

Melting and Multi-stage Metasomatism in the Mantle Wedge beneath a Frontal Arc Inferred from Highly Depleted Peridotite Xenoliths from the Avacha Volcano, Southern Kamchatka

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Peridotite xenoliths from the Avacha volcano, Kamchatka, derived from the mantle beneath the volcanic front of the Kamchatka arc, are mainly highly depleted clinopyroxene-poor harzburgites with highly forsteritic olivine (Fo 90–92) and high Cr-number spinel (0.5–0.7). The Avacha peridotites have experienced metasomatism to various extents, with the formation of metasomatic orthopyroxene replacing primary olivine, by infiltration of SiO₂-rich fluids. The metasomatic orthopyroxenes can be subdivided into two textural types; (1) radially aggregated prismatic grains (opx II-1); (2) stout grains associated with interstitial glass and metasomatic minerals (opx II-2). The Avacha peridotites exhibit light rare earth element (LREE) enrichment relative to heavy REE (HREE), even in primary lithologies with <2 vol.% of metasomatic orthopyroxene. However, the metasomatism has not altered the chemical characteristics of the Avacha peridotites significantly, and the Fo contents of olivine do not increase with an increase in the Cr-number of spinel. The clinopyroxene in the most depleted primary peridotite, with the highest spinel Cr-number, has the highest Ce_N (where subscript N indicates normalized to primitive mantle) and relatively low Yb_N contents. We conclude that the Avacha peridotites are residues of high-degree melting induced by infiltration of an aqueous fluid with relatively high Fe/Mg and LREE/HREE ratios. In situ

analysis of olivine grain boundaries by laser-ablation inductively coupled plasma mass spectrometry (ICP-MS) showed significant concentrations of some trace elements (Ce and Ba), even on glass-free boundaries; such grain boundaries can be a repository for large-ion lithophile elements (LILE). Orthopyroxene and Ca-amphibole contribute to the HREE and middle REE (MREE) budget, respectively, of the bulk peridotites. Three types of mantle metasomatism are recorded in the Avacha peridotites. The agent that formed HREE-poor opx II-1 was a slab-derived aqueous fluid rich in SiO₂. It was a successor of the fluid influx involved in the initial partial melting event. On the other hand, the metasomatic minerals in highly metasomatized peridotites have high LILE (Th, U and Sr) and LREE contents relative to HREE, indicating involvement of a hydrous melt of adakitic affinity derived from the subducted slab. Glasses associated with opx II-2 are similar in their trace-element characteristics to the host Avacha volcanic rocks, indicating the likelihood that the metasomatic agent was a forerunner of the recent Avacha arc magmatism.

KEY WORDS: Avacha volcano; southern Kamchatka arc; depleted peridotite xenoliths; hydrous melting; mantle metasomatism

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INTRODUCTION

Sub-arc mantle peridotites are expected to be more depleted in magmatic components, on average, than peridotites from other tectonic settings, especially mid-ocean ridges; this is reflected in the strongly depleted nature of some arc magmas compared with mid-ocean ridge basalts (MORB) (e.g. Dick & Bullen, 1984; Arai, 1994a). The nature of the depleted sub-arc mantle beneath present-day arcs has, however, not been discussed in detail because mantle peridotite xenoliths are much rarer than in other tectonic settings (e.g. Nixon, 1987). Depleted peridotites have been sampled from fore-arc regions (e.g. Parkinson & Pearce, 1998), but typically have been substantially altered at low temperatures.

Peridotite xenoliths from Avacha volcano in the Kamchatka arc, Russia, are mostly harzburgites, highly depleted in magmatic components (i.e. major-element depleted). They have not been subjected to low-temperature alteration and have experienced variable extents of metasomatism by silica-rich fluids and/or melts (Arai *et al.*, 2003a). They provide us with many pieces of information, not only about the genesis of the highly depleted harzburgite protoliths, but also about metasomatism within the supra-subduction zone mantle wedge. The peridotite xenoliths from Avacha represent fragments of the upper mantle beneath an active volcanic front, which are comparatively rare (see Arai *et al.*, 2004).

Metasomatized peridotite xenoliths (mostly harzburgites) from arc settings have been reported from several localities: Cascades, USA (e.g. Ertan & Leeman, 1996), Colorado Plateau, USA (e.g. Smith *et al.*, 1999), Patagonia (e.g. Gorrington & Kay, 2000; Kilian & Stern, 2002), Batan Island, Philippines (e.g. Schiano *et al.*, 1995; Arai & Kida, 2000; Arai *et al.*, 2004), Papua New Guinea (e.g. McInnes *et al.*, 2001; Grégoire *et al.*, 2001; Franz *et al.*, 2002), Tallante, SE Spain (Arai *et al.*, 2003b; Beccaluva *et al.*, 2004; Shimizu *et al.*, 2004) and northern Kamchatka (e.g. Kepezhinskas *et al.*, 1995, 1996). The geochemical characteristics of the depleted harzburgites, which are metasomatized to variable degrees, can provide important constraints on mantle-wedge processes (i.e. the depletion of magmatic components by partial melting and re-fertilization by metasomatism).

Salters & Shimizu (1988) suggested that the bulk-rock trace-element signatures of fertile mantle peridotites are controlled by the clinopyroxene trace-element budget; however, this is not the case for more depleted peridotites (e.g. Maury *et al.*, 1992; Grégoire *et al.*, 2001; Franz *et al.*, 2002; Kilian & Stern, 2002). It is well known that 'grain-boundary components' in peridotites are rich in incompatible trace elements, such as large ion lithophile elements (LILE) (Zindler & Jagoutz, 1988). Recently, the importance of the grain-boundary components has been highlighted, and their chemical characteristics have been estimated in some peridotite

xenoliths (e.g. Condie *et al.*, 2004; Ionov, 2004). However, the methods used have typically been indirect, involving subtraction of calculated bulk-rock compositions, estimated based on modal mineralogy and mineral chemistry, from analyzed bulk-rock compositions. There have, however, been a few direct studies on grain boundaries (Suzuki, 1987; Hiraga *et al.*, 2002, 2003, 2004). The Avacha peridotite xenoliths have advantages for grain-boundary research: the grain boundaries of the primary mantle minerals are devoid of low-temperature alteration and are completely preserved. This makes a good contrast to those fore-arc depleted peridotites (e.g. Parkinson & Pearce, 1998), in which serpentinization has destroyed the original grain boundaries between the mantle minerals. The grain-boundary components are relatively easily detected in the Avacha peridotites because of the low LILE contents in the surrounding mantle mineral grains. The importance of the grain boundary as a sink for LILE is highlighted in the Avacha peridotites because of the extremely small amounts of potentially LILE-rich minerals such as clinopyroxene and amphibole.

GEOLOGICAL BACKGROUND

The Avacha (=Avachinsky) volcano is located in the southern part of the Kamchatka Peninsula, which is a relatively mature arc (Fig. 1). The Pacific plate is subducting at a relatively rapid rate (70–90 mm/year, Minster *et al.*, 1974) beneath the southern part of the Kamchatka Peninsula along the Kuril–Kamchatka trench. In the northern part of the Kamchatka Peninsula, young and hot oceanic lithosphere, produced in the Komandorsky Basin, was subducted until ~2 Ma (Hochstaedter *et al.*, 1994). Peridotite xenoliths, which have experienced Na-metasomatism by a slab melt, have been reported from Nb-enriched host basalts in northern Kamchatka (e.g. Kepezhinskas *et al.*, 1995). The dip angle of the subducting plate decreases from 55° to 35° from south to north in southern Kamchatka (Gorbatov *et al.*, 1997), where there are three sub-parallel volcanic chains at distances from the trench of 200 km, 320 km and 400 km, respectively (Tatsumi *et al.*, 1994; Fig. 1). The Avacha volcano is in the frontal chain that forms the volcanic front (VF); the depth to slab here is about 120 km (Gorbatov *et al.*, 1997) and the depth to the Moho is about 37 km (Levin *et al.*, 2002).

Avacha is a stratovolcano, rising ~2741 m above the sea level. Its volcanic activity began in the late Pleistocene, and is divided into two stages, IAv and IIAv, based on the chemical composition of its ejecta (Braitseva *et al.*, 1998). Andesitic pyroclastic flows and tephra are characteristic of IAv, from 7250 to 3700 years bp, whereas basaltic andesite lavas have been produced in IIAv, from 3500 years bp to the

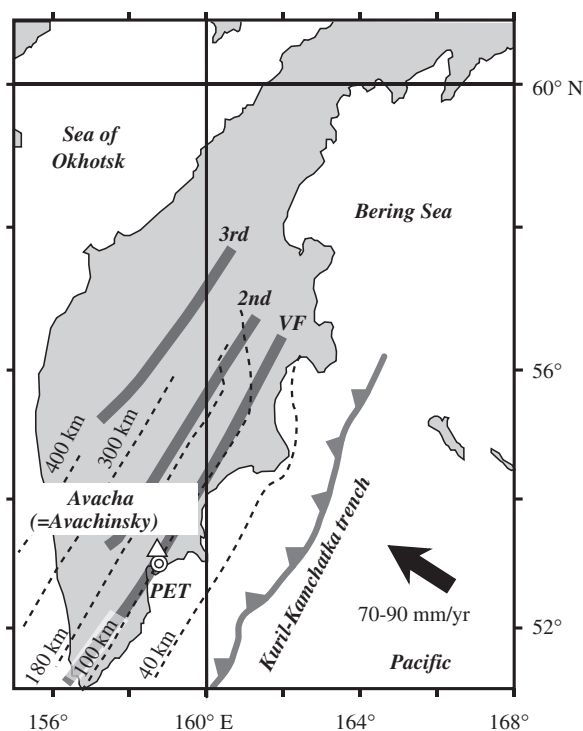


Fig. 1. Location of the Avacha volcano. Map of the Kamchatka region shows the contours of the Wadati-Benioff zone [adapted from Gorbatov *et al.* (1997)], and the location of the three volcanic chains from Tatsumi *et al.* (1994). PET is Petropavlovsk-Kamchatsky, the capital city of Kamchatka. VF, volcanic front.

present (Braitseva *et al.*, 1998). All the effusive rocks are calc-alkaline in chemistry; some contain megacrysts of hornblende (Braitseva *et al.*, 1998). Abundant peridotite xenoliths are enclosed in some of the andesitic pyroclastic deposits of IAv (Braitseva *et al.*, 1998) as ejecta occasionally coated by thin lava films.

SAMPLE DESCRIPTIONS

Host rocks of the xenoliths

The host rock of the peridotite xenoliths is a basaltic andesite, containing phenocrysts and microphenocrysts of olivine, plagioclase, amphibole, clinopyroxene and orthopyroxene. Olivine is euhedral to rounded and sometimes includes tiny crystals of chromian spinel. Many of the plagioclase phenocrysts contain abundant melt (glass) inclusions and are strongly zoned. Orthopyroxene exhibits weak pleochroism, and amphibole is euhedral and has strong pleochroism from brown to yellowish brown. The groundmass has an intergranular texture.

Peridotite xenoliths

Most of the xenoliths from Avacha are spinel harzburgites; subordinate pyroxenites (clinopyroxenite and orthopyroxenite), dunite and hornblende-gabbros are also found.

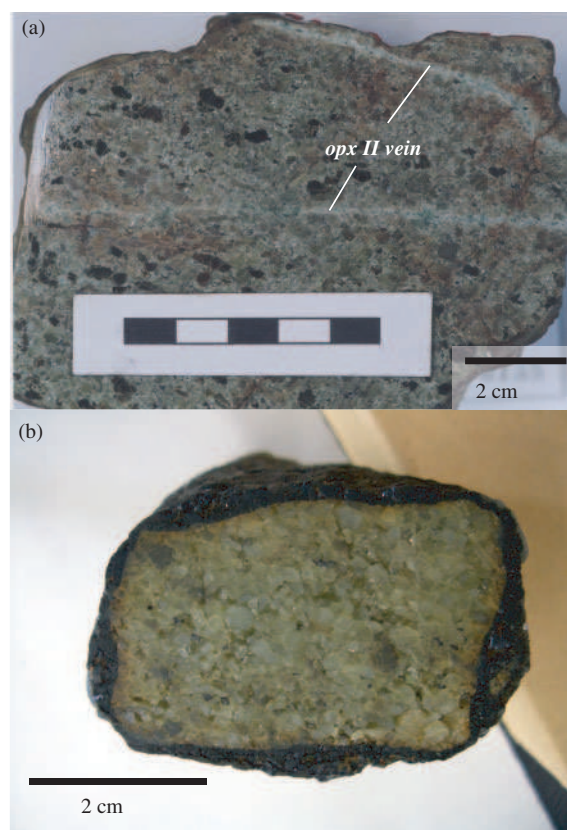


Fig. 2. Photographs of hand specimens of coarse-grained peridotite xenoliths from the Avacha volcano. (a) Peridotite xenolith (sample 725) penetrated by thin metasomatic orthopyroxene veins. (b) Peridotite xenolith (sample 181) surrounded by hornblende selvage.

Clinopyroxene-bearing hornblende sometimes coats the peridotite xenoliths, forming a thin selvage as well as cutting them as veinlets (Fig. 2b). Such characteristics have been observed in other sub-arc mantle xenoliths exhumed by arc magmas; for example, those from Iraya volcano, Philippines (Arai *et al.*, 1996) and Oshima-Ōshima volcano, northern Japan (Ninomiya & Arai, 1992). Klügel (1998) found similar hornblende selvages on peridotite xenoliths from the Canary Islands (oceanic hotspot), and interpreted them as a reaction product between the host magma and mantle peridotite at shallow depths within the lithosphere.

The xenoliths are subangular to angular in shape and predominantly 5–6 cm (up to 40 cm) across (Fig. 2). The spinel harzburgites occasionally have thin bands (<2 cm in thickness) of orthopyroxenite (Fig. 2a) to websterite. The grain size of the peridotite xenoliths is variable; some of them are very fine-grained with olivine of less than 1 mm across (down to less than 0.1 mm) (Arai *et al.*, 2003a). The coarse-grained peridotite xenoliths (with olivine >1–2 mm to 10 mm) are the main focus of this study and are subsequently referred to simply

as peridotite xenoliths. The fine-grained peridotites are highly heterogeneous and with complex textures and mineral chemistry, and will be discussed elsewhere. The modal proportions of minerals in the peridotites were determined by point-counting based on 2000–4000 points per thin section (Table 1; Fig. 3). The peridotites are sometimes heterogeneous, and the modal proportion of orthopyroxene in standard size thin sections (48 mm × 28 mm) is highly variable.

The peridotite xenoliths are modally metasomatized to various extents, irrespective of their textures, resulting in the formation of metasomatic orthopyroxene, usually replacing olivine (Arai *et al.*, 2003a; Fig. 4b, d–g). There is no systematic distribution of the metasomatic orthopyroxene; this occurs mainly as radial aggregates in olivine-dominant parts. All peridotites contain the metasomatic orthopyroxene. In the subsequent discussion, the terms ‘primary peridotite’ and ‘metasomatized peridotite’ are used to refer to peridotites that contain metasomatic orthopyroxene replacing olivine by <2.0 vol.% and ≥2.0 vol.%, respectively.

The primary peridotites from Avacha are refractory harzburgites that contain only a small amount of primary clinopyroxene (<2 vol.%) and 10–27 vol.% (17 vol.% on average) of primary orthopyroxene (Table 1; Fig. 3). They usually have protogranular to porphyroclastic textures; the grain size of the olivine and orthopyroxene is up to 1 cm. The olivine and orthopyroxene frequently contain lamellae of chromian spinel and clinopyroxene, respectively. Many of the orthopyroxene grains are kinked and have thin lamellae of clinopyroxene (Fig. 4a). Discrete clinopyroxene grains are subhedral to anhedral, and smaller than the olivine and orthopyroxene. Chromian spinel is opaque, subhedral to anhedral and mostly small in size (~1 mm). Almost all the peridotites contain discrete amphibole, which may be a primary phase (Fig. 4h). Tiny grains (~10 µm) of monosulfide solid solutions (MSS) are occasionally observed, especially in metasomatized peridotites.

Two types of textures are exhibited by olivine-replacing metasomatic orthopyroxene: (1) replacing olivine with ragged boundaries, and sometimes forming radial aggregates (opx II-1) (Fig. 4b); (2) forming stout euhedral to subhedral grains with interstitial amphibole, clinopyroxene and/or highly silicic glass (opx II-2) (Fig. 4e–g). The metasomatized peridotites are often cross-cut by metasomatic orthopyroxene veinlets, composed of opx II-1 with clinopyroxene, amphibole and pentlandite. Stout grains of opx II-2 sometimes form pockets with interstitial silicic glass, amphibole and clinopyroxene. In addition to the olivine-replacing orthopyroxene, the metasomatized peridotites contain another type of metasomatic orthopyroxene (‘recrystallized orthopyroxene’), formed

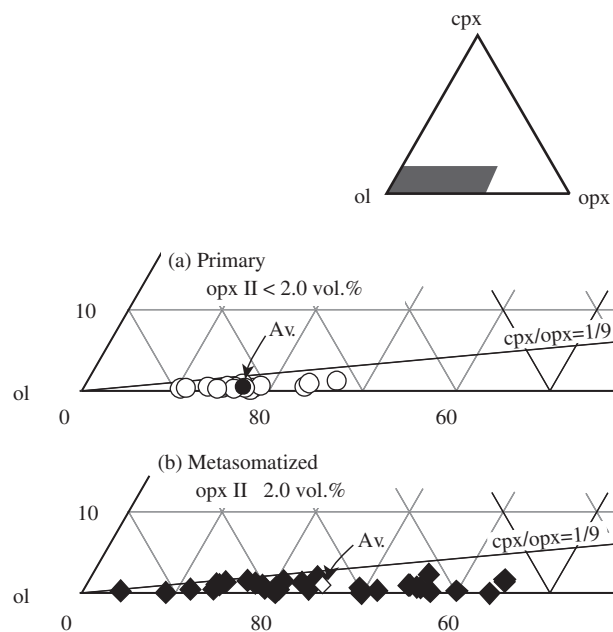


Fig. 3. Modal amounts (vol.%) of olivine (ol), orthopyroxene (opx) and clinopyroxene (cpx) in the Avacha peridotite xenoliths. The xenoliths are subdivided into two types based on the modal amounts of metasomatic orthopyroxene (opx II). The reference line showing a clinopyroxene/orthopyroxene ratio of 1/9 defines the boundary between lherzolite and harzburgite based on solidus mineral compositions (Arai, 1984b). (a) Primary peridotites including <2.0 vol.% opx II. (b) Metasomatized peridotites including ≥2.0 vol.% of opx II. It should be noted that olivine-rich peridotites are of dunite origin. Av., average.

by recrystallization of primary orthopyroxene porphyroclasts, especially along grain margins or within cracks, into smaller grains. The recrystallization is associated with coarsening of clinopyroxene lamellae (Fig. 4c). Clinopyroxenes and amphiboles closely associated with the metasomatic orthopyroxenes are also of metasomatic origin, having been precipitated from, or modified by, metasomatic fluids or melts. The metasomatic orthopyroxenes are totally free of clinopyroxene exsolution and deformation. The total proportion of orthopyroxene is about 25 vol.% on average in the metasomatized peridotites, significantly higher than that in the primary peridotites (17 vol.% on average; Fig. 3). The metasomatic clinopyroxene and amphibole proportions are negligible in the metasomatized peridotites except in sample 629 (Fig. 3; Table 1). Silicic glasses are not only accompanied by opx II-2, but are also observed as rare interstitial films along grain boundaries or as inclusions embedded in primary spinel and olivine grains. One of the highly metasomatized peridotites samples (sample 629; Table 1) is especially rich in glass (amount not determined) both as inclusions in spinel and as a film associated with opx II-2. We have found only one grain of phlogopite, exhibiting strong pleochroism

Table 1: Modal amounts (vol.%) of minerals and major-element compositions of peridotite xenoliths from Avacha volcano

Sample no.:	Primary peridotites							Metasomatized peridotites										
	213	200	F1	181	729	106	Avx-33	10	187	Avx-35	24	227	Avx-31	629	375	59	Avx-1	203
Ol	83.1	74.8	85.3	88.0	80.3	79.8	82.5	77.5	81.3	78.1	67.7	64.4	76.7	76.6	75.8	86.5	76.71	69.8
Sp	0.3	0.5	0.8	1.2	0.3	1.3	1.0	1.0	0.4	0.8	0.7	0.3	1.4	1.0	0.9	0.4	2.22	0.2
Opx I	15.3	21.9	11.6	8.9	17.7	16.5	15.0	18.1	14.3	14.6	13.4	14.5	18.0	2.2	19.1	8.7	8.75	9.5
Opx II	0.4	1.1	1.5	1.3	0.2	0.7	0.9	2.4	2.9	5.7	17.8	19.9	2.8	17.6	2.8	3.4	10.55	20.2
Cpx	0.8	1.2	0.6	0.4	1.5	1.3	0.6	0.5	1.0	0.8	0.4	1.0	1.0	0.1	1.4	0.2	0.68	0.0
Amph	0.2	0.5	0.2	0.3	0.0	0.6	0.0	0.6	0.1	0.0	0.1	0.0	0.0	2.4	0.1	0.9	1.10	0.3
Glass	-	-	-	-	+	+	+	-	-	-	-	-	+	+	+	+	+	+
SiO ₂	42.93	41.93	42.75	n.a.	42.24	42.59	42.96	43.19	42.16	42.36	n.a.	n.a.	41.80	44.53	n.a.	n.a.	n.a.	n.a.
TiO ₂		0.01	0.00	n.a.	0.00						n.a.	n.a.		0.02	n.a.	n.a.	n.a.	n.a.
Al ₂ O ₃	0.42	0.56	0.69	n.a.	0.50	0.50	0.65	0.71	0.49	0.53	n.a.	n.a.	0.46	1.37	n.a.	n.a.	n.a.	n.a.
FeO*	8.41	8.22	8.18	n.a.	8.40	8.15	8.29	8.07	8.29	7.91	n.a.	n.a.	8.21	7.70	n.a.	n.a.	n.a.	n.a.
MnO	0.13	0.12	0.12	n.a.	0.13	0.13	0.12	0.13	0.13	0.12	n.a.	n.a.	0.12	0.13	n.a.	n.a.	n.a.	n.a.
MgO	43.94	46.83	46.03	n.a.	45.29	45.33	46.18	43.16	47.39	47.17	n.a.	n.a.	46.67	41.36	n.a.	n.a.	n.a.	n.a.
CaO	0.69	0.59	0.63	n.a.	0.57	0.54	0.72	0.90	0.57	0.51	n.a.	n.a.	0.49	1.25	n.a.	n.a.	n.a.	n.a.
Na ₂ O				n.a.	0.04			0.00			n.a.	n.a.		0.12	n.a.	n.a.	n.a.	n.a.
K ₂ O		0.00		n.a.		0.00					n.a.	n.a.		0.02	n.a.	n.a.	n.a.	n.a.
P ₂ O ₅	0.00	0.00	0.00	n.a.	0.00	0.00	0.00	0.00	0.00	0.00	n.a.	n.a.	0.00	0.01	n.a.	n.a.	n.a.	n.a.
Total	96.52	98.25	98.41	n.a.	97.17	97.24	98.93	96.17	99.03	98.59	n.a.	n.a.	97.76	96.51	n.a.	n.a.	n.a.	n.a.
FeO*/MgO	0.191	0.175	0.178	n.a.	0.185	0.180	0.180	0.187	0.175	0.168	n.a.	n.a.	0.176	0.186	n.a.	n.a.	n.a.	n.a.

Ol, olivine. Sp, chromian spinel. Opx I, primary orthopyroxene. Opx II, metasomatic orthopyroxene. Cpx, clinopyroxene. Amph, amphibole (both primary and metasomatic). FeO*, total iron as FeO. Opx II grains in sample 629 are partly 'recrystallized' orthopyroxenes from the primary ones (see text). Glass: + indicates present; - indicates absent. Blank, below detection limit; n.a., not analyzed.

and included in olivine in a metasomatized peridotite. Fluid inclusion trails were commonly found in both the primary and metasomatized peridotites (Fig. 4h).

Within the Avacha peridotite xenolith suite, sample 227 is an atypical, highly metasomatized harzburgite, containing a relatively thick orthopyroxene vein, 2 mm thick, which is considered in detail below. The orthopyroxene vein is composed of radial aggregates of opx II-I and metasomatic clinopyroxene and amphibole (Fig. 4d). The modal amount of the metasomatic orthopyroxene attains 20%. Pentlandite is also observed and prevalent throughout the peridotite, especially around the vein. Primary orthopyroxene porphyroclasts far from the veins have recrystallized rims and sometimes have coarsened clinopyroxene lamellae and subhedral to anhedral amphibole (Fig. 4c). Minute fluid inclusions are prevalent in the olivine and other minerals.

ANALYTICAL METHODS

Bulk-rock analysis

Samples for bulk-rock chemical analysis were cut using a diamond saw and washed in an ultrasonic bath to

avoid contamination. Chips were selected to be representative of the samples concerned, and any hornblende selvages and dikelets were carefully removed to allow geochemical characterization free from the effects of the hornblende. After drying the sample chips for almost 1 day, they were crushed with an iron hammer and ground in an agate mortar. Major-element contents were determined by X-ray fluorescence (XRF) spectroscopy (X-ray spectrometer; System-3270, Rigaku) at Kanazawa University on glass discs made from 0.5 g ($\pm 0.5\%$) powder.

Trace-element contents in bulk-rocks were determined by inductively coupled plasma mass spectrometry (ICP-MS; X7, Thermo Electron) at Kanazawa University. De-ionized water purified by a milli-Q Element A-10 system (Millipore) was used throughout the procedure, and all acids used (HNO₃, HClO₄, HF) were of Ultrapure grade (Kantokagaku, Japan). Rock powders of 100 mg were weighed into screw-cap Savillex® Teflon® beakers, and 1.0 ml of HNO₃, 1.0 ml of HClO₄ and 1.5 ml of HF were added to each sample. We made three solution samples for each sample to check random errors, and standard deviations (1σ) for each analysis are

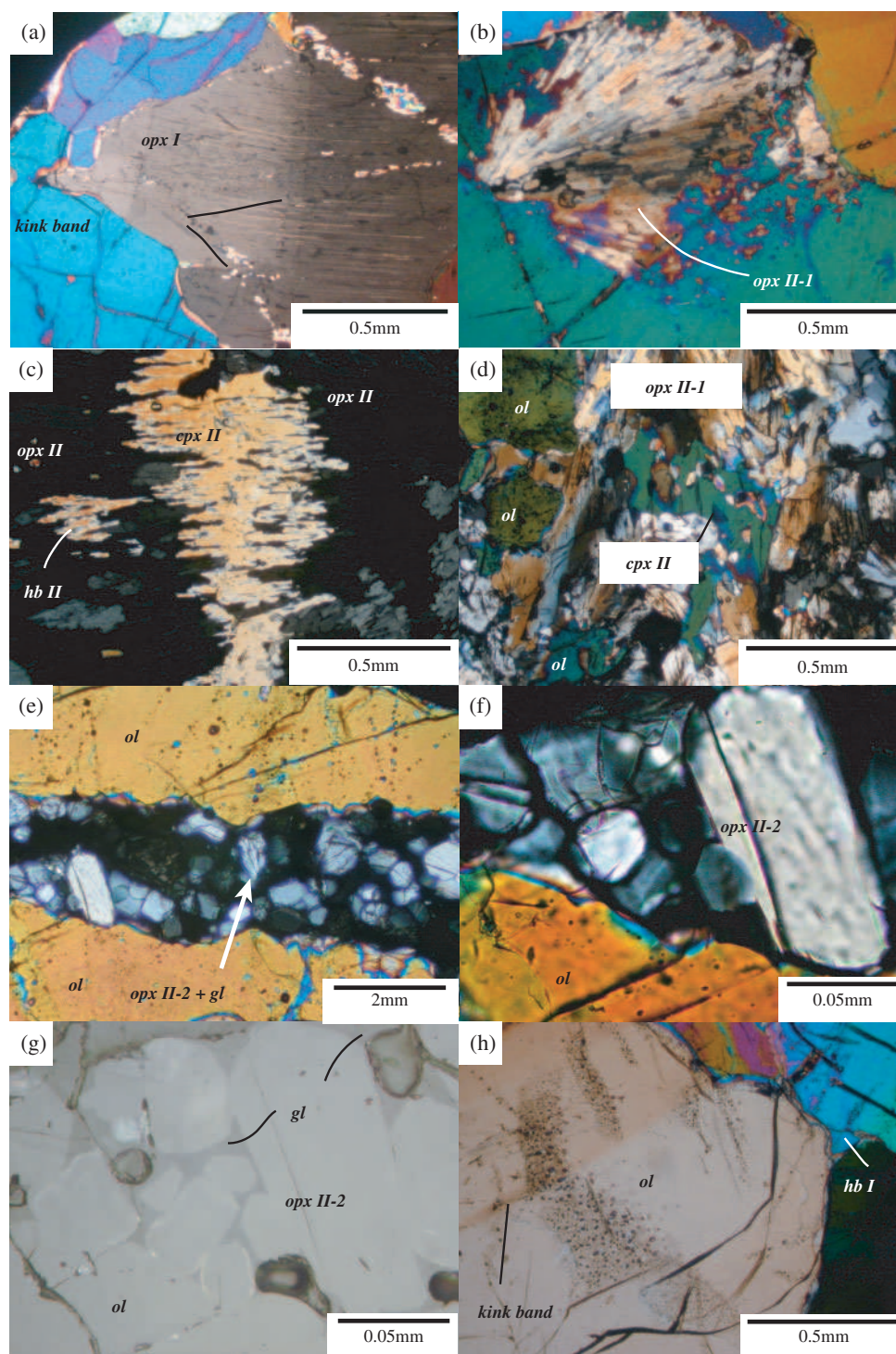


Fig. 4. Photomicrographs of primary and metasomatized Avacha peridotites. All except (g) are in transmitted cross-polarized light. (a) Primary orthopyroxene (opx I) with clinopyroxene lamellae and kink bands in a primary harzburgite with glass (Avx-33). (b) Metasomatic orthopyroxene (opx II-1) in a metasomatized peridotite (sample 24). The radial aggregate of crystals should be noted. (c) Coarsened clinopyroxene lamellae in recrystallized orthopyroxene (opx II) in a highly metasomatized peridotite, sample 227. This type of clinopyroxene is sometimes altered to hornblende (hb II). (d) Metasomatic clinopyroxene (cpx II) within a metasomatically formed orthopyroxenite vein in the highly metasomatized peridotite (sample 227). Surrounding wall-rock olivine is replaced by opx II-1. (e) A vein of metasomatic orthopyroxene (opx II-2) cross-cutting primary olivine (ol) in sample 203, a metasomatized peridotite with glass. (f) Close-up view of (e). The stout prismatic form of opx II-2 should be noted. (g) Reflected light image of (f). Glass (gl) is associated with the metasomatic orthopyroxene (opx II-2). (h) Inclusion-rich domain in olivine (ol) in sample 59, a primary peridotite with glass.

shown in Tables 2 and 3; only analyses with low RSD% (<5%) are presented. The samples were carefully heated to around 110°C ($\pm 10^\circ\text{C}$) for 3–7 days after being agitated in an ultrasonic bath for 10 min. After dissolution, the solutions were diluted with water to 100 µg/g using 100 ml Teflon® PFA volumetric flasks (VIT-LAB). Some spinel grains were insoluble and were removed before analysis, as spinel has a negligible effect on the trace-element budget of the peridotites (e.g. Stosch & Seck, 1980; Bedini & Bodinier, 1999). For quantitative analysis, mixed standard solutions were prepared from XSTC-1, -7, -8 and -13 (SPEX), and 1 ng/g ^{115}In was used for signal-drift correction during each analytical run. Geological reference materials for peridotite (JP-1) and basalt (JB-2) were also analyzed to monitor analytical quality. Determination limits for most elements are 0.1–100 ppb and 0.1–10 ppb for volcanic rock and peridotite analysis, respectively. Detailed operational settings for ICP-MS analysis of bulk peridotite samples are shown in Appendix A (see Shirasaka *et al.*, 2004).

In situ analysis

The major-element compositions of minerals and glasses were determined by electron microprobe (JXA8800, JEOL) at the Center for Co-operative Research of Kanazawa University. Analytical conditions were 20 kV accelerating voltage, 20 nA probe current and 3 µm probe diameter for minerals, and 15 kV accelerating voltage, 10 nA probe current and 3 µm probe diameter for glasses. The analytical conditions for glasses were set to minimize the contamination from surrounding minerals and the loss of alkalis. Ferrous and ferric iron contents in chromian spinel were calculated based on spinel stoichiometry.

Trace-element abundances in the major phases in peridotites (olivine, orthopyroxene, clinopyroxene, amphibole and glass) were determined using a laser ablation system (GeoLas Q-Plus, MicroLas) coupled to an ICP-MS system (Agilent 7500s, Yokogawa Analytical Systems). The laser-spot diameter was 50 µm for clinopyroxenes, amphiboles and glasses, and 100 µm for orthopyroxenes, fluid or melt inclusions and their host olivines. The energy of laser ablation was 5 Hz and 8 J/cm². The NIST 612 standard glass was used for calibration with Si as an internal standard. We used the Si contents of the host olivine for the calibration of concentrations in the inclusions. Details of the analytical procedures have been described by Ishida *et al.* (2004) and Morishita *et al.* (2005). In addition, we also attempted to estimate the trace-element concentrations within olivine grain boundaries in the peridotite xenoliths, as described below in detail. The energy of laser ablation for grain-boundary analysis was 12 Hz and 8 J/cm² and scan speed was 5 µm/s.

Table 2: Bulk-rock chemical compositions of Avacha volcanic rocks (basaltic andesite and andesite)

	Avacha volcanics			
	basaltic andesite		andesite	
Sample no.:	578		580	
SiO ₂	52.87		59.78	
TiO ₂	0.85		0.64	
Al ₂ O ₃	16.37		18.31	
FeO*	8.20		6.35	
MnO	0.15		0.16	
MgO	7.26		2.77	
CaO	9.15		7.95	
Na ₂ O	3.25		3.63	
K ₂ O	0.61		0.70	
P ₂ O ₅	0.13		0.13	
Total	98.84		100.42	
FeO*/MgO	1.13		2.29	
(ppm)		(1σ)		(1σ)
Sc	24.6	0.5	14.6	0.4
Ti	5783	80	4058	69
V	310	8	191	3
Ni	148	2	9.9	0.7
Rb	8.22	0.13	10.1	0.0
Sr	338	5	353	2
Y	18.3	0.3	16.7	0.1
Zr	74.3	1.2	77.2	0.4
Nb	0.985	0.042	0.988	0.061
Cs	0.625	0.015	0.500	0.013
Ba	239	4	290	2
La	4.83	0.08	4.89	0.01
Ce	12.3	0.2	12.0	0.0
Pr	1.88	0.04	1.79	0.01
Nd	9.37	0.14	8.59	0.07
Sm	2.72	0.06	2.35	0.03
Eu	0.943	0.019	0.881	0.005
Gd	3.05	0.04	2.66	0.03
Tb	0.535	0.008	0.452	0.006
Dy	3.26	0.08	2.82	0.02
Ho	0.664	0.010	0.579	0.003
Er	2.04	0.03	1.82	0.01
Tm	0.283	0.005	0.261	0.001
Yb	1.93	0.03	1.82	0.02
Lu	0.288	0.005	0.277	0.003
Hf	1.98	0.04	2.00	0.01
Pb	3.77	0.07	3.75	0.01
Th	0.550	0.012	0.592	0.000
U	0.281	0.007	0.307	0.002

Italicized values have low certainties and are only for reference. Major and trace elements were analyzed by XRF and ICP-MS, respectively. FeO*, total iron as FeO.

Table 3: Trace-element compositions (ppm) of peridotite xenoliths from Avacha volcano

	Primary peridotites											
	213	(1 σ)	200	(1 σ)	F1	(1 σ)	729	(1 σ)	106	(1 σ)	Avx-33	(1 σ)
Sc	10.2	0.1	7.38	0.41	10.3	0.267	7.85	0.17	9.15	0.22	10.3	0.22
Ti	13.5	0.2	67.6	3.9	34.3	0.234	43.8	1.4	14.1	0.1	28.0	0.6
V	54.7	0.4	40.9	0.9	53.9	2.497	48.1	3.7	53.2	3.6	73.5	2.3
Ni	1917	18	2106	115	2170	58	2221	123	1990	14	2640	3
Rb					0.102	0.023			0.090	0.004		
Sr	0.133	0.003	1.46	0.026	1.16	0.018	1.27	0.02	0.453	0.001	1.34	0.022
Y	0.054	0.001	0.109	0.002	0.096	0.000	0.128	0.003	0.053	0.002	0.081	0.001
Zr	0.095	0.003	0.376	0.010	0.315	0.003	0.214	0.007	0.098	0.002		
Nb												
Cs												
Ba	0.244	0.006	0.427	0.019			0.443	0.007	0.336	0.015	0.502	0.011
La	0.011	0.001	0.025	0.000			0.014	0.001	0.015	0.001	0.013	0.000
Ce	0.023	0.002	0.066	0.002			0.039	0.001	0.038	0.002	0.032	0.000
Pr	0.003	0.000	0.010	0.000	0.009	0.001	0.007	0.000	0.006	0.000		
Nd	0.014	0.001	0.043	0.001	0.041	0.003	0.038	0.001	0.027	0.001	0.033	0.002
Sm	0.004	0.000	0.012	0.000	0.011	0.000	0.015	0.000	0.008	0.000		
Eu	0.001	0.000	0.004	0.000	0.004	0.000	0.006	0.000	0.003	0.000		
Gd	0.004	0.000	0.012	0.000	0.011	0.000	0.017	0.001	0.008	0.000		
Tb	0.001	0.000	0.002	0.000	0.002	0.000	0.003	0.000	0.002	0.000		
Dy	0.007	0.000	0.015	0.000	0.013	0.000	0.023	0.000	0.009	0.000	0.014	0.001
Ho	0.002	0.000	0.004	0.000	0.003	0.000	0.005	0.000	0.002	0.000	0.003	0.000
Er			0.016	0.000	0.014	0.000	0.017	0.000	0.008	0.000	0.014	0.001
Tm	0.002	0.000	0.003	0.000	0.003	0.000	0.003	0.000	0.002	0.000	0.003	0.000
Yb	0.015	0.001	0.026	0.001	0.027	0.000	0.025	0.000	0.016	0.000	0.026	0.001
Lu	0.003	0.000	0.005	0.000	0.006	0.000	0.005	0.000	0.004	0.000	0.005	0.000
Hf	0.003	0.000	0.009	0.000	0.009	0.001	0.007	0.000	0.003	0.000		
Pb	0.108	0.005										
Th			0.005	0.000	0.004	0.000			0.003	0.000		
U	0.001	0.000	0.001	0.000	0.001	0.000			0.001	0.000		

	Metasomatized peridotites									
	10	(1 σ)	187	(1 σ)	Avx-35	(1 σ)	Avx-31	(1 σ)	629	(1 σ)
Sc	10.1	0.31	8.86	0.08	7.35	0.16	9.46	0.06	11.6	0.29
Ti	22.2	0.6	8.27	0.05	65.2	0.9	24.7	1.3	144	2.4
V	58.8	2.1	56.3	5.1	55.4	3.3	63.4	1.7	53.9	1.3
Ni	1870	57	2580	110	2596	12	2819	15	2287	31
Rb										
Sr	1.45	0.041			0.853	0.031			10.4	0.047
Y	0.094	0.003	0.028	0.001	0.075	0.000	0.069	0.003	0.502	0.002
Zr	0.323	0.013			0.071	0.001			1.69	0.032
Nb	0.020	0.001								
Cs										
Ba	0.774	0.030			0.613	0.007			4.29	0.056
La	0.024	0.002							0.107	0.000
Ce	0.065	0.002			0.029	0.001	0.027	0.002	0.300	0.001
Pr	0.010	0.000	0.002	0.000	0.005	0.000	0.004	0.000	0.048	0.000
Nd	0.048	0.002	0.010	0.000	0.022	0.000	0.018	0.001	0.246	0.002
Sm	0.014	0.000	0.004	0.000			0.006	0.000	0.073	0.000
Eu	0.005	0.000							0.029	0.000
Gd	0.012	0.000	0.003	0.000	0.010	0.001	0.007	0.000	0.078	0.001
Tb	0.002	0.000	0.001	0.000	0.002	0.000	0.001	0.000	0.014	0.000
Dy	0.014	0.000	0.004	0.000	0.013	0.001	0.011	0.001	0.090	0.001
Ho	0.003	0.000	0.001	0.000	0.003	0.000	0.003	0.000	0.019	0.000
Er	0.014	0.001	0.006	0.000	0.013	0.000	0.011	0.000	0.064	0.000
Tm	0.003	0.000	0.001	0.000	0.003	0.000	0.002	0.000	0.010	0.000
Yb	0.026	0.000	0.016	0.000	0.023	0.001	0.020	0.001	0.077	0.001
Lu	0.005	0.000	0.003	0.000	0.005	0.000	0.004	0.000	0.013	0.000
Hf	0.008	0.000							0.046	0.001
Pb										
Th	0.004	0.000							0.013	0.000
U	0.002	0.000	0.001	0.000					0.005	0.000

Italicized values have low certainties, and are only for reference; blank, below detection limit.

BULK-ROCK CHEMISTRY

Avacha volcanics

The bulk-rock compositions of two samples of volcanic rocks (samples 578 and 580) obtained as fragments of ejecta in the pyroclastic deposits that contain the studied peridotite xenoliths are listed in Table 2. They are a basaltic andesite and an andesite (SiO_2 53.5 and 59.5 wt %, on an anhydrous basis) with low K_2O contents (0.62 and 0.69 wt %). The total alkali contents and the FeO^* (=total iron as FeO) to MgO ratio are low, 3.91 wt % and 1.13 for sample 578, and 4.31 wt % and 2.29 for sample 580, indicating a calc-alkaline affinity. The host rocks in direct contact with the xenoliths are too small in amount for bulk-rock analysis, but are petrographically similar to the basaltic andesite (sample 578) analyzed here.

The rare earth element (REE) and other trace-element compositions of the Avacha volcanic rocks are also listed in Table 2. Primitive mantle-normalized REE patterns are somewhat light REE (LREE)-enriched, with $(\text{La}/\text{Yb})_N$ (where subscript N indicates normalized to primitive mantle) of around 1.8 (Fig. 5). The Avacha volcanics are depleted extensively in Nb and Ti relative to other incompatible elements (Fig. 5). The two Avacha volcanic samples show almost the same trace-element pattern (Fig. 5).

Peridotite xenoliths

Bulk-rock compositions were determined for 11 peridotite xenoliths from Avacha (Tables 1 and 3). Contents of Al_2O_3 , CaO and SiO_2 show negative correlations with MgO (Fig. 6). The MgO contents are high (>43 wt %), and the CaO and Al_2O_3 contents are low (<1 wt %), indicating the highly depleted character of the peridotites (Fig. 6), even for the metasomatized peridotites. It should be noted that the metasomatic mineral contents are <6 vol. % in the analyzed metasomatized

peridotites, except sample 629 (Table 1), and therefore their presence does not alter the primary bulk-rock major-element compositions significantly. Sample 629 contains appreciably higher amounts of metasomatic orthopyroxene and Ca-amphibole than the other samples (Table 1). The most highly metasomatized peridotite xenoliths, with more than 30 vol.% total orthopyroxene (Fig. 3), are generally small in size and unsuitable for bulk-rock analysis. The SiO_2 contents are slightly higher in the Avacha peridotites than in typical abyssal peridotites at a given MgO content (Fig. 6). There are no obvious correlations between the amount of silicic glasses and major-element concentrations in the peridotites, except for sample 629, which contains large amounts of glass and has different chemistry from the other samples (Tables 1 and 3; Fig. 6).

Primitive mantle-normalized trace-element patterns of the peridotites are shown in Fig. 7. Except for the highly metasomatized harzburgite (sample 629) (Table 1), the REE abundances are roughly one-tenth or less of the primitive mantle values (McDonough & Sun, 1995). All of the samples have similarly concave-upward REE patterns with a marked positive slope from Er to Lu, irrespective of the presence or absence of silicic glasses and metasomatic orthopyroxene (Fig. 7). Sample 629, which is rich in glass and metasomatic orthopyroxene, has abundances of some elements 10 times higher than the other peridotites (Fig. 7). There are no obvious correlations between the REE_N abundances and modal amounts of clinopyroxene (Fig. 8e–h). Almost half the peridotites are enriched in Sr relative to neighboring elements (Fig. 7b and d). Some LILE, for example, Ba, U, Th and Sr, are detectable but very low in abundance in the peridotites. All the Avacha peridotites exhibit similar REE patterns, which are almost flat or weakly concave downward, similar to those of harzburgites from various localities (e.g. McDonough & Frey, 1989; Takazawa *et al.*, 2000). Niu (2004) reported almost flat REE distribution patterns for abyssal peridotites, in which clinopyroxenes have LREE-depleted REE patterns.

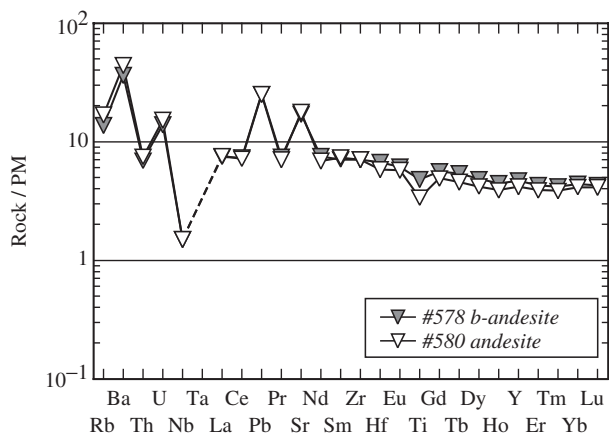


Fig. 5. Primitive mantle-normalized (McDonough & Sun, 1995) incompatible trace-element patterns in whole-rock volcanic rocks from Avacha volcano.

MINERAL AND GLASS CHEMISTRY OF THE PERIDOTITE XENOLITHS

Major-element compositions

Representative mineral and glass compositions are listed in Tables 4–6. Olivines have slightly variable Fo contents from one sample to another (90.5–92.0), but show no obvious intra-grain chemical zoning irrespective of the degree of metasomatism. Chromian spinels have high Cr-number [=Cr/(Al + Cr) atomic ratio], from 0.5 to 0.7, and low $\text{Fe}^{3+}/(\text{Al} + \text{Cr} + \text{Fe}^{3+})$ atomic ratios (<0.1). All of the peridotites from Avacha plot within the olivine–spinel

mantle array (OSMA), defining a spinel peridotite restite trend (Arai, 1994b); however, their Fo contents do not show an appreciable increase, and may even show a slightly decrease with an increase of spinel Cr-number (Fig. 9). Moreover, the SiO₂ contents in the bulk-rock peridotites have no correlation with the Cr-number of chromian spinel, although they show a weak negative correlation with the Fo contents of olivine (Fig. 8a and b). There are no obvious correlations between the modal amounts of opx II, Cr-number of spinel and Fo contents of olivine (Fig. 8c and d), although the formation of metasomatic orthopyroxene is the most prominent modal change induced by the metasomatism.

All the clinopyroxenes in the peridotite xenoliths are chromian diopsides with around 0.5 wt % Cr₂O₃ and high Mg-number [=Mg/(Mg + total Fe) atomic ratio] varying from 0.92 to 0.94 (Table 4). There are no

systematic chemical differences between the primary and metasomatic clinopyroxenes within the peridotites. The TiO₂ contents of the clinopyroxenes are extremely low (<0.10 wt %) and the contents of Al₂O₃ and Na₂O are also low (1.0–3.0 wt % and <0.5 wt %, respectively) (Table 4).

Orthopyroxenes of both primary and metasomatic origin have a relatively narrow range of Mg-number (0.91–0.93) (Table 4). All orthopyroxenes have low Al₂O₃, Cr₂O₃ and CaO contents, and opx II-1 has especially low Cr₂O₃ contents (Table 4, Fig. 10). No obvious correlations are evident between the Mg-number and Al₂O₃, Cr₂O₃ and CaO contents. It is noteworthy that opx II-2 is included in the compositional spread of the primary orthopyroxenes (Fig. 10).

All the amphiboles analyzed belong to the calcic amphibole group (Leake *et al.*, 1997), but are variable in

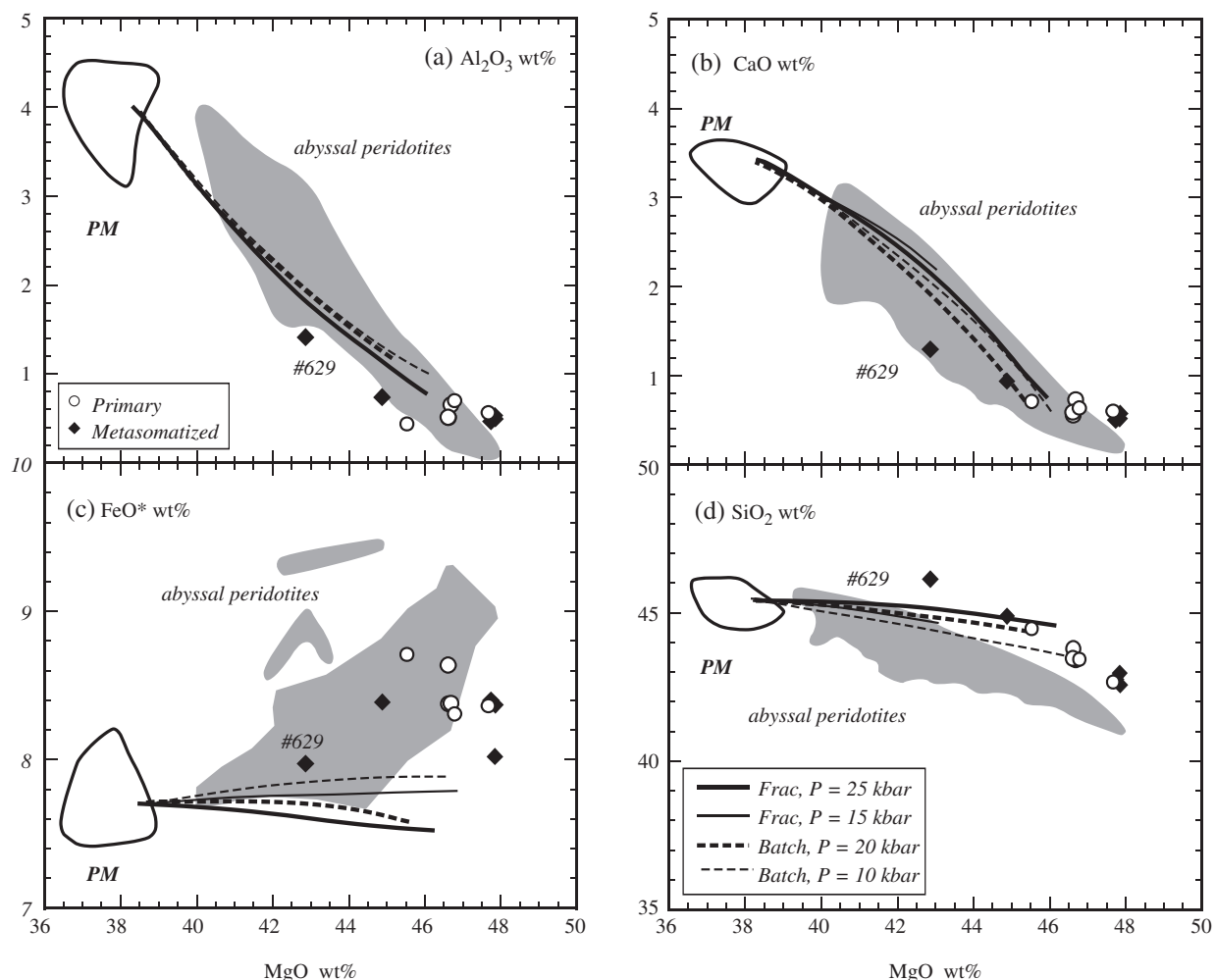


Fig. 6. Variation diagrams of major oxides vs MgO in bulk-rock peridotites. Shaded area represents the composition field of abyssal peridotites from Niu *et al.* (1997). Primitive mantle values are from the literature (McDonough & Sun, 1995, and references therein). Continuous and dashed lines represent the compositions of residual peridotites (after Niu, 1997) calculated by models of polybaric near-fractional (1 % melt porosity) melting ($P = 15$ and 25 kbar) and of isobaric batch melting ($P = 10$ and 20 kbar).

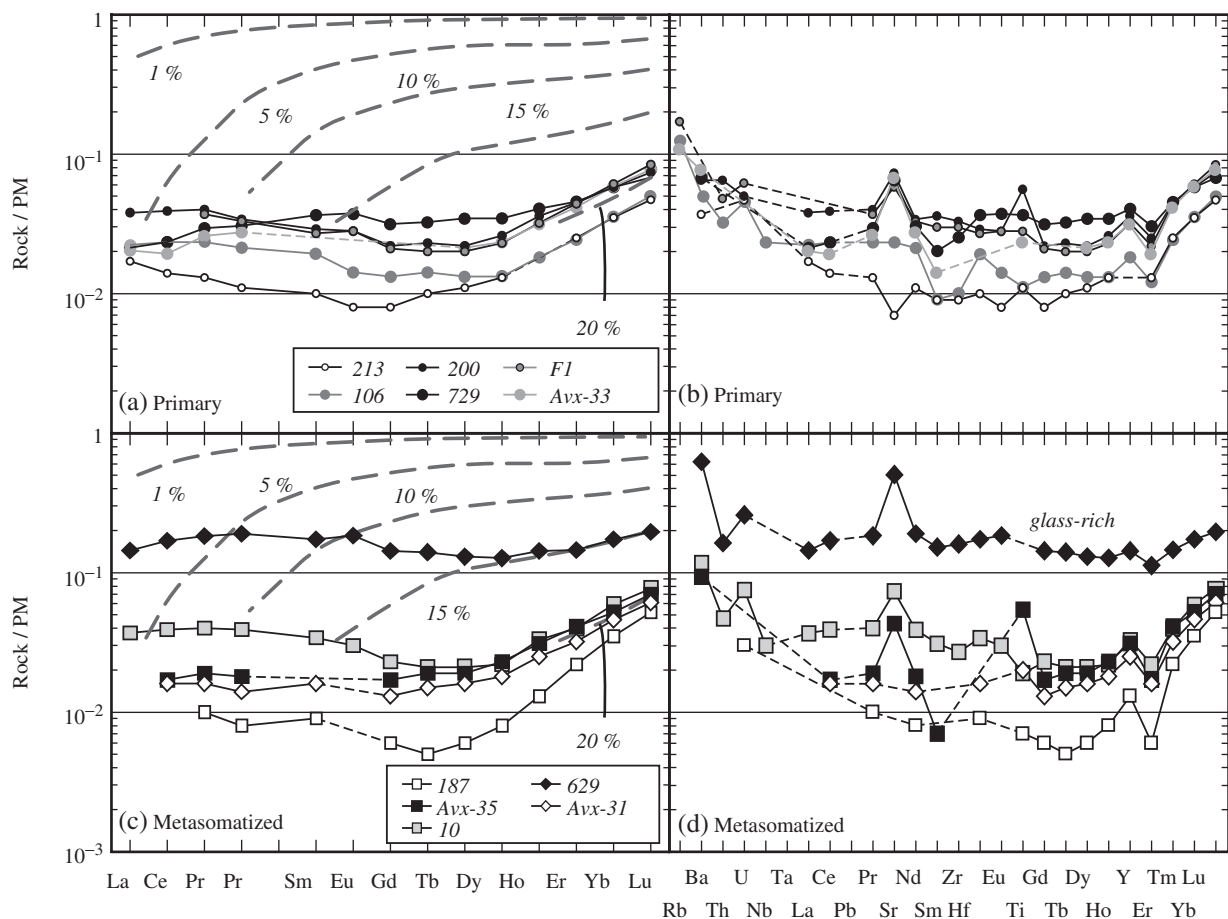


Fig. 7. Primitive mantle-normalized (McDonough & Sun, 1995) REE patterns and multi-element patterns in bulk-rock Avacha peridotites. (a) REE in primary peridotites. (b) Trace elements in primary peridotites. (c) REE in metasomatized peridotites. (d) Trace elements in metasomatized peridotites. Dashed lines with numbers (degree of partial melting) in (a) and (c) indicate calculated compositions of incremental partial melting residues of spinel peridotite from Ionov (2004).

chemistry from pargasite through edenite (primary amphibole) to magnesio-hornblende (metasomatic amphibole) (Leake *et al.*, 1997). We refer to them collectively as hornblende. They have relatively high Mg-number (0.89–0.91) and Cr_2O_3 contents (up to 2.3 wt %). The Mg-number of the hornblendes correlates positively with their TiO_2 and Al_2O_3 contents, and negatively with the Cr_2O_3 contents. The primary hornblendes are slightly higher in Al_2O_3 and TiO_2 , on average, than the metasomatic ones (Table 4).

The phlogopite in sample 375, included in a primary olivine ($\text{Fo}_{90.8}$), has a low TiO_2 content (<0.1 wt %) and relatively high Mg-number (*c.* 0.90). The $\text{Na}/(\text{Na} + \text{K})$ ratio of this phlogopite is relatively high (*c.* 0.23) and similar to those of phlogopites in spinel peridotites (Arai, 1986). The number of Si atoms recalculated on $\text{O} = 22$ (anhydrous basis) is around 5.5, indicating a significant amount of the eastonite molecule, and falls within the range of phlogopite in spinel peridotites (Arai, 1984a).

The sulfide found in the metasomatized peridotites is MSS with an Fe:Ni atomic ratio of around 2:1.

Silicate glasses, both as glass inclusions and interstitial glasses to opx II-2, have variable major-element concentrations with high SiO_2 (56–73 wt % on anhydrous basis) and Al_2O_3 (14–21 wt %) contents (Table 5). The glass inclusions in primary spinels have lower oxide totals (80–95 wt %) in microprobe analyses than the interstitial glasses (around 100 wt %) (Table 5). This result means that the former may include higher amounts of volatile components, such as H_2O . A preliminary Fourier transform infrared (FT-IR) analysis of the glass inclusions within spinels shows a broad peak around 3400 cm^{-1} , resulting from the H_2O molecule. The glass inclusions have higher SiO_2 and Al_2O_3 and lower MgO and FeO^* contents than the interstitial glasses (Table 5), exhibiting high normative quartz (up to 45 wt %) and feldspar (55–70 wt %) contents, with or without normative corundum (0–7 wt %).

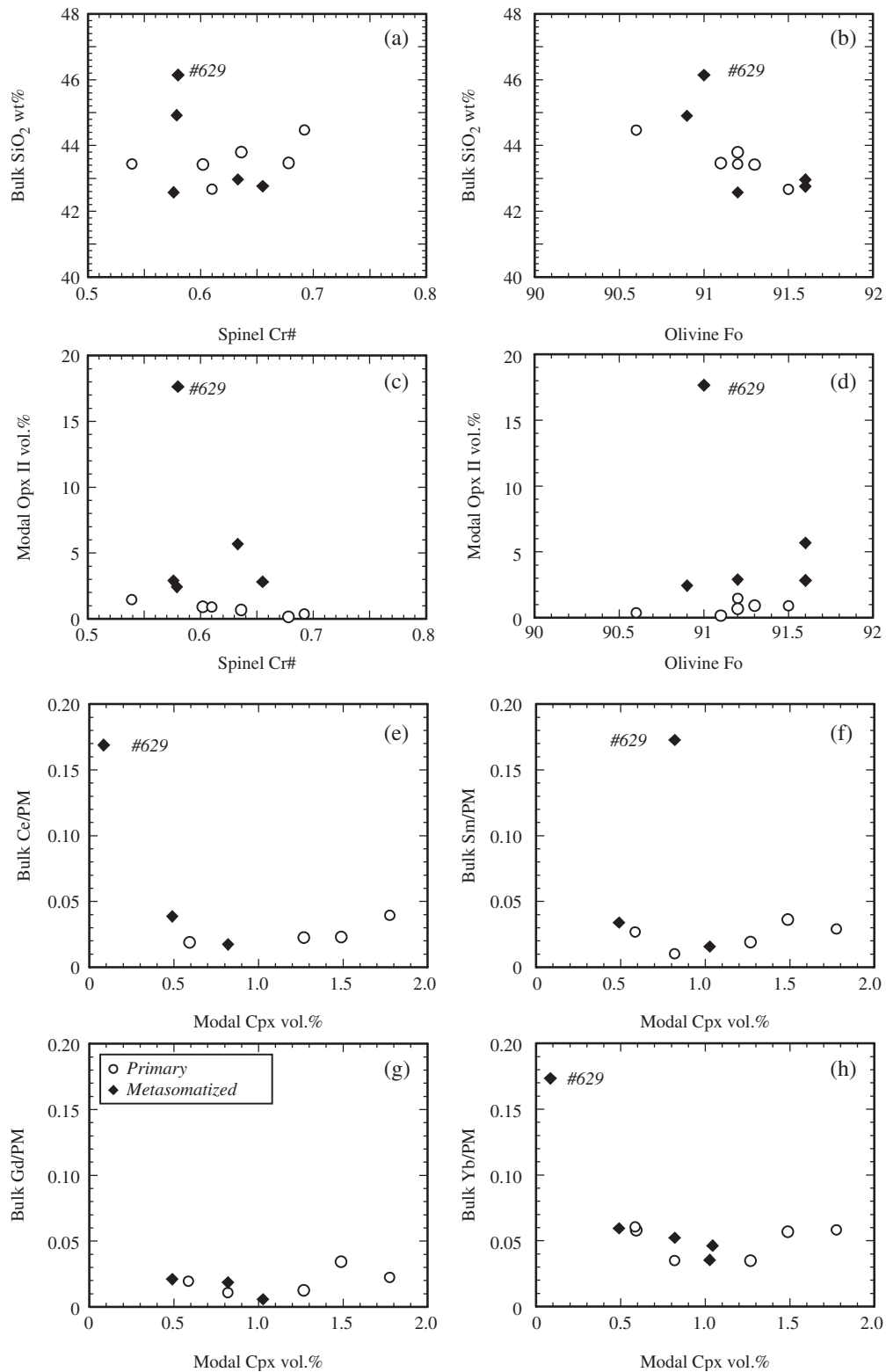


Fig. 8. Relationships between mineral compositions, modal amounts of orthopyroxene and clinopyroxene, and selected REE contents in bulk peridotites. (a) Average Cr-number of spinel vs SiO₂ wt% in bulk peridotites. (b) Average Fo contents of olivine vs SiO₂ wt% in bulk peridotites. (c) Average Cr-number of spinel vs modal amounts of opx II. (d) Average Fo contents of olivine vs modal amounts of opx II. (e)–(h) Relationships between modal amounts of clinopyroxene and REE_N concentrations in bulk peridotites.

Table 4: Representative major-element compositions of minerals in peridotite xenoliths from Avacha volcano

Primary peridotites															
No.:	213					200					F1				
Phase:	ol	sp	opx I	opx II-1	cpx I	ol	sp	opx I	cpx I	amph II	ol	sp	opx I	cpx I	amph I
SiO ₂	40.54	0.00	57.87	57.38	54.43	41.29	0.00	57.71	54.48	46.65	41.37	0.00	56.59	53.93	45.91
TiO ₂	0.00	0.02	0.00	0.00	0.01	0.00	0.06	0.05	0.11	0.30	0.00	0.02	0.01	0.10	0.47
Al ₂ O ₃	0.00	15.99	1.14	1.41	1.49	0.02	18.43	1.89	2.00	11.21	0.00	23.77	1.95	2.14	11.44
Cr ₂ O ₃	0.00	52.55	0.46	0.47	1.02	0.01	48.53	0.38	1.03	1.81	0.00	41.01	0.60	0.63	2.17
FeO*	9.21	17.91	5.85	5.95	1.97	8.32	18.13	5.56	1.80	3.63	8.75	19.20	5.60	2.44	3.85
MnO	0.06	0.34	0.08	0.09	0.04	0.12	0.24	0.14	0.03	0.05	0.12	0.24	0.12	0.07	0.06
MgO	49.25	12.86	33.74	33.99	17.07	51.00	14.07	35.04	17.28	19.53	50.86	14.98	33.90	17.51	19.51
CaO	0.03	0.01	1.13	0.61	23.02	0.06	0.00	0.80	23.45	11.92	0.04	0.00	1.57	23.24	11.83
Na ₂ O	0.00	0.00	0.02	0.01	0.20	0.00	0.00	0.01	0.24	2.22	0.00	0.01	0.00	0.22	2.34
K ₂ O	0.01	0.01	0.01	0.03	0.02	0.03	0.03	0.02	0.01	0.18	0.00	0.03	0.01	0.01	0.19
NiO	0.35	0.06	0.07	0.10	0.06	0.38	0.13	0.10	0.03	0.09	0.37	0.16	0.09	0.07	0.09
Total	99.46	99.75	100.36	100.03	99.31	101.23	100.16	101.69	100.47	97.57	101.50	99.41	100.44	100.36	97.85
Mg-no.	0.905	0.608	0.911	0.920	0.939	0.916	0.653	0.918	0.945	0.906	0.912	0.678	0.915	0.928	0.900
Cr-no.		0.688						0.639				0.537			
Y _{Cr}		0.659						0.599				0.492			
Y _{Al}		0.299						0.339				0.425			
Y _{Fe}		0.041						0.063				0.083			

Primary peridotites															
No.:	106					Avx-33					729				
Phase:	ol	sp	opx I	cpx I	amph I	ol	sp	opx I	opx II-1	cpx I	ol	sp	opx I	cpx I	
SiO ₂	41.06	0.00	58.39	54.62	46.83	41.13	0.00	57.00	57.34	54.09	40.69	0.04	56.91	54.44	
TiO ₂	0.00	0.00	0.00	0.00	0.32	0.00	0.08	0.01	0.00	0.03	0.00	0.01	0.00	0.02	
Al ₂ O ₃	0.00	17.96	1.31	1.99	11.04	0.00	20.10	1.77	1.56	2.04	0.00	16.70	1.34	1.60	
Cr ₂ O ₃	0.00	50.03	0.45	0.66	1.64	0.02	45.85	0.49	0.39	0.73	0.00	49.81	0.47	0.58	
FeO*	8.51	17.92	5.73	2.45	3.95	8.56	19.50	5.64	5.54	2.62	8.68	19.41	5.71	2.40	
MnO	0.12	0.28	0.12	0.04	0.06	0.16	0.28	0.11	0.15	0.09	0.06	0.31	0.14	0.08	
MgO	51.07	13.99	35.12	17.70	19.26	50.54	14.17	34.06	34.66	17.57	49.65	13.43	34.44	17.81	
CaO	0.05	0.00	0.52	23.65	11.62	0.11	0.00	0.89	1.01	23.16	0.05	0.02	0.75	23.20	
Na ₂ O	0.01	0.03	0.01	0.25	2.37	0.00	0.01	0.04	0.00	0.29	0.00	0.00	0.05	0.29	
K ₂ O	0.02	0.00	0.01	0.01	0.18	0.03	0.01	0.01	0.02	0.03	0.01	0.01	0.02	0.01	
NiO	0.40	0.00	0.06	0.04	0.10	0.36	0.13	0.08	0.09	0.04	0.36	0.13	0.07	0.06	
Total	101.23	100.82	101.72	101.42	97.38	100.90	100.14	100.08	100.77	100.68	99.51	99.86	99.89	100.47	
Mg-no.	0.914	0.648	0.916	0.928	0.897	0.913	0.650	0.915	0.918	0.923	0.911	0.630	0.915	0.930	
Cr-no.		0.651					0.605					0.667			
Y _{Cr}		0.614					0.559					0.620			
Y _{Al}		0.329					0.365					0.310			
Y _{Fe}		0.057					0.076					0.070			

(continued)

Table 4: Continued

Metasomatized peridotites															
No.:	10					187					Avx-35				
Phase:	ol	sp	opx I	opx II-1	cpx I	ol	sp	opx I	opx II-1	cpx I	amph II	ol	sp	opx II-2	cpx I
SiO ₂	40.66	0.00	56.70	56.54	54.06	41.41	0.00	57.64	58.28	54.86	49.58	41.35	0.00	56.39	54.14
TiO ₂	0.01	0.01	0.01	0.04	0.01	0.00	0.00	0.00	0.00	0.01	0.06	0.00	0.14	0.03	0.04
Al ₂ O ₃	0.00	21.97	1.75	1.97	1.93	0.00	22.64	1.76	1.40	1.47	9.56	0.00	19.35	1.91	1.40
Cr ₂ O ₃	0.00	44.45	0.51	0.37	0.53	0.01	46.81	0.64	0.12	0.42	1.46	0.00	49.90	0.48	0.51
FeO*	8.78	18.62	5.86	5.76	2.40	8.74	15.77	5.77	5.84	2.30	3.45	8.30	15.52	5.51	2.21
MnO	0.11	0.26	0.10	0.05	0.05	0.14	0.29	0.13	0.10	0.10	0.05	0.15	0.26	0.12	0.10
MgO	49.23	14.55	33.14	33.90	17.52	50.12	14.45	34.56	35.69	17.84	19.96	51.09	14.67	34.62	17.87
CaO	0.02	0.00	0.89	0.76	22.18	0.02	0.00	0.54	0.17	24.12	12.16	0.03	0.02	0.43	23.46
Na ₂ O	0.02	0.00	0.01	0.01	0.22	0.00	0.00	0.01	0.00	0.01	1.85	0.01	0.02	0.03	0.15
K ₂ O	0.01	0.00	0.02	0.02	0.00	0.02	0.01	0.02	0.02	0.01	0.23	0.01	0.00	0.01	0.01
NiO	0.36	0.16	0.05	0.10	0.05	0.36	0.10	0.11	0.08	0.05	0.10	0.38	0.09	0.09	0.05
Total	99.21	100.02	99.04	99.51	98.94	100.82	100.06	101.18	101.70	101.19	98.46	101.33	99.97	99.60	99.94
Mg-no.	0.909	0.662	0.910	0.913	0.929	0.911	0.657	0.914	0.916	0.933	0.912	0.916	0.673	0.918	0.935
Cr-no.		0.576					0.581						0.634		
Y _{Cr}		0.536					0.564						0.610		
Y _{Al}		0.395					0.407						0.353		
Y _{Fe}		0.068					0.029						0.037		

Metasomatized peridotites															
No.:	Avx-31					227					Avx-1				
Phase:	ol	sp	opx I	opx II-1	cpx I	ol	sp	opx I	opx II-1	cpx II	amph II	ol	sp	opx II-1	cpx I
SiO ₂	41.26	0.01	57.78	57.93	55.14	41.30	0.00	57.93	58.35	54.82	49.41	41.35	0.02	59.14	54.57
TiO ₂	0.01	0.02	0.01	0.00	0.02	0.00	0.04	0.04	0.00	0.01	0.02	0.01	0.01	0.00	0.03
Al ₂ O ₃	0.00	17.54	1.28	0.93	0.98	0.01	14.88	1.15	1.31	1.46	8.69	0.00	21.49	0.41	1.54
Cr ₂ O ₃	0.00	51.48	0.32	0.26	0.35	0.00	51.89	0.51	0.03	0.62	1.58	0.04	45.93	0.00	0.57
FeO*	8.47	16.80	5.62	5.37	1.97	7.92	19.64	5.30	5.34	2.08	3.27	8.42	17.66	5.23	2.31
MnO	0.13	0.30	0.13	0.13	0.07	0.13	0.27	0.16	0.14	0.05	0.06	0.12	0.22	0.11	0.06
MgO	51.00	13.81	35.23	35.87	17.78	50.67	13.22	34.85	35.04	18.00	20.56	50.88	14.49	36.18	17.97
CaO	0.03	0.00	0.71	0.59	23.93	0.01	0.01	1.09	0.53	23.45	11.84	0.06	0.01	0.38	23.06
Na ₂ O	0.00	0.01	0.03	0.01	0.11	0.01	0.00	0.02	0.02	0.19	2.01	0.00	0.03	0.00	0.25
K ₂ O	0.00	0.04	0.02	0.00	0.01	0.00	0.03	0.02	0.02	0.01	0.20	0.02	0.01	0.01	0.02
NiO	0.37	0.08	0.08	0.08	0.05	0.43	0.15	0.10	0.10	0.05	0.12	0.42	0.14	0.09	0.05
Total	101.26	100.08	101.20	100.69	100.41	100.483	100.124	101.152	100.886	100.746	97.752	101.31	100.001	101.54	100.413
Mg-no.	0.915	0.643	0.918	0.922	0.941	0.919	0.624	0.921	0.921	0.939	0.918	0.915	0.661	0.925	0.933
Cr-no.		0.663					0.701						0.589		
Y _{Cr}		0.636					0.650						0.556		
Y _{Al}		0.323					0.278						0.388		
Y _{Fe}		0.041					0.072						0.057		

(continued)

Table 4: Continued

Metasomatized peridotites													
No.:	629						375						
Phase:	ol	sp	opx I	opx II-2	cpx I	amph II	ol	sp	opx I	opx II-1	cpx I	amph II	phlog
SiO ₂	41.53	0.00	57.42	57.77	54.22	46.63	41.26	0.00	57.75	58.72	54.93	47.90	39.38
TiO ₂	0.02	0.11	0.00	0.02	0.17	0.33	0.00	0.03	0.01	0.00	0.00	0.82	0.05
Al ₂ O ₃	0.00	19.71	1.82	0.99	2.21	11.03	0.00	14.58	0.97	0.52	0.92	9.93	16.62
Cr ₂ O ₃	0.01	44.67	0.64	0.32	0.73	2.27	0.00	53.02	0.48	0.08	0.69	1.33	1.48
FeO*	8.81	19.41	5.68	5.27	2.78	3.95	8.35	18.73	5.60	5.48	1.74	4.59	4.20
MnO	0.16	0.30	0.13	0.14	0.12	0.05	0.14	0.29	0.15	0.12	0.06	0.07	0.00
MgO	50.89	14.09	34.65	35.46	17.89	19.29	50.37	11.79	34.35	35.13	17.65	19.17	22.79
CaO	0.02	0.04	0.77	0.94	22.37	11.68	0.02	0.01	1.20	0.35	23.47	10.87	0.03
Na ₂ O	0.00	0.00	0.01	0.02	0.31	2.29	0.00	0.00	0.00	0.02	0.16	2.33	1.44
K ₂ O	0.02	0.02	0.02	0.01	0.02	0.31	0.03	0.01	0.02	0.01	0.03	0.26	7.86
NiO	0.35	0.14	0.07	0.10	0.05	0.13	0.39	0.09	0.08	0.13	0.04	0.19	0.00
Total	101.80	98.49	101.21	101.03	100.85	97.94	100.54	98.55	100.60	100.54	99.67	97.46	93.851
Mg-no.	0.911	0.657	0.916	0.923	0.920	0.897	0.915	0.571	0.916	0.920	0.948	0.882	0.906
Cr-no.		0.603						0.709					
Y _{Cr}		0.554						0.681					
Y _{Al}		0.364						0.279					
Y _{Fe}		0.082						0.040					

Metasomatized peridotites									
No.:	59					203			
Phase:	ol	sp	opx I	cpx II	amph II	ol	sp	opx II-2	cpx II
SiO ₂	40.96	0.15	57.50	54.22	47.60	41.74	0.03	57.25	55.16
TiO ₂	0.01	0.11	0.05	0.00	0.16	0.00	0.20	0.07	0.05
Al ₂ O ₃	0.00	20.04	1.81	2.46	11.12	0.00	13.06	1.21	1.60
Cr ₂ O ₃	0.01	45.40	0.49	0.66	0.78	0.04	54.69	0.45	0.67
FeO*	8.63	18.47	5.66	2.36	3.79	9.14	18.75	5.99	2.24
MnO	0.13	0.25	0.13	0.08	0.05	0.17	0.31	0.22	0.12
MgO	50.57	13.94	34.31	17.83	19.48	50.27	13.13	34.60	18.25
CaO	0.03	0.10	1.07	22.52	11.23	0.10	0.01	0.84	21.04
Na ₂ O	0.00	0.01	0.00	0.19	2.41	0.00	0.00	0.03	0.31
K ₂ O	0.00	0.00	0.00	0.02	0.25	0.05	0.01	0.00	0.03
NiO	0.38	0.15	0.04	0.05	0.11		0.11	0.02	
Total	100.72	98.62	101.07	100.38	96.97	101.49	100.29	100.67	99.45
Mg-no.	0.913	0.650	0.915	0.931	0.902		0.623	0.911	0.936
Cr-no.		0.603					0.737		
Y _{Cr}		0.563					0.692		
Y _{Al}		0.370					0.246		
Y _{Fe}		0.067					0.061		

Blank, below detection limit. FeO*, total iron as FeO. Y_{Cr}, Y_{Al}, and Y_{Fe}, cationic ratio of Cr, Al and Fe³⁺, respectively, to (Cr + Al + Fe³⁺). I and II, primary and metasomatic, respectively.

Table 5: Representative major-element and CIPW normative compositions of glasses in metasomatized peridotite xenoliths (samples 375, 629 and 203) from Avacha volcano

Type:	I-sp						I-sp-cr	I-ol		Inter			
Sample no.:	203	203	203	375	375	375	203	203	203	629	629	203	203
SiO ₂	60.18	62.90	59.96	66.63	66.46	65.52	57.45	63.54	60.39	60.52	61.70	62.63	62.69
TiO ₂	0.24	0.13	0.20	0.11	0.03	0.07	0.53	0.39	0.42	0.19	0.20	0.46	0.44
Al ₂ O ₃	18.55	16.91	17.76	16.37	16.81	17.06	19.61	19.65	18.85	19.72	20.30	19.38	20.02
Cr ₂ O ₃	0.70	0.67	1.04	1.78	1.20	0.73	4.06	0.00	0.03	0.03	0.00	0.00	0.02
FeO*	0.73	1.19	1.08	1.07	0.88	0.92	4.07	2.11	5.69	2.70	2.75	2.28	2.26
MnO	0.12	0.00	0.13	0.00	0.02	0.01	0.05	0.08	0.09	0.05	0.13	0.09	0.09
MgO	0.15	0.31	0.30	1.15	0.57	0.51	3.41	1.36	2.02	2.35	2.49	2.17	1.96
CaO	5.85	5.40	6.00	3.05	2.63	3.55	7.04	5.69	7.22	7.65	6.91	7.02	5.95
Na ₂ O	3.39	2.32	4.01	4.90	5.78	3.96	4.49	5.30	4.43	4.78	4.99	4.74	5.33
K ₂ O	0.77	0.89	0.81	1.26	0.88	1.19	0.79	1.12	0.88	0.81	0.84	0.91	0.91
P ₂ O ₅	0.13	0.03	0.11	0.11	0.05	0.02	0.00	0.09	0.02	0.31	0.34	0.00	0.12
Total	90.80	90.75	91.39	96.43	95.30	93.54	101.49	99.31	100.04	99.11	100.64	99.67	99.78
Mg-no.	0.272	0.316	0.329	0.658	0.534	0.497	0.598	0.535	0.387	0.608	0.617	0.630	0.607
<i>Norm</i>													
ap	0.35	0.09	0.29	0.28	0.11	0.06	0.00	0.21	0.05	0.75	0.79	0.00	0.27
cm	1.13	1.09	1.68	2.72	1.86	1.15	5.90	0.00	0.04	0.05	0.00	0.00	0.03
il	0.50	0.27	0.41	0.21	0.06	0.13	0.99	0.74	0.80	0.37	0.38	0.88	0.84
or	5.02	5.77	5.22	7.69	5.45	7.52	4.59	6.64	5.20	4.85	4.95	5.36	5.39
ab	31.55	21.61	37.09	42.96	51.26	35.84	37.40	45.11	37.42	40.78	41.94	40.21	45.14
an	30.99	29.27	30.74	14.92	13.40	18.68	30.59	26.73	28.96	30.22	30.31	29.03	28.12
di	0.00	0.00	0.84	0.00	0.00	0.00	3.08	0.89	5.59	4.85	1.26	4.74	0.56
C	2.01	2.64	0.00	1.74	1.76	3.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
mt	0.31	0.38	0.43	0.32	0.28	0.29	1.20	0.66	1.71	0.82	0.88	0.72	0.71
hy	1.16	2.32	1.72	4.24	2.66	2.54	11.29	5.18	9.05	6.83	8.91	5.45	6.94
Q	27.38	36.90	22.15	25.79	23.77	31.12	6.88	13.85	11.22	10.53	10.63	13.62	12.04
Total	100.40	100.35	100.58	100.88	100.60	100.37	101.91	100.03	100.04	100.05	100.05	100.02	100.04

I-sp, glass inclusions in spinel. I-sp-cr, glass filling cracks of spinel. Inter, glass interstitial to opx Il-2. I-ol, glass inclusions in olivine. Normative compositions are calculated based on $\text{Fe}^{3+} = 0.2\%$ of total Fe. ap, apatite; cm, chromite; il, ilmenite; or, orthoclase; ab, albite; an, anorthite; di, diopside; C, corundum; mt, magnetite; hy, hypersthene; Q, quartz.

Effects of the formation of hornblende selvages

The host magma, which precipitated hornblende around the peridotite xenoliths (Fig. 2b), could have modified their chemical characteristics. To evaluate the chemical effects of the formation of the hornblende selvage, we examined a typical hornblende-coated peridotite xenolith, sample 181, in detail. Olivines have a low Fo content (Fo_{79.6}) in contact with the hornblende selvage, but rapidly become more magnesian (Fo_{91.2}), in the range of primary mantle olivines (Fo_{90.5–92.0}), 5 mm away from the hornblende selvage (Table 6). The rim of a chromian spinel grain adjoining the hornblende has been changed to magnetite with appreciable amounts of Cr₂O₃ and Al₂O₃ (9.8 wt % and 11.7 wt %, respectively), whereas the core is unaltered. Chromian spinels are also

totally intact within the interior more than 5 mm inward from the hornblende. Clinopyroxenes in and adjacent to the hornblende selvage have high TiO₂ and Al₂O₃ contents (up to 0.5 wt % and 4.5 wt %, respectively), and low Mg-number (=0.80). The hornblendes (pargasites; Leake *et al.*, 1997), forming the hornblende selvages or veins, have low Mg-number (0.70–0.77) and Cr₂O₃ contents (up to 0.2 wt %), and are rich in TiO₂ (up to 2.0 wt %) (Table 6).

Trace-element compositions

Trace-element compositions of representative minerals and glasses are listed in Table 7, and their primitive mantle-normalized REE and incompatible trace-element patterns are shown in Figs 11–15.

Table 6: Representative major-element compositions of minerals related with the hornblendite selvage in a primary peridotite, sample 181 and a metasomatized peridotite with glass, sample 59

	Olivine							Spinel									
	181-4-2	181-4-3	181-4-4	181-4-5	181-4-6	181-4-7		181-1-1	181-1-3	181-1-4	181-2-1	181-2-2	181-2-3				
	selvage contact			→				peridotite interior			selvage contact			→			peridotite interior
SiO ₂	38.99	39.39	39.69	39.99	40.99	41.30	SiO ₂	0.14	0.02	0.01	0.01	0.00	0.04				
TiO ₂	0.01	0.00	0.00	0.01	0.01	0.00	TiO ₂	5.84	1.74	4.92	0.07	0.06	0.06				
Al ₂ O ₃	0.01	0.00	0.02	0.01	0.00	0.00	Al ₂ O ₃	8.12	13.73	9.05	13.76	13.12	15.40				
Cr ₂ O ₃	0.00	0.02	0.03	0.00	0.02	0.00	Cr ₂ O ₃	0.66	24.81	6.23	52.03	54.38	50.43				
							Fe ₂ O ₃	56.04	28.42	50.03	5.03	4.78	6.08				
FeO*	20.06	16.85	13.39	10.45	8.69	8.49	FeO*	23.77	22.97	24.06	14.38	14.39	13.48				
MnO	0.30	0.22	0.19	0.16	0.12	0.13	MnO	0.26	0.31	0.27	0.25	0.28	0.25				
MgO	40.79	43.74	46.36	48.69	50.58	50.95	MgO	4.09	6.66	4.47	12.48	12.78	13.47				
CaO	0.13	0.06	0.05	0.02	0.04	0.05	CaO	0.16	0.04	0.00	0.00	0.00	0.04				
Na ₂ O	0.01	0.00	0.00	0.00	0.01	0.00	Na ₂ O	0.00	0.00	0.00	0.00	0.02	0.00				
K ₂ O	0.02	0.02	0.02	0.01	0.01	0.00	K ₂ O	0.02	0.00	0.03	0.02	0.03	0.01				
NiO	0.18	0.29	0.30	0.35	0.35	0.39	NiO	0.06	0.12	0.07	0.13	0.11	0.13				
Total	100.49	100.60	100.05	99.69	100.83	101.31	Total	99.15	98.83	99.14	98.16	99.97	99.38				
Mg	0.784	0.822	0.861	0.893	0.912	0.915	Mg	0.235	0.341	0.249	0.607	0.613	0.640				
							Cr	0.052	0.548	0.316	0.717	0.735	0.687				
							YCr	0.010	0.343	0.092	0.673	0.693	0.637				
							YAl	0.183	0.283	0.200	0.265	0.249	0.290				
							YFe	0.807	0.374	0.707	0.062	0.058	0.073				
	Clinopyroxene					Hornblende											
	181		59			181		59									
	selvage	peridotite	selvage	peridotite		selvage	interstitial	selvage	selvage	discrete	interstitial						
SiO ₂	52.63	54.57	51.55	54.22	SiO ₂	40.19	45.97	42.81	42.52	47.14	47.06						
TiO ₂	0.26	0.01	0.51	0.00	TiO ₂	1.83	0.22	1.79	1.90	0.23	0.08						
Al ₂ O ₃	2.97	2.35	4.52	2.46	Al ₂ O ₃	13.93	10.93	13.12	13.87	11.01	10.65						
Cr ₂ O ₃	0.57	0.64	0.04	0.66	Cr ₂ O ₃	0.02	2.05	0.17	0.03	0.96	2.22						
FeO*	6.16	2.62	6.58	2.36	FeO*	10.56	3.67	10.64	8.43	3.82	3.74						
MnO	0.13	0.13	0.14	0.08	MnO	0.10	0.06	0.11	0.10	0.06	0.06						
MgO	15.72	17.74	14.70	17.83	MgO	14.08	19.05	14.63	16.08	19.44	19.18						
CaO	21.17	22.16	22.07	22.52	CaO	11.54	11.24	11.35	11.41	11.62	11.13						
Na ₂ O	0.29	0.28	0.32	0.19	Na ₂ O	2.48	2.51	2.60	2.74	2.41	2.31						
K ₂ O	0.01	0.01	0.01	0.02	K ₂ O	0.27	0.34	0.25	0.24	0.35	0.29						
NiO	0.02	0.06	0.02	0.05	NiO	0.01	0.10	0.02	0.04	0.12	0.10						
Total	99.92	100.57	100.45	100.38	Total	95.01	96.15	97.49	97.35	97.16	96.81						
Mg-no.	0.820	0.923	0.799	0.931	Mg-no.	0.704	0.903	0.710	0.773	0.901	0.901						

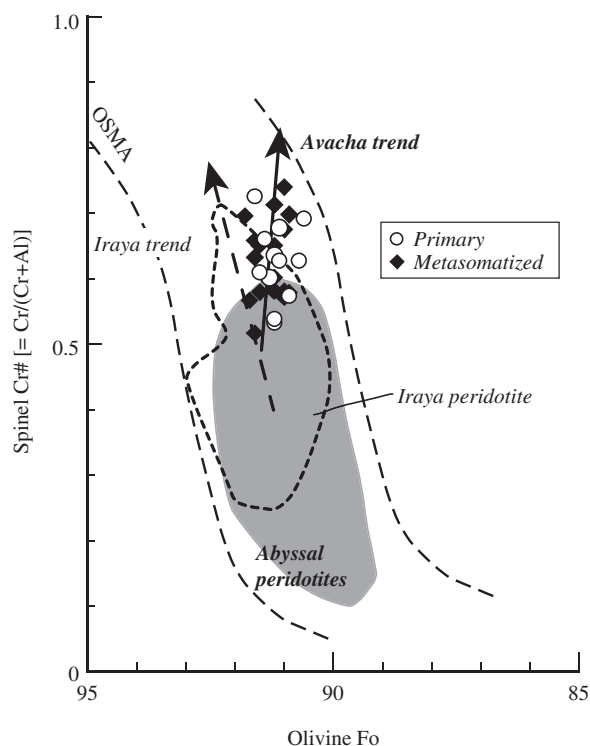


Fig. 9. Relationships between the Fo contents of olivine and Cr-number of chromian spinel in Avacha peridotite xenoliths. OSMA (olivine-spinel-mantle array) represents the residual trend of spinel peridotites (Arai, 1994b). Shaded area represents abyssal peridotites (Arai, 1994b). Short-dashed line encircles the compositional range of coarse-grained peridotites from Iraya volcano, the Luzon Arc, Philippines (Arai & Kida, 2000). The residual trend for the Iraya peridotites (dashed line with arrowhead) is different from that for the Avacha peridotites (continuous line with arrowhead).

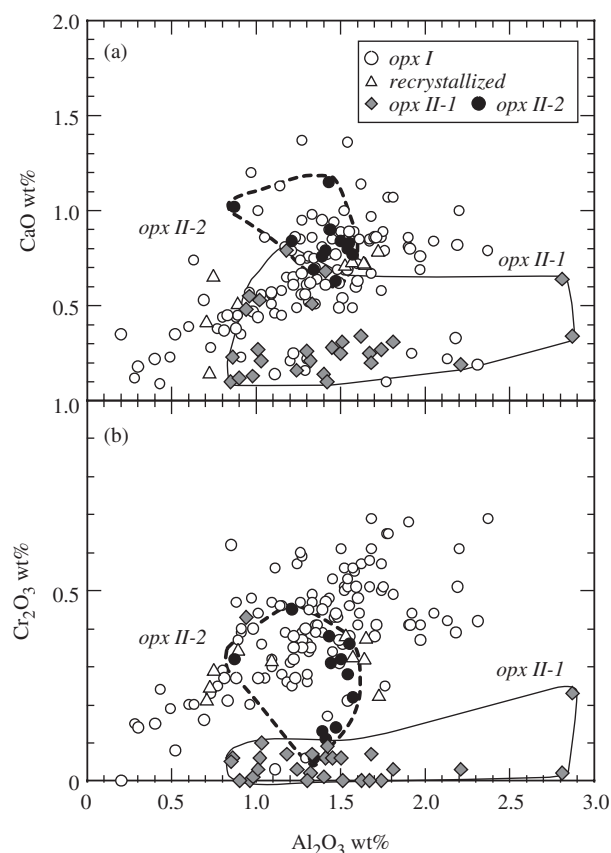


Fig. 10. Major-element chemical variations in orthopyroxene. (a) Al_2O_3 wt% vs CaO wt%. (b) Al_2O_3 wt% vs Cr_2O_3 wt%. The difference between the two types of metasomatic orthopyroxenes (opx II-1 and opx II-2), as well as the similarity between opx II-2 and opx I, should be noted.

Clinopyroxene

Almost all the clinopyroxenes in the peridotites have similar heavy REE (HREE) abundances although the LREE to middle REE (MREE) patterns exhibit sample-by-sample variations (Fig. 11a and b). They show clear depletion in Zr and Ti relative to adjacent elements in the primary peridotites, and there are no such spikes in clinopyroxenes from the metasomatized peridotites (Fig. 11a and b). The discrete clinopyroxenes both in the primary and metasomatized peridotites have LREE-depleted, HREE-enriched patterns, and MREE are below detection limits in most of them (Fig. 11a and b).

Metasomatic clinopyroxenes within a metasomatically formed orthopyroxene vein in the highly metasomatized peridotite (sample 227) are extremely enriched in LREE, LILE, Zr and Hf relative to other clinopyroxenes (Figs 11 and 12a). Discrete or coarsened lamellar clinopyroxenes in sample 227, located far from the orthopyroxene vein, have slightly lower concentrations than

those in the orthopyroxene vein, although these are higher than the primary clinopyroxenes from the other samples (Figs 11 and 12a).

Orthopyroxene

REE concentrations in orthopyroxenes are low, and only La, Ce and the HREE were above detection limits (Fig. 13). The trace-element patterns have gentler slopes from MREE to HREE for opx II-2 than for the primary orthopyroxenes (Fig. 13a and c). On the other hand, almost all the REE are below detection limits in opx II-1 (Fig. 13b). HREE abundances are almost the same for all orthopyroxenes, although MREE contents are slightly variable. LREE concentrations are very different between the metasomatic orthopyroxenes, especially those in sample 227, and the primary orthopyroxene (Figs 12b and 13). Both orthopyroxenes, primary and metasomatic, observed in sample 227 exhibit especially high concentrations of LILE (Ba, Th and U), Zr and Hf relative to

Table 7: Representative trace-element compositions (ppm) of minerals in peridotite xenoliths from Avacha volcano

	Clinopyroxene										
	primary						lamellar		in opx II-1 vein		
	106-24-1	200-3	200-21	375-6	375-18	227-14	375-1	227-1	227-21	227-18	227-19
Sc	99.5	52.1	55.9	81.9	78.3	75.7	97.1	78.1	67.8	44.1	62.8
Ti	199	440	512	96.2	81.7	75.8	80.3	103	104	69.7	87.0
V	218	203	196	176	173	114	120	156	186	110	147
Cr	4556	9848	8644	6067	5875	4217	3521	6160	1810	3509	4863
Co	23.3	23.8	26.2	21.7	20.9	67.3	24.8	25.4	23.8	39.0	28.9
Ni	441	392	432	364	351	1544	322	436	608	613	485
Rb							0.265				
Sr	11.04	1.63	6.24	1.84	1.80	9.26	6.21	15.9	38.5	11.2	17.2
Y	1.44	1.33	1.98	0.761	0.666	0.696	0.843	0.791	1.37	0.488	0.691
Zr	0.986	0.307	0.918	0.670	0.563	3.43	1.76	5.71	25.2	3.55	5.02
Nb		0.047	0.063	0.045	0.038	0.055	0.046	0.057	0.030	0.037	0.073
Cs											
Ba	0.138	0.285	0.667	0.080	0.055	0.319	5.66	0.037	0.054	0.127	0.597
La	0.101	0.060	0.082	0.027	0.034	0.634	0.110	0.836	3.25	0.577	0.864
Ce	0.470	0.116	0.328	0.077	0.075	1.06	0.320	1.69	7.68	1.27	1.82
Pr	0.082	0.016	0.068	0.013	0.013	0.092	0.056	0.144	0.648	0.105	0.150
Nd	0.506		0.334			0.273	0.246	0.385	1.65	0.293	0.450
Sm	0.174						0.082		0.210		
Eu			0.052						0.090		0.028
Gd	0.201		0.157				0.083		0.186		
Tb	0.054		0.035						0.024		
Dy	0.187	0.185	0.307	0.106	0.095		0.101	0.121	0.179	0.069	
Ho	0.060	0.051	0.084	0.027	0.026		0.036	0.026	0.047	0.023	0.024
Er	0.150	0.218	0.259	0.105	0.098	0.112	0.106	0.097	0.158	0.064	0.082
Tm		0.037	0.044	0.019	0.022	0.022	0.020	0.022	0.032		0.018
Yb	0.282	0.290	0.355	0.166	0.136	0.153	0.203	0.182	0.259	0.103	0.143
Lu	0.041	0.044	0.049	0.028		0.028	0.026	0.030			0.023
Hf							0.069	0.156	1.12	0.083	0.120
Ta											
Pb		2.16	1.89	1.26	1.68	3.70	1.57	2.40	2.85	4.38	2.94
Th								0.045	0.224	0.034	0.052
U						0.035		0.032	0.089		0.030

	Orthopyroxene								
	opx I				opx II-1	opx II-1	opx II-2	opx II-1 vein	
	Avx1-7-2	106-2-1	200-10-3	227-3-1	Avx1-7-5	Avx1-7-10	203-1	227-1-1	227-5-1
Sc	28.0	27.9	20.5	17.0	12.7	17.0	23.324	8.39	6.22
Ti	33.8	29.2	205	49.5	76.0	27.7	190.200	34.4	22.6
V	92.0	94.4	91.8	55.8	68.6	57.4	59.263	40.5	32.9
Cr	3758	3833	3988	2789	155	1661	2843	387	728
Co	53.7	54.4	53.4	58.3	62.5	52.6	55.7	60.9	59.3
Ni	605	625	617	784	878	576	700	763	701
Rb							0.046		
Sr	0.193	0.057	0.262	0.077	0.034		0.648	0.141	0.037
Y	0.046	0.043	0.150	0.052	0.069	0.018	0.237	0.122	0.057
Zr	0.017	0.034	0.072	0.112	0.428	0.025	0.188	1.29	1.40
Nb	0.017	0.030	0.025	0.024		0.008	0.017	0.008	0.008
Cs									
Ba	0.117	0.052	0.099	0.150	0.020		0.407	0.280	0.075
La			0.004	0.006			0.005	0.016	0.011
Ce	0.008		0.014	0.016	0.008		0.020	0.042	0.022
Pr								0.005	
Nd							0.017		
Sm									
Eu									
Gd							0.014		
Tb							0.004		
Dy							0.027		
Ho			0.005				0.008		
Er			0.023				0.032	0.016	
Tm	0.006		0.008				0.007	0.004	
Yb	0.052	0.038	0.071	0.031	0.034		0.053	0.046	
Lu	0.010	0.009	0.013	0.006	0.006		0.011	0.009	0.004
Hf								0.033	0.030
Ta									
Pb	0.170	0.168		0.092			0.251	0.062	0.064
Th				0.015				0.022	0.063
U				0.011				0.009	0.015

(continued)

Table 7: Continued

	Hornblende								Glass		
	selvage		discrete		interstitial			in opx II-1 vein		interstitial (with opx II-2)	
	59-1-3	106	200-10-2	106-12-2	200-6-1	59-6-1	227-1-1	227-1-2		203-1	203-2
Sc	117	91.1	50.4	104	38.7	70.4	64.0	42.8	Sc	12.4	23.1
Ti	13637	2047	6719	2231	3225	1579	242	580	Ti	1626	3062
V	788	571	374	589	341	304	230	349	V	87	158
Cr	225	10080	646	11823	3062	9036	8087	840	Cr	1077	293
Co	62.7	39.2	40.9	39.6	41.2	39.1	33.5	40.2	Co	37.7	11.3
Ni	89.5	851	879	902	971	891	1001	1031	Ni	684	81
Rb	0.549				0.659	0.459	0.184	0.449	Rb	18.742	11.509
Sr	166	53.9	95.0	54.9	124	76.4	16.7	78.5	Sr	188.3	343.0
Y	17.3	6.74	14.5	8.06	9.87	4.36	1.055	2.76	Y	5.694	8.00
Zr	10.2	7.81	12.1	9.22	20.2	8.92	10.6	79.4	Zr	25.7	31.1
Nb	0.206	0.190	0.287	0.197	0.461	0.224	0.648	2.12	Nb	0.696	0.46
Cs									Cs	0.769	0.893
Ba	49.7	10.7	24.2	12.2	31.2	15.7	15.0	64.8	Ba	153.1	201.9
La	0.389	0.366	0.591	0.388	1.27	0.521	1.51	4.95	La	3.08	2.57
Ce	2.03	1.94	3.20	2.06	5.59	2.35	2.82	14.8	Ce	5.56	6.9
Pr	0.545	0.388	0.697	0.504	1.07	0.467	0.218	1.58	Pr	0.828	1.04
Nd	4.18	2.62	4.83	3.12	6.12	2.49	0.591	4.79	Nd	3.569	5.05
Sm	2.04	0.907	1.85	1.08	1.75	0.760		0.545	Sm	0.882	1.232
Eu	0.760	0.311	0.719	0.317	0.625	0.326	0.036	0.320	Eu	0.273	0.454
Gd	3.02	1.13	2.54	1.47	1.76	0.763	0.076	0.399	Gd	0.924	1.556
Tb	0.505	0.177	0.413	0.215	0.261	0.104		0.055	Tb	0.152	0.231
Dy	3.34	1.24	2.87	1.49	1.72	0.872	0.141	0.416	Dy	0.945	1.498
Ho	0.742	0.270	0.593	0.348	0.379	0.168	0.031	0.086	Ho	0.186	0.287
Er	1.91	0.796	1.54	0.949	0.977	0.511	0.145	0.307	Er	0.530	0.839
Tm	0.224	0.131	0.220	0.112	0.159	0.073	0.025	0.048	Tm	0.089	0.125
Yb	1.60	0.853	1.49	0.941	1.15	0.545	0.222	0.424	Yb	0.539	0.811
Lu	0.226		0.185	0.182	0.145	0.081	0.047	0.087	Lu	0.089	0.113
Hf	0.554	0.370	0.530	0.458	0.760	0.348	0.318	2.13	Hf	0.694	0.77
Ta					0.031		0.051	0.222	Ta	0.066	0.032
Pb	0.280				0.472			0.370	Pb	2.310	2.926
Th							0.041	0.366	Th	0.576	0.257
U								0.173	U	0.268	0.109

Blank, below detection limit.

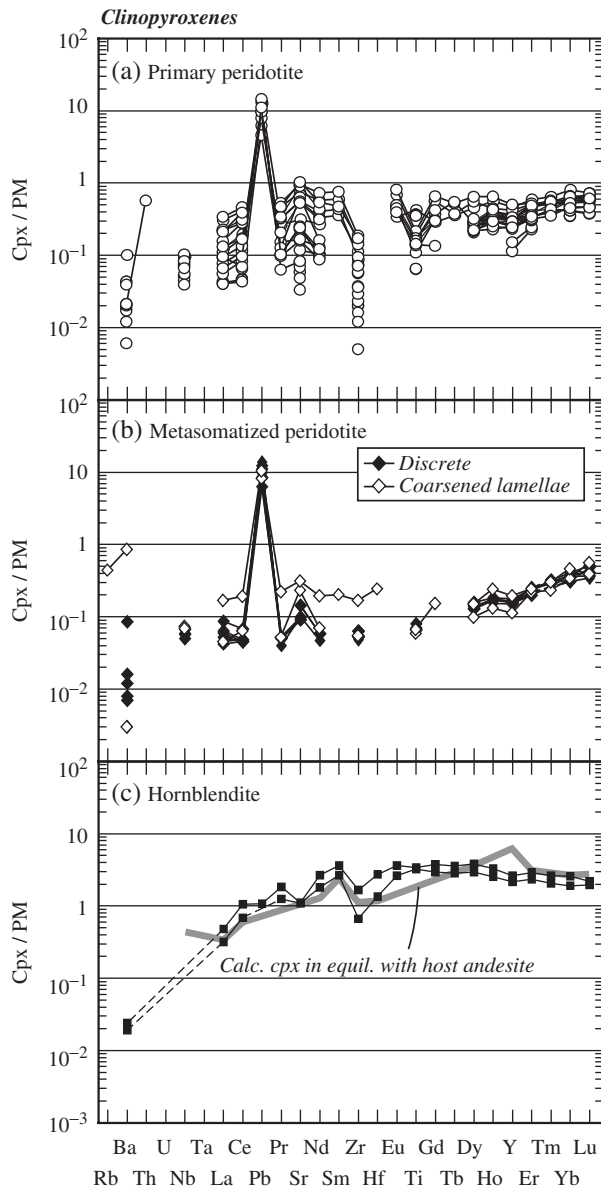


Fig. 11. Primitive mantle-normalized (McDonough & Sun, 1995) trace-element patterns of clinopyroxenes. (a) Primary clinopyroxenes in primary peridotite. (b) Primary and coarsened lamellar clinopyroxene, associated with recrystallized orthopyroxene, in metasomatized peridotites. (c) Clinopyroxene in hornblende selvage. Thick gray line shows calculated abundances for clinopyroxenes in equilibrium with the basaltic andesite and andesite (samples 578 and 580), using the partition coefficients of Fujimaki *et al.* (1984).

primary orthopyroxenes in the other samples (Fig. 12b). The trace-element patterns are variable for the metasomatic orthopyroxenes, which do not always have high trace-element concentrations (Figs 12b and 13). Compared with the other samples, the trace-element concentrations of orthopyroxene of sample 227 are as distinctive as its clinopyroxene chemical characteristics.

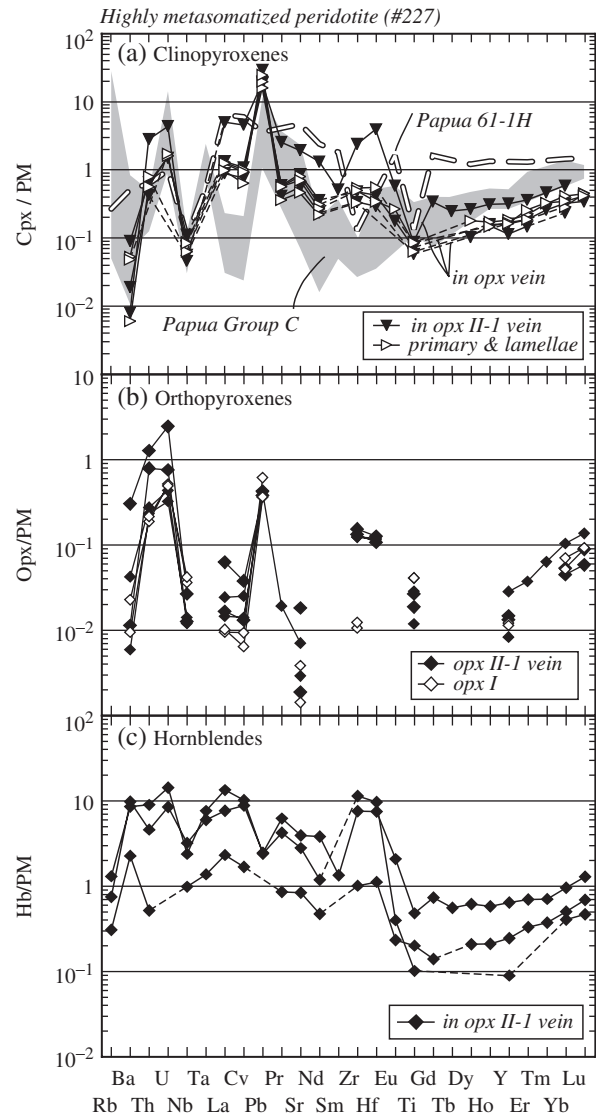


Fig. 12. Primitive mantle-normalized (McDonough & Sun, 1995) trace-element patterns of minerals in a highly metasomatized peridotite, sample 227 (Fig. 4c and d). (a) Clinopyroxenes. The white-dashed line and shaded area are for metasomatized peridotites from Papua New Guinea (Grégoire *et al.*, 2001): the most metasomatized peridotite (61-1H) and moderately metasomatized peridotites (Group C), respectively. (b) Orthopyroxenes. (c) Hornblende.

Hornblende

Primitive mantle-normalized trace-element patterns of hornblende are shown in Figs 12c and 14. They are almost the same as those of clinopyroxene (Figs 11 and 12). The hornblende has basically the same trace-element patterns but with different abundances. The primary hornblende has distinctly lower (LREE/HREE)_N ratios than the selvage hornblende, although the patterns are very similar (Fig. 14). The metasomatic hornblende in

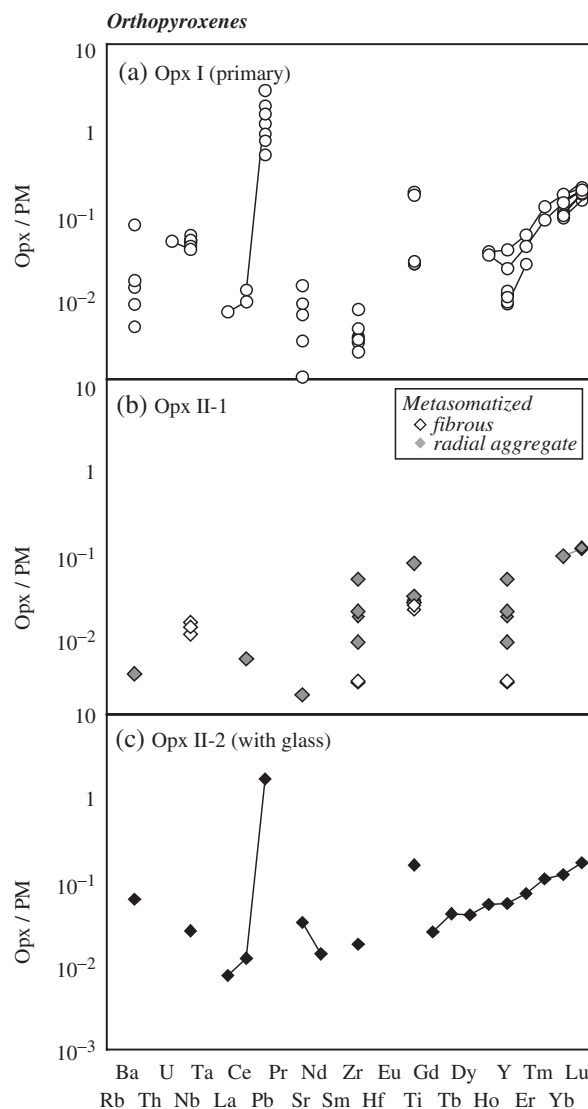


Fig. 13. Primitive mantle-normalized (McDonough & Sun, 1995) trace-element patterns of orthopyroxenes. (a) Primary orthopyroxene (opx I). (b) Metasomatic orthopyroxene (opx II-1). Gray and open diamonds are orthopyroxenes replacing olivine and forming radial aggregates, respectively. (c) Metasomatic orthopyroxenes (opx II-2) with glass.

the orthopyroxenite vein of sample 227 is rich in LILE, LREE, Zr and Hf and depleted in MREE (Fig. 12c). It is strikingly lower in HREE concentrations than the other hornblendes, which have patterns with gentle negative slopes from MREE to LREE and flat floors from MREE to HREE (Figs 12c and 14).

Inclusions

We examined the trace-element abundances of minute melt or fluid inclusions, which are embedded in olivine porphyroclasts (see Fig. 4h). We analyzed the inclusion-rich

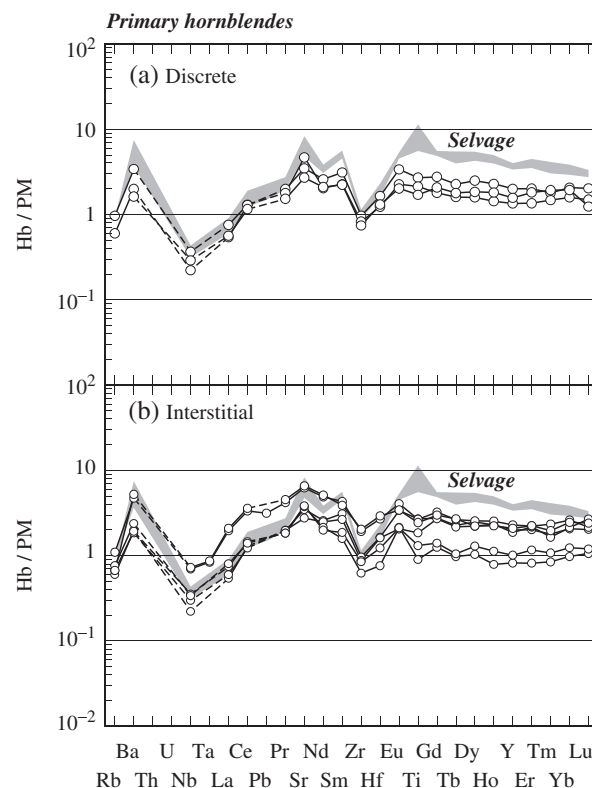


Fig. 14. Primitive mantle-normalized (McDonough & Sun, 1995) trace-element patterns of primary hornblendes in primary peridotites. (a) Discrete hornblende. (b) Interstitial hornblende. Shaded area shows the composition of the selvage hornblende.

parts of olivine and inclusion-free parts as their background (Fig. 15a). Although the nominal trace-element abundances were far lower than the real ones in the inclusions, because of dilution by the background olivine, we found enrichment of Ba, Ce, Sr, Zr, Ti and Y in the inclusions relative to olivine (Fig. 15b).

Glass

The silicic glasses interstitial to opx II-2 (Fig. 4e–g) have trace-element patterns with LILE and LREE enrichment (Fig. 15c). The $(La/Yb)_N$ ratios are not so high (2.16–3.88), and the patterns are notably similar to those of the Avacha volcanic rocks (Fig. 5).

Mineral chemical correlations

The Cr-number values of spinels show positive correlations with the Ce_N and Sm_N contents of clinopyroxenes in the primary peridotites (Fig. 16a and c), and a weak negative correlation with Yb_N (Fig. 16e). On the other hand, there are no obvious correlations between the REE_N of primary clinopyroxenes and the Fo content of olivines (Fig. 16b, d and f). As shown in Fig. 17, the Avacha

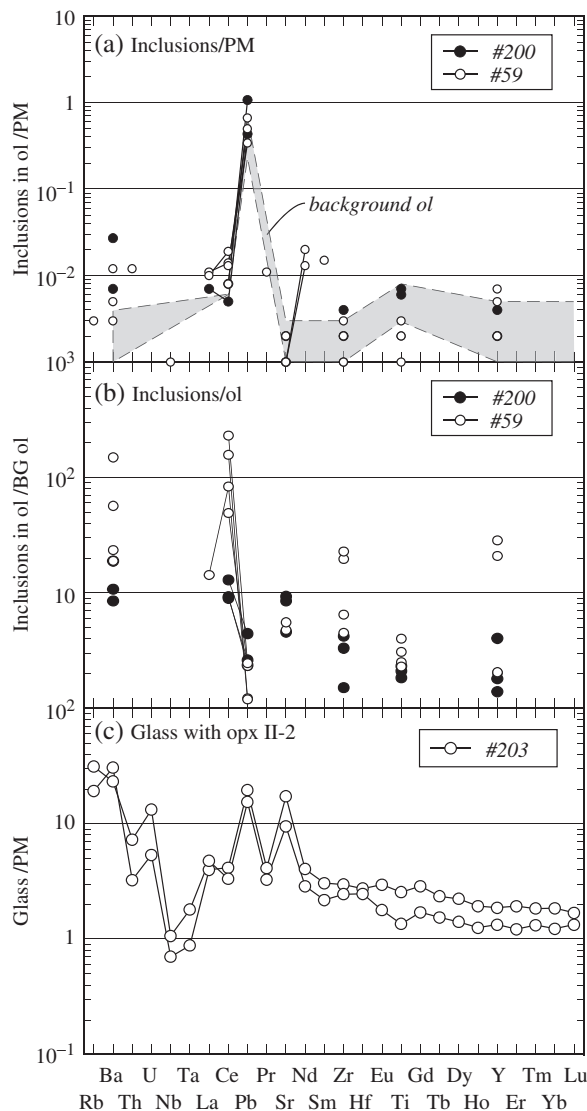


Fig. 15. Trace-element characteristics of fluid or melt inclusions embedded in olivine porphyroclasts and interstitial silicic glasses associated with opx II-2. (a) Fluid or melt inclusions normalized to the primitive mantle (McDonough & Sun, 1995). Analysis was made on the inclusion-rich domain of olivine (see Fig. 4g and h). Dashed lines indicate concentrations of the elements from the inclusion-free olivine domain as a background. It should be noted that LILE and LREE were detectable from the inclusions. (b) Fluid or melt inclusions normalized to background olivine. The high concentrations of Ce in inclusions relative to background olivines should be noted. (c) Silicic glasses normalized to the primitive mantle (McDonough & Sun, 1995). The similarity in pattern to the Avacha volcanics (Fig. 5) should be noted.

peridotites also show high concentrations of Ce in clinopyroxene relative to the trend of abyssal peridotite data defined by Hellebrand *et al.* (2001).

HREE_N contents of orthopyroxene are positively correlated with the Fo content of olivine in the primary peridotites, with and without glasses, but have negative correlations with the Cr-number of spinel (Fig. 16g–i).

Minerals in the hornblende selvage

Trace-element concentrations of minerals within the hornblende selvage are different from those of the peridotite minerals (Figs 11c and 14). The primitive mantle-normalized trace-element pattern of the clinopyroxene within the hornblende selvage is slightly LREE-depleted and flat from MREE to HREE (Fig. 11c). The selvage clinopyroxene has a similar trace-element pattern to some of the primary clinopyroxenes, but the abundances are very different, especially for HREE (3–4 times higher in the former) (Fig. 11c). This is very different from the metasomatic clinopyroxene in the highly metasomatized peridotite (sample 227) (Fig. 12c). Pargasite in the hornblende selvage has almost the same trace-element pattern as the primary hornblende in the peridotites, although the trace-element abundances are different, especially for HREE (Fig. 14).

Thermobarometry

The two-pyroxene thermometer of Wells (1977) yields similar ranges of equilibrium temperature for the primary peridotites (900–1046°C) and the metasomatized peridotites (890–1100°C) (see Appendix B). We also calculated equilibrium temperatures using the geothermometers of Ballhaus *et al.* (1991) and Nimis & Taylor (2000), and the values do not show great differences (see Appendix B). Equilibrium pressures were not calculated because of the lack of appropriate barometers. Arai *et al.* (2003a) favoured conditions in the spinel lherzolite stability field for a highly metasomatized fine-grained peridotite (not discussed in this study) that contains a low-Cr-number (<0.2) spinel. We found composite xenoliths of fine-grained and coarse-grained peridotites (Ishimaru & Arai, in preparation), indicating that the coarse-grained peridotites, discussed here, also originated from the spinel lherzolite field.

The redox state of the Avacha peridotites was calculated using the oxygen geobarometer of Ballhaus *et al.* (1990, 1991). The calculated oxygen fugacity assuming $P=1.5$ GPa is high in both primary peridotites [$\Delta\log(fO_2)_{FMQ}=-0.2$ to $+1.2$], and metasomatized peridotites [$\Delta\log(fO_2)_{FMQ}=0$ to $+1.5$]. The Avacha primary peridotites are distinctly more oxidized than abyssal peridotites [$\Delta\log(fO_2)_{FMQ}=-2.5$ to $+0.5$; Bryndzia & Wood, 1990], and are similar in redox state to other sub-arc mantle peridotite xenoliths (Brandon & Draper, 1996; Blatter & Carmichael, 1998; Arai *et al.*, 2006).

GRAIN-BOUNDARY CHEMISTRY

We examined *in situ* incompatible trace-element concentrations along olivine grain boundaries of the primary

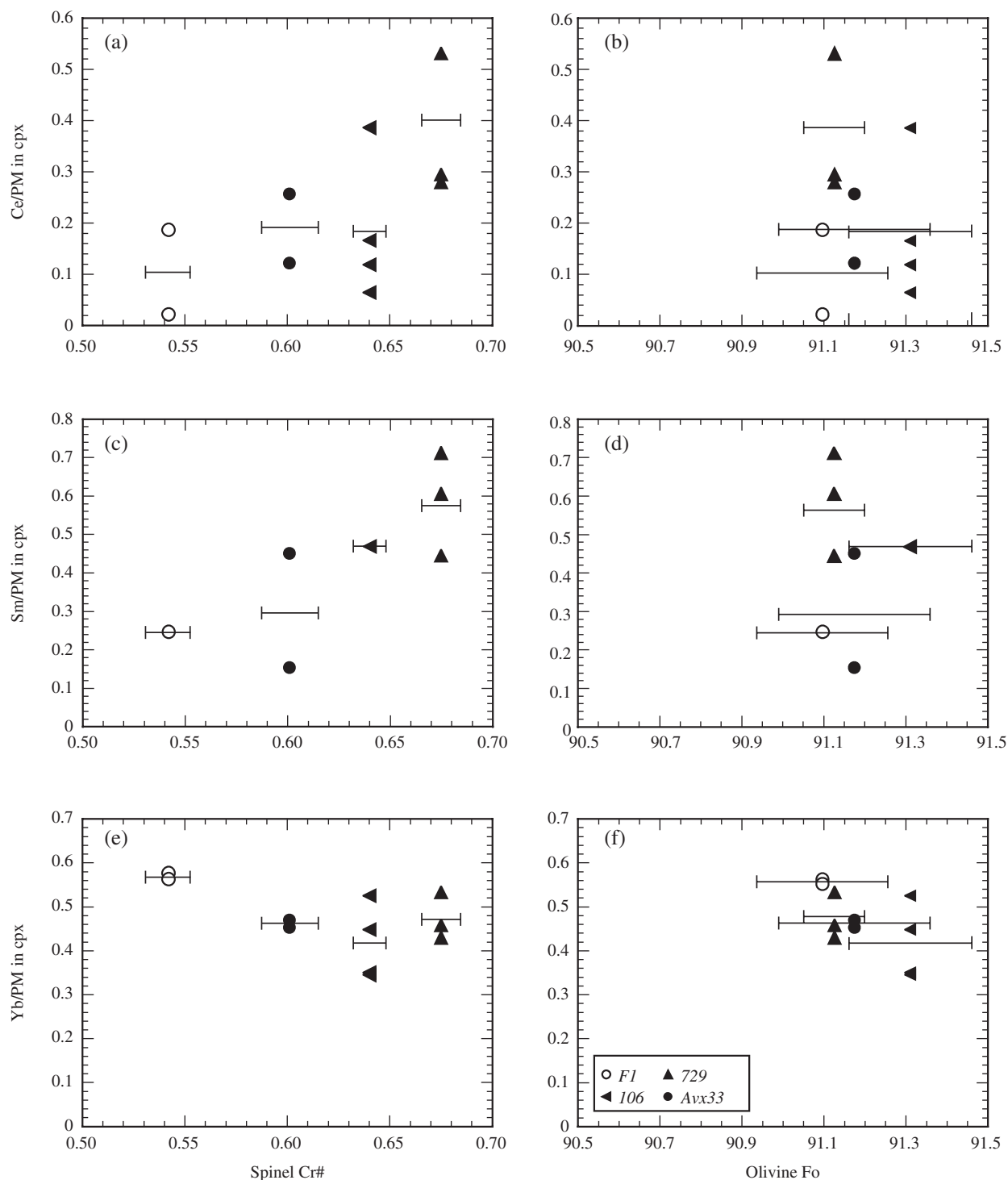
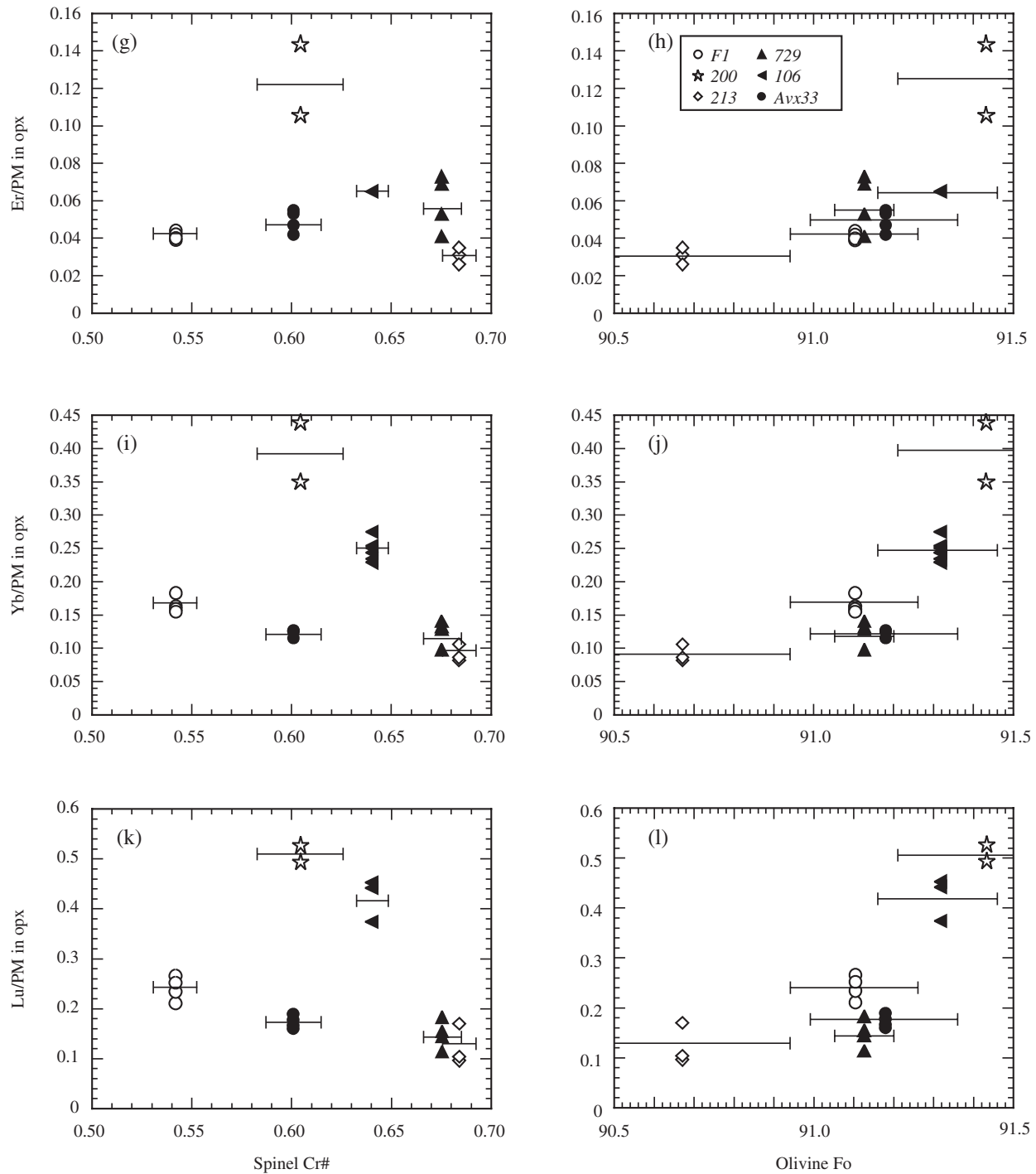


Fig. 16. Relationships between trace-element characteristics of pyroxenes and major-element compositions of olivine and chromian spinel in primary peridotites. Error bars show ranges for $\pm 1\sigma$. (a), (c) and (e), Cr-number of spinel vs Ce_N , Sm_N and Yb_N in clinopyroxene, respectively. (b), (d) and (f), Fo contents of olivine vs Ce_N , Sm_N and Yb_N in clinopyroxene, respectively. (g), (i) and (k), Cr-number of spinel vs Er_N , Yb_N and Lu_N in orthopyroxene, respectively. (h), (j) and (l), Fo contents of olivine vs Er_N , Yb_N and Lu_N in orthopyroxene, respectively. Symbols are shown in (f) for (a)–(f), and in (h) for (g)–(l).

**Fig. 16.** Continued.

peridotites by LA-ICP-MS. As described by Suzuki (1987) and Hiraga *et al.* (2002, 2003, 2004), incompatible trace elements are frequently concentrated on grain boundaries. We made chemical profiles across and along grain boundaries (Fig. 18a) to detect *in situ* concentrations,

if any, relative to background olivine. We designed four line traverses to enhance the sensitivity of the ICP-MS and sampling precision of the grain-boundary components; one was just along the grain boundary, another was across the boundary, and the other two were on both

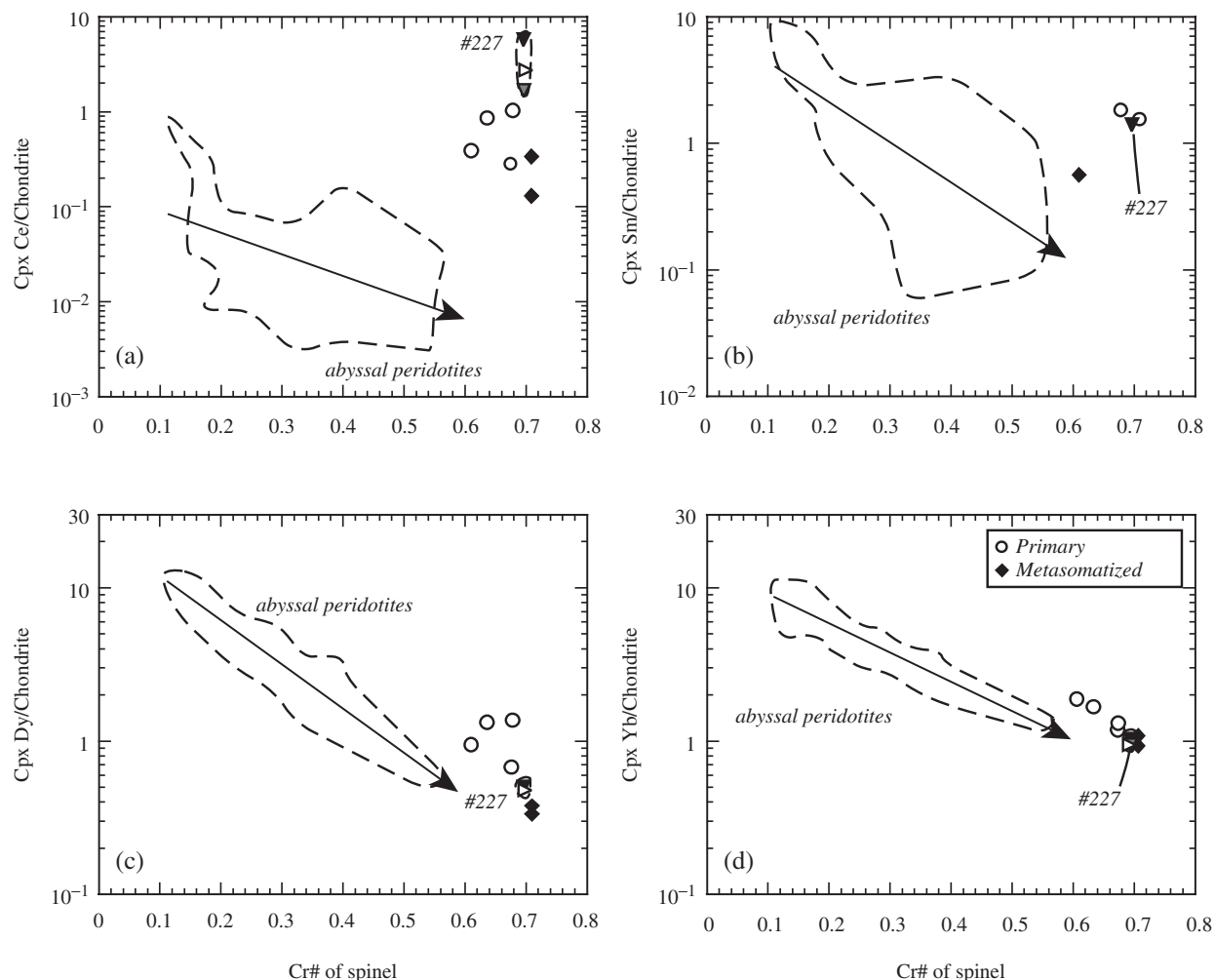


Fig. 17. Relationships between Cr-number of spinel and chondrite-normalized concentrations of Ce, Sm, Dy and Yb in clinopyroxene. Dashed line encloses the field for abyssal peridotites, and the continuous arrowed line denotes a residual trend of fractional melting (Hellebrand *et al.*, 2001).

sides of the olivine parallel to the grain boundary (see Fig. 18a). The energy of laser ablation for this analysis was 12 Hz and 8 J/cm² and the scan speed was 5 µm/s to avoid penetration of the laser beam through the thin section into the epoxy resin or bottom glass slide. We could recognize such penetration by monitoring elements such as Li and B, which are highly concentrated in the glass and resin, respectively. The analytical conditions were set so as to avoid the laser beam penetrating the thin section (<30 µm in thickness) to the resin and bottom glass slide. It took 26–30 s, equivalent to 130–150 shots, to reach the resin when the energy of laser ablation was 5 Hz and 8 J/cm². We then took 120 shots (about 24 µm sampling depths) at each point in our grain-boundary line analysis with high resolution. The length of each traverse depends on the texture, but was normally 200 µm. As we used a 50 µm laser beam, an analysis on each point (Fig. 18a) was

representative of a circular area with a radius of 25 µm around the point. Another advantage of using such a wide beam is to collect signals even from grain boundaries oblique to the thin-section surface.

The Avacha peridotite xenoliths sometimes include silicic glass films along the grain boundaries; we analyzed both types of grain boundary, one with glass and the other without. We recognized high concentrations of LILE and LREE, and some HFSE (high field strength elements, e.g. Zr and Nb) relative to olivine at the glass-filled grain boundaries (Fig. 18b), which are probably a contribution from the glass. On the other hand, the traverses across the grain boundaries without visible glasses do not show obviously high concentrations of such elements, but show slightly higher counts in Ce and probably Y than the background olivine (Fig. 18c). The traverses along the glass-free grain boundaries exhibit Ce enrichment relative to the background olivine (Fig. 18c). It is noteworthy

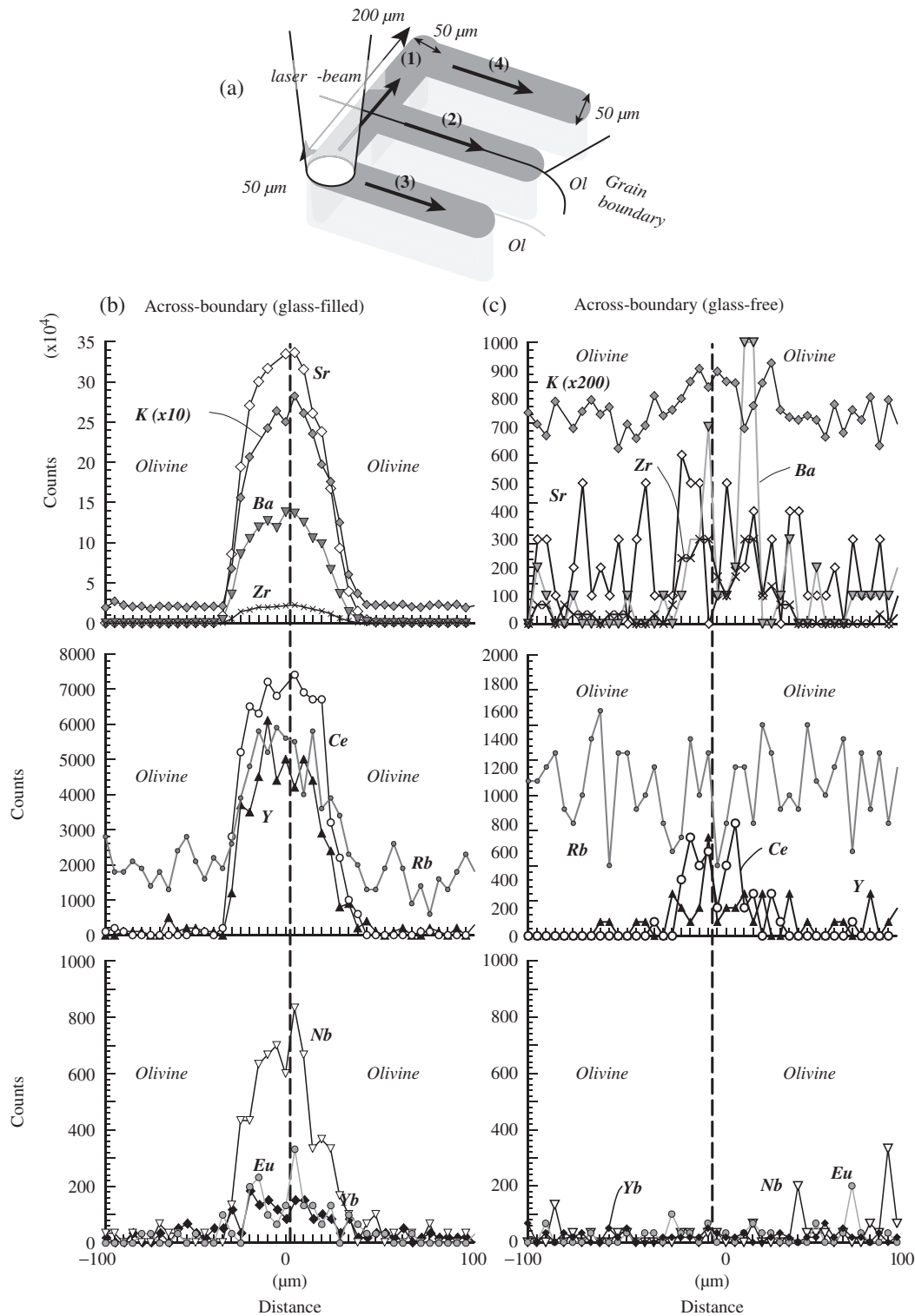


Fig. 18. Chemical characteristics of olivine-olivine grain-boundary components for two examples (glass-filled and glass-free boundaries). (a) Illustration of the analytical design: (1) a traverse across the grain boundary; (2) a traverse along the grain boundary itself; (3) and (4) traverses on both side of olivine parallel to the grain boundary. (b), (c) Across-boundary chemical profiles for glass-filled and glass-free boundaries, respectively. The distance from ‘-100 μm ’ to ‘100 μm ’ was calculated from the ablation time, with the origin on grain boundary. (d), (e) Along-boundary chemical profiles for glass-filled and glass-free boundaries, respectively. It should be noted that each point represents the center of the 50 μm laser beam (a). (See text for detail)

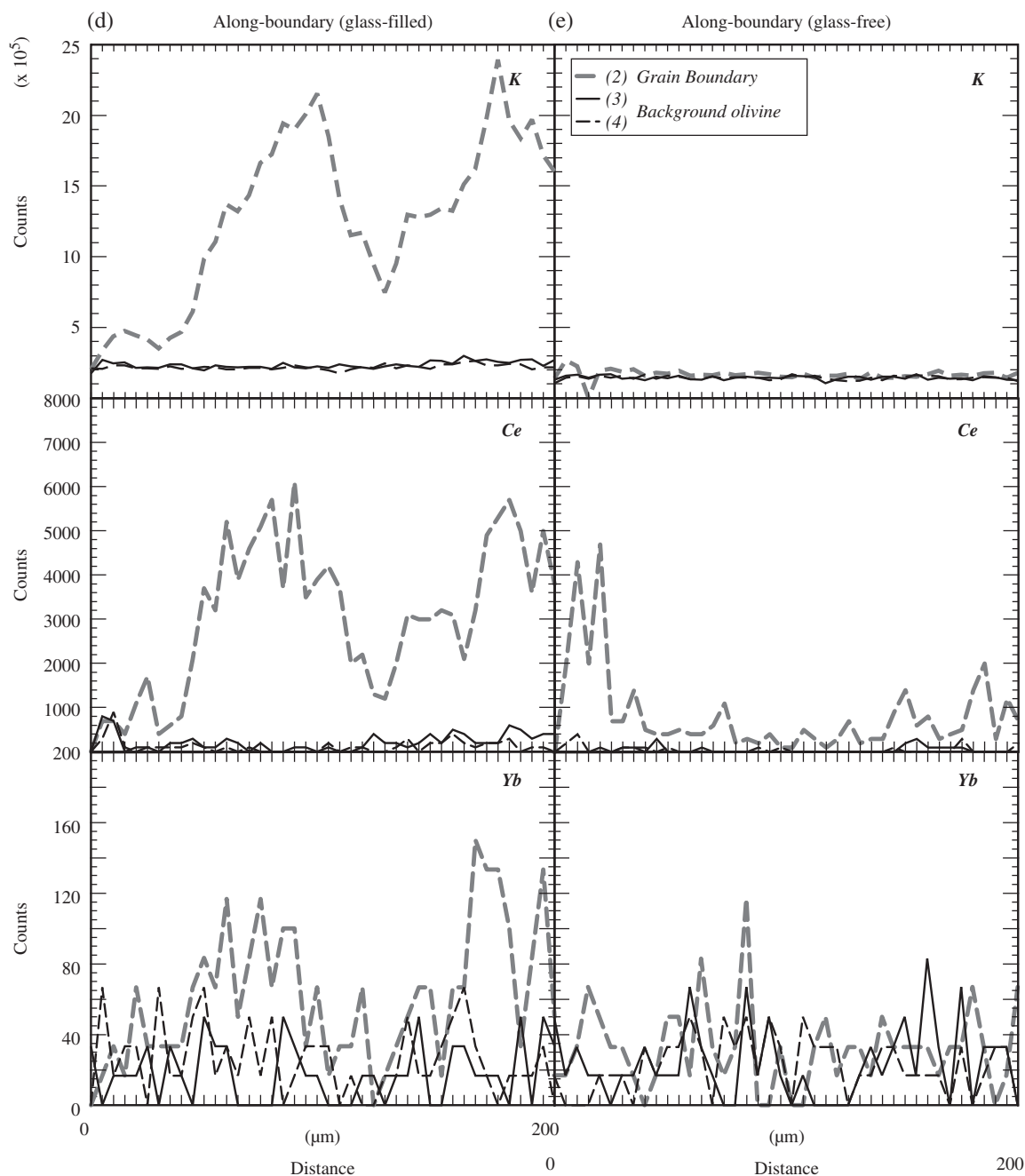


Fig. 18. Continued.

that the trace-element concentrations are not homogeneous along the grain boundaries with or without glass (Fig. 18d and e). The glass-free grain boundaries have lower concentrations of incompatible trace elements than the glass-filled ones, but nevertheless have appreciable amounts of Ce relative to the background olivine. Some incompatible elements such as K (Fig. 18b–e) are detectable only on the glass-filled grain boundaries, although

some incompatible trace elements (e.g. Ce) are detectable on both types of grain boundaries (Fig. 18).

DISCUSSION

As shown above (Figs 3, 6 and 7) and discussed by Arai *et al.* (2003a), the Avacha peridotite xenoliths are highly depleted in magmatic components and are modally

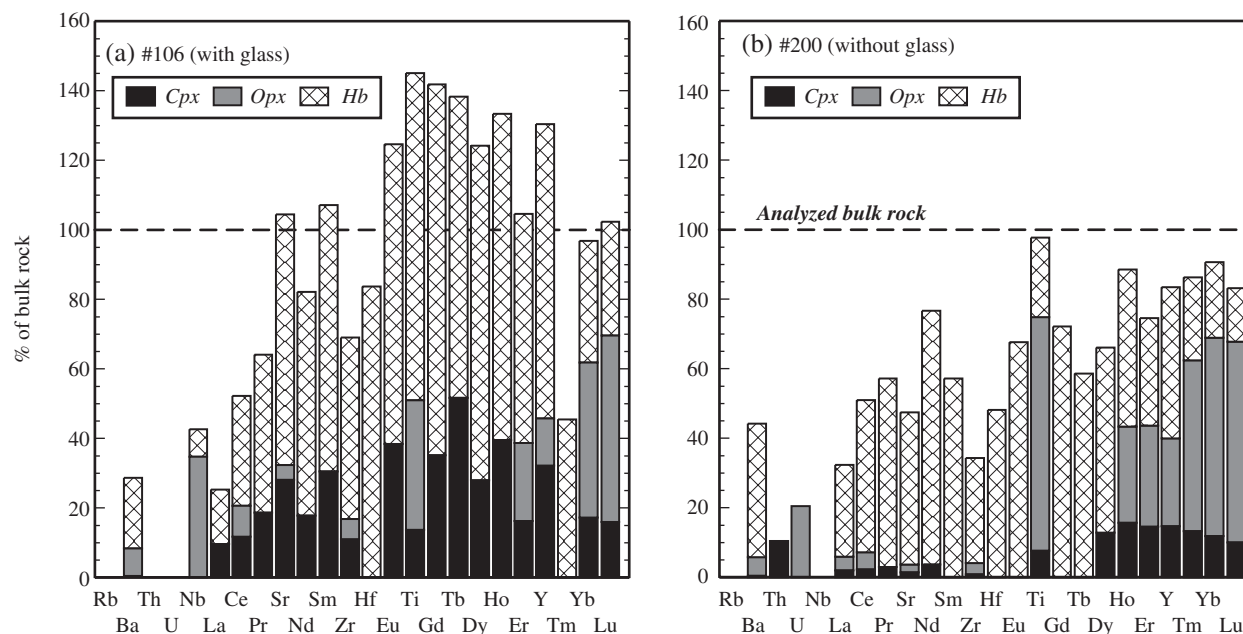


Fig. 19. Histograms showing contributions of mineral phases to trace-element concentrations of Avacha primary peridotites, calculated from mineral compositions and modal proportions. (a) Sample 106; (b) sample 200. In sample 106, the contributions from minerals are higher than the analyzed bulk compositions for some elements, possibly because of an unrepresentative modal composition obtained by point counting. Cpx, clinopyroxene; Opx, orthopyroxene; Hb, hornblende.

metasomatized. Here, we discuss their geochemical characteristics in the context of processes of partial melting and metasomatism.

Significance of the grain-boundary components in depleted peridotites from Avacha

The high and low modal amounts of olivine and clinopyroxene, respectively (Fig. 3), and low abundances of HREE (Fig. 7) indicate that the peridotite xenoliths from Avacha have distinctly depleted characteristics. The factors that govern the trace-element characteristics of clinopyroxene-poor harzburgites have not been well constrained in the literature. Contributions of chromian spinel to the incompatible trace-element budget of bulk-rock peridotites are negligible (e.g. Stosch & Seck, 1980; Bedini & Bodinier, 1999). However, Bodinier *et al.* (1996) claimed that very thin layers of titanium oxides and/or phlogopite exist around spinels, and are capable of storing incompatible trace elements, especially HFSE (Nb, Ta, Zr and Hf). The trace-element compositions of spinel peridotites can be controlled by the following accessory phases in addition to the main minerals: (1) accessory minerals associated with metasomatism, such as amphibole, phlogopite, apatite, and zircon (e.g. Bedini & Bodinier, 1999); (2) fluid inclusions in minerals (e.g. Schiano *et al.*, 1995); (3) the

grain boundaries (e.g. Eggins *et al.*, 1998; Condie *et al.*, 2004; Ionov, 2004).

Trace-element patterns of bulk-rock Avacha peridotites, with low modal amounts of clinopyroxene, differ from those of clinopyroxene (Figs 5 and 11), although those of lherzolitic peridotites mimic their clinopyroxenes (Salters & Shimizu, 1988). We calculated the contributions of each mineral phase to the bulk-rock trace-element concentrations for two samples of peridotite (samples 106 and 200), based on the modal proportions and mineral compositions (Fig. 19a and b). Sample 106 contains glasses especially as inclusions in chromian spinel, whereas sample 200 is free from visible glasses. Bulk-rock HREE abundances are dominated by the contribution from pyroxenes, especially orthopyroxene. Figure 19 indicates that there should be some storage of LILE and LREE in phases other than pyroxenes and hornblende although the bulk-rock MREE and HREE concentrations can be largely accounted for by these phases. Ratios of LILE and LREE relative to HREE in glasses are not so high (Fig. 15c), and the glasses could not be a perfect repository for LILE and LREE because of a large deficiency of LILE and LREE relative to HREE in the bulk peridotites (Fig. 19). The glasses, however, control the abundances and patterns of trace elements in the Avacha peridotites to various degrees; for example, the sample 629 peridotite, which is exceptionally rich in glasses, has the highest trace-element contents (Fig. 7).

Suzuki (1987) and Hiraga *et al.* (2002, 2003, 2004) confirmed that the grain boundaries in mantle peridotites show high concentrations of incompatible trace elements relative to background minerals. We detected the *in situ* enrichment of the incompatible trace elements Ce, Ba and Y along glass-free grain boundaries (e.g. Fig. 18c), consistent with the observations of Hiraga *et al.* (2004), who noted that elements with large ionic radii tend to concentrate along grain boundaries. The grain boundaries may be suitable repositories for LILE and LREE, complementary to the mineral and glass phases (Fig. 19). We detected almost exclusively Ba (LILE) and Ce (LREE) along the glass-free grain boundaries. The grain-boundary components as detected in this study are responsible for the metasomatism that produces no visible metasomatic minerals (e.g. Frey & Green, 1974). Minute glass or fluid inclusions in olivine may also contribute to the trace-element budget if they are appreciable in volume.

Partial melting

In general, the Fo and NiO contents of olivine and the Cr-number of chromian spinel increase with increasing degree of partial melting in residual spinel peridotites. Incompatible trace-element concentrations in bulk-rock peridotites and the modal amounts of clinopyroxene also decrease simultaneously. The Avacha peridotite xenoliths are characterized by low modal amounts of clinopyroxene (Table 1; Fig. 3), high Cr-number of spinel (Table 4; Fig. 9) and low concentrations of magmatic components and incompatible trace elements (Tables 1 and 3; Figs 6 and 7), indicating their highly depleted residual character. They are more depleted in magmatic components than abyssal peridotites on average (Figs 6 and 9).

The variations in the Fo content of olivine and Cr-number of spinel in the Avacha peridotites are, however, not concordant with the ordinary residual mantle trend (=OSMA); that is, the Fo contents of olivine do not increase with increasing Cr-number in the spinel (Fig. 9). The Fo contents of olivine are lower at a given Cr-number of spinel in the Avacha peridotites than in peridotite xenoliths from Iraya volcano, the Luzon Arc, Philippines (Arai *et al.*, 2004), which have the characteristics expected of simple restites (e.g. Jaques & Green, 1980) (Fig. 9). There is no correlation between the modal amounts of opx II, Fo contents of coexisting olivine and Cr-number of coexisting spinel (Fig. 8c and d). This indicates that the formation of opx II did not give rise to the high Cr-number of spinel and relatively low Fo contents of olivine. The correlations between the Cr-number of spinel and REE_N concentrations in the clinopyroxene of primary peridotites (Fig. 16a, c and e) further constrain their characteristics. For example, the clinopyroxene in sample 729, which shows the highest Cr-number of spinel, has the highest Ce_N and relatively low Yb_N contents (Fig. 16). It should be noted that HREE_N abundances in orthopyroxenes of the primary

peridotites also show negative correlations with the Cr-number of coexisting spinel and positive correlations with the Fo content of coexisting olivine (Fig. 16i–l). Simple extraction of melts cannot produce these chemical characteristics in residual minerals, and consequently influx melting (i.e. melting combined with melt or fluid influx) is the most probable process for the formation of the Avacha primary peridotites. The fluid or melt flux that triggered melting would have been rich in Fe relative to Mg because the Fo contents of primary peridotite olivine decrease with an increase in Cr-number of spinel (i.e. with an increase in the degree of melting). Hirose & Kawamoto (1995) and Matsukage & Kubo (2003) suggested that peridotites with high-Cr-number spinel are residues of high-degree partial melting induced either by an influx of H₂O-rich melt (or fluid) or by extremely high temperatures in the case of dry conditions. The former condition is much more likely in the mantle wedge above the subduction zone. The presence of hornblende suggests the hydrous nature of the fluid influx. This was probably an aqueous fluid rich in LREE relative to HREE (Bizimis *et al.*, 2000), in addition to being rich in Fe relative to Mg. The high LREE/HREE ratios of the primary clinopyroxenes relative to clinopyroxenes from abyssal peridotites (e.g. Johnson *et al.*, 1990) are consistent with the involvement of a LREE-rich fluid in partial melting. This melting assisted by a silica-rich fluid is one of the possible explanations for the silica enrichment of the Avacha peridotite relative to abyssal peridotites at a given MgO (Fig. 6d). The Cr-number of spinel shows a weak negative correlation with the HREE_N of orthopyroxene (Fig. 16g, i and k). The Fo contents of olivine, on the other hand, have positive correlations with the HREE_N of orthopyroxene (Fig. 16h, j and l). In general, HREE have lower incompatibility and lower mobility during alteration than LREE, and therefore, the HREE abundances in clinopyroxene are a good indicator of the degree of melting in abyssal peridotites (Hellebrand *et al.*, 2001). Figure 16 indicates that the HREE contents of orthopyroxene may have the potential to indicate the degree of melting even in clinopyroxene-poor or -free peridotites.

The hydrous fluid involved is inferred to be derived from the subducting oceanic slab because of its high concentrations of incompatible trace elements (see Tatsumi & Kogiso, 1997; Bizimis *et al.*, 2000). It may have become further enriched in incompatible trace elements through percolation through the peridotite of the mantle wedge (e.g. Ionov *et al.*, 2002). The fluid most probably percolated through the residual peridotite just after the initial partial melting in the same sense as envisaged by Niu (2004) for the refertilization of abyssal peridotites.

Metasomatism

Aqueous fluids or H₂O-rich melts are important metasomatic agents in the mantle wedge above subduction zones,

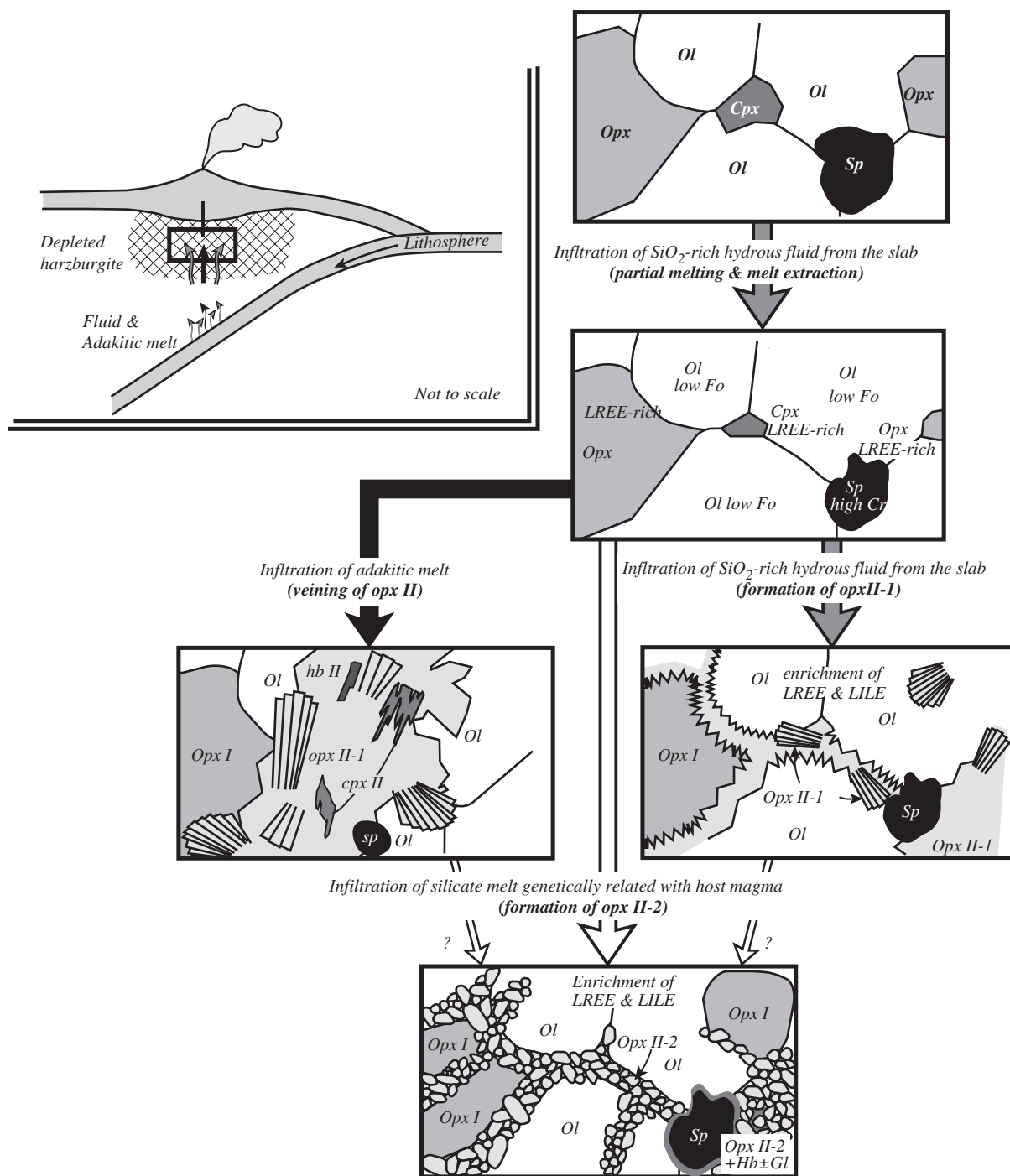


Fig. 20. Schematic illustration of the evolution of the Avacha peridotites. The initial (primary) characteristics reflect melting of less refractory peridotite assisted by aqueous fluids rich in LREE and FeO* from the slab. The subsequent metasomatism, the formation of metasomatic orthopyroxenes at the expense of olivine, resulted from at least three kinds of agent. An aqueous fluid with small of silicate component (SiO₂ dominant) was involved in the formation of opx II-1 at the expense of olivine. The fluid was possibly a successor to the fluid influx that triggered the initial partial melting of the protolith of the influx on the preceding partial melting. An adakitic hydrous melt metasomatically formed metasomatic orthopyroxene-rich lithologies such as sample 227. After the formation of opx II-1, a melt genetically related to the host magma was active in the upper mantle and involved in the formation of opx II-2.

and can react with peridotite to produce metasomatic orthopyroxene, as described by, for example, Schiano *et al.* (1995), Smith *et al.* (1999), Arai & Kida (2000) and Grégoire *et al.* (2001). In the interpretations of those workers most of the fluid was ultimately derived from a subducting slab and enriched the mantle-wedge peridotite in silica (see Nakamura & Kushiro, 1974). Adakite melts, formed by partial melting of subducted young and/or hot oceanic crust, have been also considered as one of the metasomatic agents in the mantle wedge (Kepezhinskas *et al.*, 1995; Kilian & Stern, 2002). Evidence of carbonatite metasomatism has been reported commonly from peridotite xenoliths exhumed by intra-plate basalts (e.g. Yaxley & Kamenetsky, 1999; Neumann *et al.*, 2002) and rarely from the mantle of an arc tectonic setting (e.g. Laurora *et al.*, 2001). Metasomatized peridotite xenoliths are common in intra-plate tectonic settings, such as the Canary Islands (e.g. Neumann & Wulff-Pedersen, 1997; Neumann *et al.*, 2002), Tanzania (e.g. Jones *et al.*, 1983; Dawson, 2002) and SE Australia (e.g. Yaxley *et al.*, 1997; Varela *et al.*, 1999; Yaxley & Kamenetsky, 1999). In general, the metasomatic agents are rich in incompatible trace elements, especially the LREE.

The modal mineralogical changes attributed to the effects of metasomatism in the Avacha peridotites are the replacement of olivine by orthopyroxene and the formation of hornblende selvages. The hornblende may have been precipitated from the host andesite or basaltic andesite magma. This was the latest metasomatic event that occurred en route to the surface, because the selvage is sometimes very thin and completely coats angular or subangular xenoliths (Fig. 2b) with very local chemical effects. We do not consider that hornblende formation was related to the formation of metasomatic orthopyroxene at the expense of olivine; there are no examples of olivine-replacing metasomatic orthopyroxene associated with hornblende. Instead, the orthopyroxene in the peridotites is replaced by clinopyroxene and hornblende at the contact with the hornblende. The calculated trace-element pattern of clinopyroxene in equilibrium with the host magma, using the partition coefficients of Fujimaki *et al.* (1984), is almost identical to that of the clinopyroxene in the hornblende selvage (Fig. 11c). It is distinctly different from that of the clinopyroxene in the thick (2 mm) metasomatic vein of opx II-1 in sample 227 (Figs 11 and 12a). Thus, we conclude that the formation of the hornblende selvage was not related to the formation of metasomatic orthopyroxene within the mantle, but to the recent contact with the host magma that brought the xenoliths to the surface.

It is noteworthy that the metasomatic orthopyroxene (opx II-1) of sample 227 (Fig. 12b) has different trace-element characteristics both from opx II-2 and from opx II-1 in the other samples (Fig. 13). The latter two

metasomatic orthopyroxenes are different from each other in chemistry (Figs 10 and 13). This suggests that at least three metasomatic agents with different chemical characteristics were involved in the formation of metasomatic orthopyroxenes in the Avacha peridotites.

Opx II-1, which exhibits complex fibrous textures, may reflect involvement of a low-viscosity metasomatic agent (i.e. an aqueous fluid). The fluid could infiltrate through minute cracks or fractures in the original olivine, resulting in the formation of metasomatic orthopyroxene (opx II-1) with fibrous textures (see Arai *et al.*, 2004). Audétat & Keppler (2004) have shown that the viscosity of fluids is dramatically lowered (by 40 times) by a decrease in dissolved silicate from 40 to 30 wt %. Nakamura & Kushiro (1974) suggested the possibility that H₂O as a metasomatic agent could react with olivine to precipitate metasomatic orthopyroxene. Bizimis *et al.* (2000) demonstrated that the incompatible trace-element compositions of slab-derived fluids are likely to be rich in LREE to MREE and Sr, and poor in HREE and Ti. Aqueous fluids are more enriched in Rb and Pb, and more depleted in Th relative to U than coexisting silicate melts (Keppler, 1996). They are more enriched in trace elements when coexisting with silicic melts than with basaltic melts (Ayers & Eggler, 1995; Adam *et al.*, 1997). However, the concentrations of all trace elements, except Rb and K, are distinctly lower in fluids than in coexisting silicate melts (Ayers & Eggler, 1995; Adam *et al.*, 1997). Adam *et al.* (1997) thus claimed that aqueous fluids are inappropriate metasomatic agents to cause enrichment of incompatible trace elements. The distinctly low HREE contents (mostly below detection limits) of opx II-1 relative to other orthopyroxenes (Fig. 13) possibly indicate their precipitation from a fluid. This is consistent with the preferential partitionings of HREE into silicate melts with respect to aqueous fluids by analogy with the HREE partitioning between clinopyroxene–melt–fluid (Bizimis *et al.*, 2000). We therefore propose that an aqueous fluid with a small amount of dissolved silicate (SiO₂ dominant) component was responsible for formation of opx II-1.

The fluid involved in the formation of opx II-1 was probably a successor of the fluid influx involved in the preceding partial melting event, which depleted the original peridotite protolith. This is consistent with the similarity of the trace-element patterns between the clinopyroxenes associated with opx II-1 (Fig. 11b) and the primary clinopyroxenes (Fig. 11a). The low HREE contents of the former are likely to reflect their precipitation from aqueous fluids (Adam *et al.*, 1997). The apparent non-Fe enrichment of opx II-1 is due to lower fluid/rock ratios in metasomatism than in partial melting.

Opx II-2 was probably formed from a hydrous melt closely associated with the Avacha host magma, because

the glass associated with opx II-2 has a similar trace-element pattern to the host magma (Figs 5 and 15b). A viscous melt could not invade fine cracks and fractures, and consequently replaced olivine with opx II-2 in simple morphologies (Fig. 4e; compare Fig. 4d). The metasomatic reaction probably occurred within the mantle before incorporation of the xenoliths in the host magma because, as stated above, there are no relationships between the formation of opx II-2 and the hornblende selvages. The origin of the metasomatic melt is likely to be closely related to the genesis of the host magmas to the xenoliths, which is beyond the scope of this paper. The silicic melt prevalently invaded the peridotites along cracks and grain boundaries, leaving minute glass inclusions mostly in chromian spinels and less frequently in olivines. The enrichment of LILE and LREE in the silicic glass is consistent with the predicted chemical characteristics of aqueous fluids released from subducting slabs (e.g. Kogiso *et al.*, 1997; Tatsumi & Hanyu, 2003). Such an aqueous fluid could have triggered partial melting of the mantle wedge to produce the relatively SiO₂-rich primary magmas (e.g. Hirose, 1997) of the recent Avacha volcanism. These magmas migrated upward, percolating through previously depleted peridotite, and resulted in the precipitation of opx II-2 at the expense of olivine. The similarity of chemistry between the primary orthopyroxene and opx II-2 (Fig. 10) suggests that the migrating melt remained in equilibrium with the surrounding mantle peridotite.

The clinopyroxenes in the highly metasomatized peridotite sample 227 are characterized by relatively high incompatible trace-element concentrations with high LREE/HREE and LILE/HREE ratios (Fig. 12a; compare Fig. 11), suggesting involvement of a metasomatic melt rather than a fluid (e.g. Adam *et al.*, 1997). It is noted that the pyroxenes in this sample share similar chemical characteristics irrespective of their mode of occurrence (Fig. 12), suggesting pervasive metasomatic alteration. As stated above, the metasomatic agent involved in the formation of sample 227 was different in chemistry from the fluid involved in opx II-1 formation in the other metasomatized peridotites. The melt involved may have been of adakitic affinity, judging from the weak positive Sr spike and high LILE/HREE abundances of the metasomatic clinopyroxenes (Fig. 12a), similar to the clinopyroxenes precipitated from adakitic magmas (Yogodzinski & Kelemen, 1998; Tsuchiya *et al.*, 2005). The metasomatic clinopyroxenes in sample 227 are also similar in their trace-element characteristics to those of a highly metasomatized peridotite xenolith from Lihir volcano, Papua New Guinea, although the sample 227 clinopyroxenes have positive spikes at U, Th, Zr, Hf and Ti (Fig. 12a). The metasomatism observed in the Lihir peridotites has been attributed to a hydrous melt derived from a subducting slab (Grégoire *et al.*, 2001; McInnes

et al., 2001). We therefore conclude that one of the metasomatic events recorded in the Avacha peridotites was caused by invasion of a melt derived from a subducting slab, possibly of adakitic affinity.

Each metasomatic event may have added the grain-boundary components through infiltration of fluids or melts along the grain boundaries. The metasomatic fluids or melts appear to have been introduced through fractures (e.g. Fig. 4e), and it is most probable that grain-boundary percolation of melts or fluids enriched the grain boundaries soon after formation of the original residual harzburgite protolith as a residue of partial melting (see Niu, 2004). Elemental abundances in the grain-boundary components were variable because of chromatographic mass-dependent fractionation of the fluids or melts during percolation (see Navon & Stolper, 1987).

The temporal relationships between the different metasomatic events are difficult to estimate (Fig. 20). Following the initial partial melting event, the residual peridotites experienced metasomatism, which formed opx II-1 by infiltration of an aqueous fluid from the subducting slab (Fig. 20). Almost simultaneously, an adakitic melt was released from the slab and metasomatically formed the orthopyroxene-rich lithologies (e.g. sample 227) (Fig. 20). A forerunner of the recent Avacha volcanism was caused by melting of the mantle wedge peridotite triggered by a slab-derived fluid (=upwelling of a hydrous asthenospheric mantle diapir). This partial melt invaded the lithospheric mantle to precipitate opx II-2 by reaction with olivine (Fig. 20). Larger-degree partial melts produced the main Avacha magmas, which exhumed fragments of the overlying lithospheric mantle peridotite as xenoliths.

SUMMARY AND CONCLUSIONS

- (1) The Avacha peridotite xenoliths are highly depleted, with low modal amounts of clinopyroxene (<1.0 vol.% on average), high Cr-number (>0.5) spinel, and highly forsteritic olivine (Fo_{90.5-92}). A slight decrease of the Fo contents of olivine with increasing Cr-number of spinel indicates addition of an FeO*-rich agent on partial melting (flux-induced melting). The influx also enriched the bulk-rock peridotites and constituent clinopyroxene in LREE.
- (2) The HREE concentrations in orthopyroxene are shown to be a good indicator of the degree of depletion of peridotites for the highly depleted harzburgites.
- (3) Orthopyroxene is largely responsible for the HREE characteristics, whereas hornblende and clinopyroxene, if any, contribute to the LREE and MREE

budget of the bulk peridotites. The grain boundaries are a repository for LILE and LREE, and are responsible for the metasomatism without visible metasomatic minerals that has been documented from peridotite xenoliths. Grain-boundary glasses may significantly modify the trace-element characteristics of the bulk-rock peridotites from Avacha to various degrees depending on the amount present. The grain-boundary components were added by migrating fluids or melts subsequent to the formation of the residual harzburgite.

- (4) The metasomatic agent was a silicate-bearing aqueous fluid for the generation of opx II-1, and a hydrous silicate melt for opx II-2; the melt was genetically related to the host Avacha magmas. The aqueous fluid was a successor of the initial influx, which triggered the partial melting and depletion of the original peridotite protolith of the harzburgites. These aqueous fluids are the likely products of dehydration reactions in the subducted slab. The agent involved in the metasomatism of sample 227 was a melt of adakitic affinity, with high LREE/HREE ratios and high concentrations of LILE (Ba, Th, U, Pb and Sr).

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APPENDIX A

Table A1: ICP-MS instrument and operational settings for bulk peridotite analysis

<i>Instrumentation</i>			
ICP-MS	Thermo Electron X7		
<i>ICP source</i>			
Incident power	1.3kW forward (<5 W reflection)		
Argon gas	Plasma:	Aux:	Carrier:
flow rate	13.0l/min	0.8l/min	0.92l/min
Sampling depth	8mm		
Water-cooled single-pass spray chamber maintained at 3 °C			
<i>Vacuum interference</i>			
Expansion	1.7×10^{-2} mbar		
Analyzer	4.2×10^{-4} mbar		
<i>Lens biases</i>			
Extraction 1	-490 V	D1	-39.3 V
L1	4.5 V	D2	-155 V
L2	-29 V	DA	-25.9 V
L3	-189.8 V	Hex. bias	4 V
Focus	20.5 V	Pole bias	1 V
<i>Mass spectrometer</i>			
Scanning mode	Peak jump mode (points per 3 peak)		
Dwell time	10 ms		
<i>Monitored isotope</i>			
Settled time	10 ms		
Ion detection	Pulse counting		
Detector type	ETP multiplier		

APPENDIX B

Table B1: Comparison of equilibrium temperatures calculated by three geothermometers

Sample no.	T/W (°C)	T/NT (°C)	T/BBG (°C)
Primary peridotites			
213	962–1046	929–1045	970
200	938–1045	864–1062	1001
F1	952–981	905–965	990
181	1023	1033	971
729	928–968	886–948	1009
106	906–980	850–961	970
Avx-33	904–994	849–975	994
Metasomatized peridotites			
10	955–1035	926–1048	976
187	890–1014	805–1007	957
Avx-35	928–933	888–892	968
227	949–958	914–926	962
Avx-31	911–976	857–943	929
629	1006–1009	1001–1005	984
375	943–1014	890–1003	939
59	1010–1018	1013	971
Avx-1	937–995	903–990	972
203	1100	1115	1035

T/W, two pyroxene geothermometer of Wells (1977); T/NT, clinopyroxene geothermometer of Nimis & Taylor (2000); T/BBG, olivine-spinel geothermometer of Ballhaus et al. (1991). Equilibrium pressure was assumed to be 1.5 GPa for the calculation of T/NT and T/BBG.