terms of Mg-Fe distribution due to slow cooling since no appreciable chemical gradient for Mg# is not found within the peridotite part. The inward fractional crystallization of the melt during subsequent cooling had produced a steep and narrow chemical gradient across the thin orthopyroxene selvage (Mg#, 0.90 to 0.87).

The melt involved in the formation of tonalite within the Tallante peridotite was silica-oversaturated and was strongly reactive with olivine to produce orthopyroxene. The partial melt of mantle peridotite tends to be oversaturated with olivine with a pressure decrease and to form dunite with consumption of orthopyroxene. The melt was most probably derived from melting of crustal materials, the descending or sinking slab beneath the Betic area [14]. The Tallante tonalite is, however, clearly lower in alkalis than the

silica-rich slab-derived melt trapped in peridotite xenoliths [15]. It is also different in chemistry from possible slab melts in experiments [16]. The melt involved in formation of the tonalitic veins had been modified by peridotite en route from the slab, forming mica and amphibole in addition to orthopyroxene in deeper parts.

B. AVACHA PERIDOTITE: FLUID ADDITION

The metasomatic orthopyroxene in peridotite from Avacha replaces olivine in very complicated ways as in the peridotite xenoliths from Iraya volcano. This suggests very high permeability or very low viscosity of the relevant metasomatic agent. This type of metasomatic orthopyroxene is characteristically free from other metasomatic minerals. We suggest that the metasomatic agent for the Avacha-type orthopyroxene formation was aqueous fluid. The main solute for the former was silica, resulting in the sole formation of orthopyroxene by replacing olivine (Fig. 1).

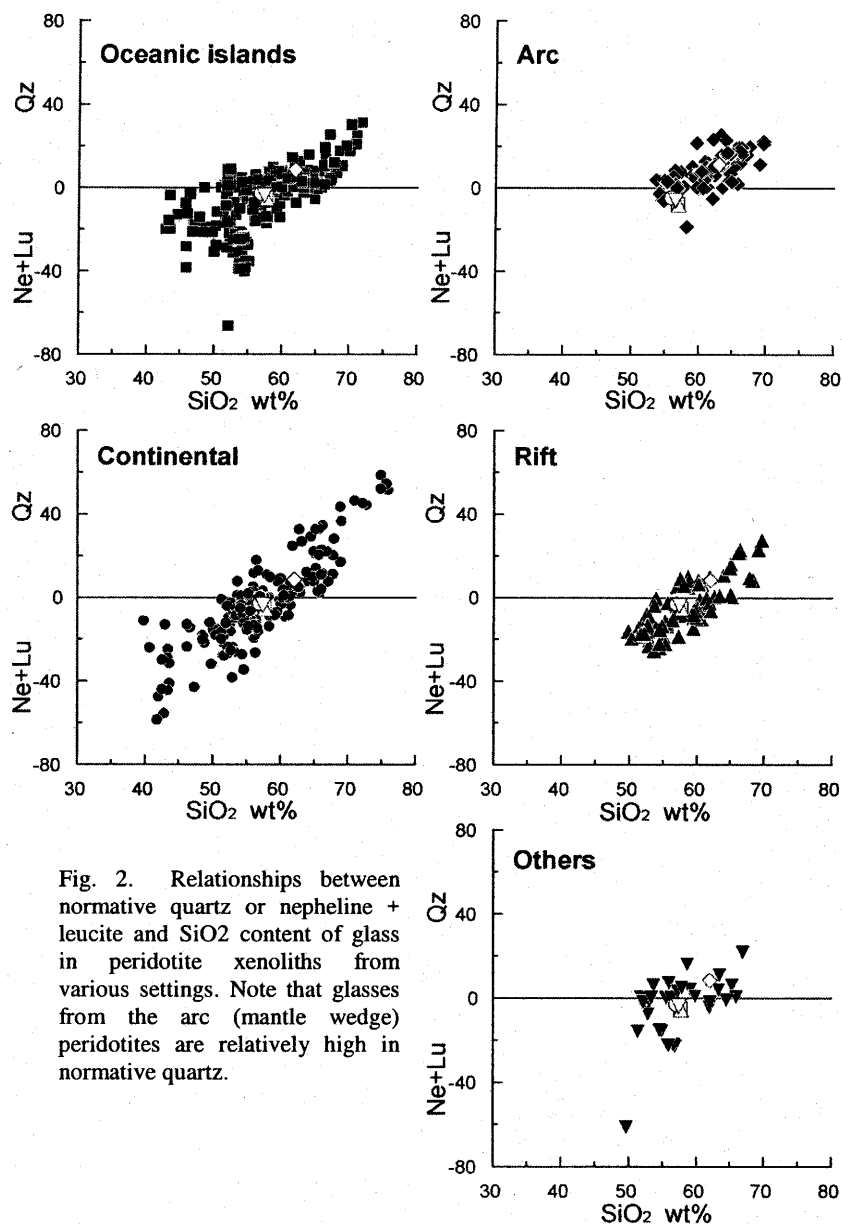


Fig. 2. Relationships between normative quartz or nepheline + leucite and SiO₂ content of glass in peridotite xenoliths from various settings. Note that glasses from the arc (mantle wedge) peridotites are relatively high in normative quartz.

V. Glass Compositions within Peridotite Xenoliths

Small amount of glass is commonly found in peridotite xenoliths from various settings [17]. They are sometimes high in silica contents, up to 70 wt%. In this chapter we intend to compare the glass compositions in mantle-wedge peridotites with those from peridotites derived from the other settings. To be surprised, the compositions of minute glass in peridotites xenoliths are not so different between various tectonic settings (Fig. 2). On average, glasses in mantle-wedge peridotites are slightly richer in silica and normative quartz than the others (Fig. 2). Although the average glass compositions from oceanic islands, continental rift zones have small amount of normative quartz, they are frequently have normative quartz, being not so different from those from mantle-wedge peridotites (Fig. 2).

The origin of the silica-rich glasses from non-arc peridotites has not been known to date. Some author favors the origin from very small degree partial melts of peridotites, which are, however, rich in alkalis and have normative nepheline and leucite [18]. The silica-rich glasses in arc-derived peridotites are sometimes interpreted as slab-derived melts [15]. We should explain the origin of silica-rich (normative quartz bearing) glasses often observed in non-arc related peridotite xenoliths.

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