

Mantle peridotites from the Western Pacific

Shoji Arai ^{a,*}, Natsue Abe ^b, Satoko Ishimaru ^a

^a Department of Earth Sciences, Graduate School of Natural Science and Technology, Kanazawa University, Kanazawa 920-1192, Japan

^b Department of Deep Sea Research, Institute for Research on Earth Evolution (IFREE), Independent Administrative Institution/Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 2-15 Natsushima-cho, Yokosuka 237-0061, Japan

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Abstract

We review petrographical and petrological characteristics of mantle peridotite xenoliths from the Western Pacific to construct a petrologic model of the lithospheric mantle beneath the convergent plate boundary. The peridotite varies from highly depleted spinel harzburgite of low-pressure origin at the volcanic front of active arcs (Avacha of Kamchatka arc and Iraya of Luzon–Taiwan arc) to fertile spinel lherzolite of high-pressure origin at the Eurasian continental margin (from Sikhote-Alin through Korea to eastern China) through intermediate lherzolite–harzburgite at backarc side of Japan island arcs. Oxygen fugacity recorded by the peridotite xenoliths decreases from the frontal side of arc to the continental margin. The sub-arc type peridotite is expected to exist beneath the continental margin if accretion of island arc is one of the important processes for continental growth. Its absence suggests replacement by the continental lherzolite at the region of backarc to continental margin. Asthenospheric upwelling beneath the continental region, which has frequently occurred at the Western Pacific, has replaced depleted sub-cratonic peridotite with the fertile spinel lherzolite. Some of these mantle diapirs had opened backarc basins and strongly modified the lithospheric upper mantle by metasomatism and formation of Group II pyroxenites.

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1. Introduction

The Western Pacific region has been one of the most mobile zones, having had many arc-trench systems and possessing more than 70% of all backarc basins on Earth. As one of the results, it has abundant ophiolitic belts on island arcs, such as the Philippine archipelago (Yumul *et al.*, 2003). The Western Pacific has been a front of continental growth by addition of solid materials by accretion or collision and of arc-related magmas. Mantle peridotite is expected to be complicated both in petrography and geochemistry, reflecting such an active tectonic environment. The active arcs are transitional to the continental margin in the Western Pacific, and we can deduce transition of characteristics of lithospheric mantle from arc to continent from mantle peridotite xenoliths.

Petrological characteristics have been less known for the mantle wedge (=sub-arc mantle) than for the subcontinental or sub-oceanic mantle simply because xenolith-bearing volcanics

are relatively rare at the former tectonic setting (e.g. Nixon, 1987). Various volcanic rocks containing peridotite xenoliths are available on arcs and continental margins of the Western Pacific, thus providing us direct information about petrological characteristics of the mantle wedge (e.g. Arai *et al.*, 2000). The Japan island arcs among them are famous for localities of mantle-derived peridotite xenoliths (e.g. Takahashi, 1978a; Aoki, 1987). The Western Pacific region is especially noteworthy to provide peridotite xenoliths captured by arc-related magmas, which are “genuine” mantle-wedge materials (cf. Arai *et al.*, 1996). Calc-alkaline andesite and related magmas with mantle-derived peridotite xenoliths erupted from some volcanoes, i.e., Megata (Kuno, 1967; Aoki and Prinz, 1975; Aoki, 1987; Takahashi, 1978a, 1986) and Oshima-Ōshima (Ninomiya and Arai, 1992) volcanoes of the Northeast Japan arc, Avacha volcano of the Kamchatka arc (Arai *et al.*, 2003a), and Iraya volcano of the Luzon–Taiwan arc (Arai and Kida, 2000; Arai *et al.*, 2004). Geological and petrological aspects of mantle peridotite xenoliths from the Japan arcs were discussed by Arai *et al.* (2005) and Abe and Arai (2005), respectively.

* Corresponding author. Fax: +81 76 264 6545.

E-mail address: ultrasa@kenroku.kanazawa-u.ac.jp (S. Arai).

Examples for peridotite xenoliths derived from the mantle wedge are rather small in number from the areas other than the Western Pacific. The Pacific side of the American continents also provides some localities for such xenoliths, e.g. Cascades of USA (e.g. Ertan and Leeman, 1996), Central Mexico and Patagonia (e.g. Blatter and Carmichael, 1998). Xenoliths in kimberlitic diatremes from the Colorado Plateau, USA, indicate some arc-related signatures (addition of SiO₂) (e.g. Smith et al., 1999), but reconstruction of arc-type tectonic settings has not been successful there. Some xenoliths from the Pannonian Basin, central Europe, have been claimed to show arc signature (Szabo et al., 1992), but its arc setting has been controversial. Peridotite xenoliths in alkali basalt from Tallante, Spain, have silicic veins possibly derived from a slab-derived melt (Arai et al., 2003b; Shimizu et al., 2004).

The Sea of Japan, one of back-arc basins, has a complicated geological structure (Tamaki et al., 1992), affected by its genesis of splitting the eastern margin of the Eurasian continent (e.g. Otofuiji and Matsuda, 1984; Otofuiji et al., 1985). Its floor is composed of ocean basin, rifted continental crust and stretched continental crust (Tamaki et al., 1992). There are a few localities ever known that produce mantle-derived xenoliths, which will provide us with information on deep processes and materials beneath the Sea of Japan.

On the margin of the Eurasian continent, many mantle xenoliths localities are distributed from Sikhote-Alin, Far East Russia, through Korea to eastern China (e.g. Nixon, 1987). We can construct a detailed petrological model of the upper mantle beneath the eastern margin of Eurasia (e.g. O'Reilly et al., 2001). Many xenoliths studies have suggested active mantle dynamics in the cratonic region of eastern China (e.g. Xu et al., 2000; Yu et al., 2006).

The mantle-wedge peridotite is expected to be depleted, on one hand, by arc-magma extraction and to be enriched, on the other hand, with incompatible elements by slab-derived melts/fluids. These processes may be detected from mantle-derived peridotite xenoliths from the Western Pacific. In this article, we intend to describe the peridotite xenoliths from the Western Pacific to delineate a comprehensive petrological model of the upper mantle there. This will contribute to more thorough understanding of the evolution of the continental mantle.

We adopt the classification of Frey and Prinz (1978), i.e. Groups I and II, for ultramafic xenoliths. Groups I and II are almost equivalent, respectively, to Cr-diopside and Al-augite groups (Wilshire and Shervais, 1973) or green and black types (Ishibashi, 1970). Rocks of Groups I and II have metamorphic textures with chromian diopside (green on hand specimens) and igneous textures with aluminous augite (black on hand specimens), respectively. Group I rocks are older than Group II, being cut and enclosed as clasts by the latter.

2. Petrography of peridotite xenoliths and geological background

We briefly describe petrographical characteristics of peridotite xenoliths and their geological background of the Western

Pacific. We tentatively classified the xenolith localities of Western Pacific region into ten areas as follows.

2.1. Kamchatka arc

There are several localities of mantle xenoliths on the Kamchatka arc (e.g. Kepezhinskias et al., 1995; Widom et al., 2003). Peridotite xenoliths from Avacha (Avachinsky) volcano (e.g. Arai et al., 2003a; Ishimaru, 2004) and the Valovayam Volcanic Field (Kepezhinskias et al., 1995) among them have been studied in detail.

2.1.1. Avacha volcano, southern Kamchatka

The Avacha volcano, near the city of Petropavlovsk-Kamchatsky, is active on the volcanic front of the Kamchatka arc. It has erupted calc-alkaline magmas of andesite to basaltic andesite compositions. One of the recent pyroclastic flows on the western flank is very famous to produce abundant peridotite xenoliths, which are up to 40 cm across (Arai et al., 2003a). They are angular to ellipsoidal in shape, and fine-grained hornblendite frequently forms thin coating and veins around and in, respectively, the xenoliths. Harzburgite is far more dominant than other rocks as xenoliths (Fig. 2). Websterite is not rare both as discrete xenoliths and as thin (<10 cm) bands in harzburgite. Harzburgite shows protogranular to weakly porphyroclastic textures, and contains very small amount of clinopyroxene associated with orthopyroxene. Some grains of olivine and orthopyroxene are kinked. The orthopyroxene has thin exsolution lamellae of clinopyroxene. Chromian spinel is subhedral and opaque in thin section. In addition to ordinary coarse-grained harzburgite, extraordinarily fine-grained peridotite has been also found as xenoliths. This is very similar to F-type (fine-grained type) peridotite xenoliths from Iraya volcano, Philippines (see below) (Arai et al., 1996, 2004; Arai and Kida, 2000).

It is noteworthy that the harzburgites from Avacha and Iraya are metasomatized to various extents (Arai et al., 2003a, 2004). Secondary orthopyroxene has been produced at the expense of olivine, sometimes forming veinlets in the harzburgites. It is divided into two types: one is elongated and sometimes shows radial aggregates, and the other is stout euhedral associated with interstitial glass (Ishimaru, 2004).

2.1.2. Valovayam Volcanic Field, northern Kamchatka

The Pliocene arc basalts from the Valovayam Volcanic Field (VVF) of the northern part of Kamchatka arc also provide ultramafic xenoliths (Kepezhinskias et al., 1995). Xenoliths of both Groups I and II have been found; spinel lherzolite and spinel dunite are predominant in Groups I and II xenoliths, respectively. The spinel lherzolite shows porphyroclastic textures, and has metasomatic felsic veinlets (Kepezhinskias et al., 1995). Considering the position of the VVF on the Kamchatka Peninsula (Fig. 1), the VVF peridotite xenoliths may represent the mantle wedge of backarc side as in the case of most of the Japan-arc peridotite xenoliths (Fig. 1; see below).

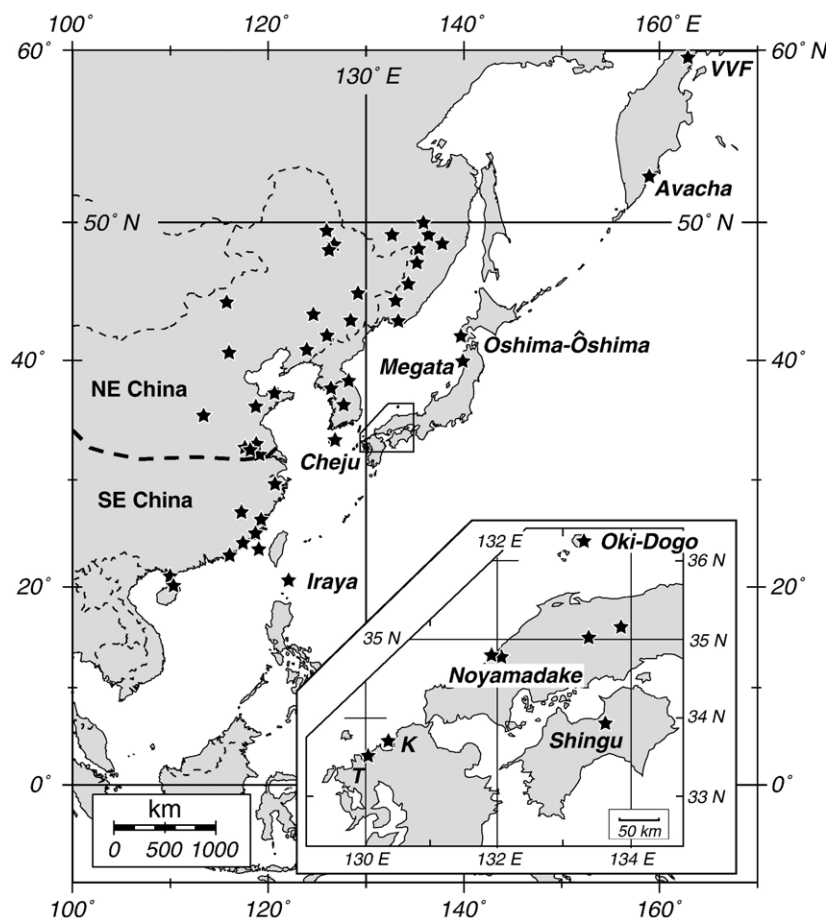


Fig. 1. Main localities (black star) of mantle peridotite xenoliths at the Western Pacific. VVF is the Valovayam Volcanic Field (Kepezhinskis et al., 1995). K and T in the inset are Kurose and Takashima, respectively. Data source: Abe (1997), Abe et al. (1992, 1995, 2003), Arai (1986), Arai et al. (2000, 2001a, 2003a, 2004), Arai and Kida (2000), Choi et al. (2001), Choi and Kwon (2005), Fan and Hooper (1989), Goto and Arai (1987), Hirai (1986), Ho et al. (2000), Ishimaru (2004), Lee (1996), Kepezhinskis et al. (1995), Nezuka (1998), Ninomiya and Arai (1992), Song and Frey (1989), Takahashi (1978a), Xu et al. (1996, 2000), Xu and Bodinier (2004), and Xu et al. (1998).

2.2. Northeast Japan arc

We have only two localities where mantle-derived peridotite xenoliths are available, Oshima-Ôshima and Megata volcanoes, in the Northeast Japan arc. Recent arc volcanics of calc-alkaline affinity host the xenoliths (Katsui et al., 1979).

2.2.1. Oshima-Ôshima volcano

The Oshima-Ôshima volcano is active and belongs to the Northeast Japan arc. It is located in the Sea of Japan 50 km off Hokkaido (Oshima Peninsula). The Nishiyama–Chubu lava of calc-alkaline andesite has been known to contain mafic to ultramafic xenoliths (Katsui et al., 1979; Yamamoto, 1983, 1984). Yamamoto (1984) described xenoliths of dunite, wehrlite, olivine clinopyroxenite and gabbros. Ninomiya and Arai (1992) found harzburgite clasts within gabbroic xenoliths (=composite xenoliths; Irving, 1980). Gabbroic rocks (>60%) predominate over clinopyroxenite (21%), wehrlite (7%) and dunite (5%) as xenoliths. According to our observations, various kinds of ultramafic and ultramafic rocks form, sometimes, complicated composite xenoliths; gabbroic to clinopyroxenitic rocks enclose clasts of peridotites. This

indicates gabbroic and clinopyroxenitic rocks are younger than peridotitic rocks.

Ultramafic rocks contain green-colored clinopyroxenes and have metamorphic textures (mosaic equigranular, porphyroclastic and weakly porphyroclastic), and are almost equivalent to Group I xenoliths. The harzburgite occurs as small (<2 cm across) clasts in gabbroic xenoliths, and has a protogranular texture. Clinopyroxene is anhedral and associated with orthopyroxene. Chromian spinel is anhedral and is reddish brown in thin section. Orthopyroxene, sometimes kinked, has thin exsolution lamellae of clinopyroxene.

2.2.2. Megata volcano

The Megata volcano, at the backarc side of the Northeast Japan arc, has three craters, Ichinomegata, Ninomegata and Sannomegata, all of which provide mafic to ultramafic xenoliths (e.g. Kuno, 1967; Aoki, 1971, 1987; Takahashi, 1978a, 1980, 1986; Arai and Saeki, 1980; Koyaguchi, 1986; Abe et al., 1995). Xenoliths are especially large and abundant in the Ichinomegata crater, and there have been a large number of studies on the Ichinomegata peridotite xenoliths (e.g. Kuno, 1967; Aoki and Prinz, 1975; Takahashi, 1980, 1986). The host

rock is calc-alkaline andesite to dacite for Ichinomegata (Katsui et al., 1979; Aoki and Fujimaki, 1982; Sakuyama and Koyaguchi, 1984), calc-alkaline andsite for Ninomegata (Abe et al., 1995), and high-Al basalt for Sannomegata (Katsui et al., 1979).

Lithological variations are so large in the Ichinomegata xenolith suite. Hornblende gabbro, gabbro and amphibolite mainly constitute the mafic crustal xenoliths, and hornblende websterite and websterite are also common. Peridotite varies from harzburgite to lherzolite, the latter being predominant (Fig. 2) (Kuno, 1967; Aoki and Prinz, 1975; Abe, 1997). To be interesting, dunite has been very rarely found (Arai and Takahashi, 1987). Some of fertile lherzolite and pyroxenites contain spinel-pyroxene symplectite, which was interpreted as a garnet pseudomorph (Kuno, 1967; Aoki, 1971). The symplectite is, however, formed only between plagioclase and olivine, and its spinel is almost colorless in thin section. It is more favorable to be a reaction product between calcic plagioclase and olivine on cooling (e.g. Takahashi, 1986). Harzburgites are generally coarser-grained than lherzolites (Abe and Arai, 1993). Peridotites are occasionally veined by feldspathic (gabbroic) and pyroxenitic rocks sometimes with surrounding depletion aureoles (Abe and Arai, 1993).

Mafic and ultramafic rocks are hydrated to various degrees (Aoki, 1971; Aoki and Shiba, 1973; Abe et al., 1992). Some of the hornblende gabbros are of igneous origin (Fukuyama, 1985), but others are of secondary origin. In mafic and pyroxenitic rocks, hornblende replaced clinopyroxene lamellae in orthopyroxene, and formed together with dark green spinel between olivine and plagioclase. In peridotite, hornblende (pale yellowish brown pargasite) cuts pyroxenes as thin veinlets

and replaces the symplectite pyroxenes (Arai, 1986). Phlogopite is rarely associated with hornblende in strongly hydrated rocks (Arai, 1986). Xenoliths from Sannomegata are claimed to be less hydrated than those from Ichinomegata (e.g. Arai and Saeki, 1980; Arai et al., 2005). Ninomegata xenoliths are also hydrated but the degree of hydration is slightly lower than in the Ichinomegata xenoliths (Abe et al., 1995).

2.3. Southwest Japan arc

There are so many localities of xenoliths in Cenozoic alkaline basalts from San-in district (Honshu) to northern Kyushu, especially along the coast of the Sea of Japan, of southwest Japan (e.g. Yamaguchi, 1964; Takamura, 1973; Arai et al., 2000). The volcanism of Cenozoic basaltic magmas had been prevalent in southwest Japan (e.g. Takamura, 1973; Uto, 1990; Iwamori, 1991), and they made small monogenetic volcanoes, which usually formed volcano clusters with distinctive ages and magma chemistries (Uto, 1990; Iwamori, 1991). Mantle peridotites (lherzolites to harzburgites) have been found from On-yama (Tsuyama Basin cluster) (Chii et al., 1975; Arai and Muraoka, 1992), Arato-yama (Kibi Plateau cluster) (Tazaki, 1971; Fujiwara and Arai, 1982; Abe and Arai, 2001), Noyamadake (solitary) (Hirai, 1983, 1986), Kawashimo (solitary) (Nagao and Sakaguchi, 1990), Kurose (solitary) (Arai and Hirai, 1983, 1986), and Fukue-jima (Umino and Yoshizawa, 1996) (Fig. 1). Arai and Kobayashi (1984) reported a xenolith of metasomatized lherzolite from Takashima (Higashi-Matsuura cluster), northern Kyushu. Dunite and other ultramafic xenoliths have been also reported from Mejika-yama (Sera Plateau cluster) (Arai and Hirai, 1985) and

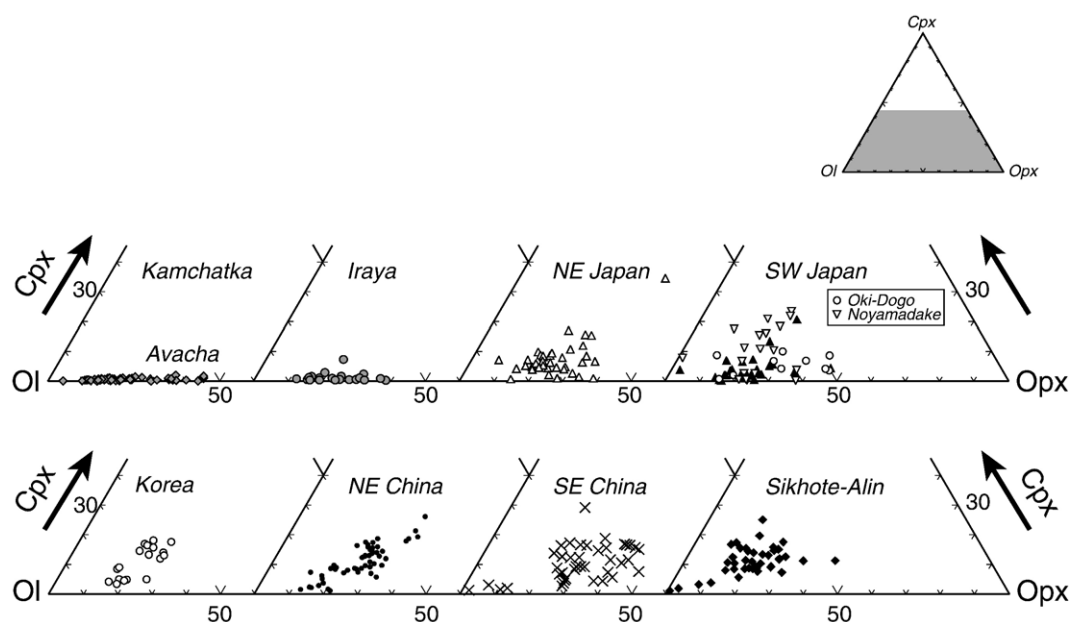


Fig. 2. Modal amounts of olivine, orthopyroxene and clinopyroxene in spinel peridotite xenoliths from the Western Pacific. Note that the peridotite on average gradually changes from depleted harzburgite in the frontal side of arc (Avacha and Iraya) to fertile lherzolite in continent (Korea, Sikhote-Alin and China) through Japan arcs (see text). Peridotite xenoliths from Oshima-Ôshima volcano and Shingu are too small for modal composition determination (Ninomiya and Arai, 1992; Goto and Arai, 1987). Note that Oki-Dogo (Fig. 1) is included in SW Japan. Data source: Abe (1997), Abe et al. (1992, 1995, 2003), Arai (1986), Choi et al. (2001), Choi and Kwon (2005), Hirai (1986), Ishimaru (2004), Kida (1998), Nezuaka (1998), Song and Frey (1989), Xu et al. (2000), and Xu et al. (1998).

Takashima (Ishibashi, 1970; Kobayashi and Arai, 1981; Arai et al., 2001a).

Arai et al. (2000) claimed that Group II xenoliths and related pyroxene megacrysts are especially abundant in alkali basalts from the monogenetic volcano clusters (e.g. Kibi Plateau, Tsuyama Basin and Higashi-Matsuura clusters). They are, on the other hand, scarce in amount in alkali basalts from solitary monogenetic volcanoes remote from the clusters (e.g. Kurose and Noyamadake). Group I xenoliths comprise mantle peridotite (lherzolite to harzburgite), dunite, wehrlite, pyroxenites and granulites). Group II xenoliths are dominated by various pyroxenites.

The lithology of mantle peridotites is variable from one locality to another (Arai et al., 1998, 2000; Abe et al., 1999; Abe and Arai, 2005) (Fig. 2). For example, only lherzolite was found from On-yama, Tsuyama Basin (Arai and Muraoka, 1992), and slightly depleted lherzolite to clinopyroxene-rich harzburgite is predominant in the Kurose xenolith suite, northern Kyushu (Arai and Hirai, 1983; Hirai, 1986; Arai et al., 2000). On the other hand, a large lithological variation from fertile lherzolite to depleted harzburgite has been recognized from Noyamadake (Hirai, 1986; Arai et al., 2000) (Fig. 2).

2.4. Shingu, Shikoku Island

This locality of mantle xenoliths is very special on the Japanese Islands. It belongs to the “Outer Zone” (Pacific side of the Median Tectonic Line) of Southwest Japan, and is distinctive from other localities that are distributed in the “Inner Zone” (Japan-Sea side) of Southwest Japan (see above). We therefore expect them to have unique information that we cannot obtain from the xenoliths elsewhere on the Japan arcs. There are two dikes (sheets) of alkali basaltic composition that contain abundant crustal and mantle xenoliths in Shingu, Shikoku Island (Takamura, 1978) (Fig. 1). They cut crystalline schists of the Sambagawa metamorphic belt of high-pressure intermediate type (Miyashiro, 1973). Goto (1986) found several other dikes of similar chemical characteristics within the Sambagawa belt in Shikoku Island. The host alkali basalt is characterized by abundance of carbonate minerals and hydrous minerals (biotite and amphibole), and the term “lampophyre” is preferable, also taking the occurrence as dike into account. The age of host rock is 18 Ma, being older than the host rocks of other mantle-derived xenoliths from the Southwest Japan arc (Uto et al., 1987; Uto, 1990). We found a variety of ultramafic xenoliths (harzburgite, lherzolite, dunite, wehrlite, pyroxenite and kaersutite), and most of the pyroxenites and kaersutite (hornblende) belong to Group II (Goto and Arai, 1987).

The peridotite xenoliths are mostly small (<5 cm across) and angular. They are rather fine-grained and show protogranular to porphyroclastic textures (Goto and Arai, 1987; Arai et al., 2000). Group I rocks are frequently penetrated by Group II rocks in individual xenoliths (=composite xenoliths; Irving, 1980). We can thus expect serious chemical effect on peridotite by the magma involved in the formation of Group II rocks (Goto and Arai, 1987; Arai et al., 2000).

2.5. Oki-Dogo Island off southwest Honshu

The Oki-Dogo Island has the basement of the Hida metamorphic rocks of low-P/T type (see Miyashiro, 1973), which has been extensively covered with basalts of Cenozoic age (3.6–0.8 Ma) (Kaneoka et al., 1977). Their alkali basalt varieties contain large amounts of ultramafic xenoliths (Takahashi, 1978a) (Fig. 1), and mantle peridotite xenoliths have been found from several localities (Takahashi, 1975, 1978a; Aoki, 1977). The petrographical diversity is very large, in terms of texture and modal amount of minerals, for the Oki-Dogo xenoliths, indicating active magmatism in deep parts, from the lower crust to upper mantle. Lherzolites are predominant over harzburgites as mantle peridotites (Takahashi, 1978a,b; Abe et al., 2003) (Fig. 2).

2.6. Sikhote-Alin, Far East Russia

There are many (more than 10) localities of mantle xenoliths captured by late Cenozoic alkali basalts in Sikhote-Alin, Far East Russia (Ionov and Hofmann, 1995; Ionov et al., 1995; Nezuka, 1998; Yamamoto et al., 2004). The Sikhote-Alin region has a very complicated tectonic history (Faure and Natal'n, 1992). Subduction and accretion in Precambrian to early Paleozoic were followed by collision of a microcontinent (Anuy microcontinent) in Jurassic to early Cretaceous at Sikhote-Alin (Faure and Natal'n, 1992). Large NE–SW trending left lateral faults have rearranged the geologic bodies after Jurassic (e.g. Xu et al., 1989; Okada and Sakai, 1993). A subduction system had been conducted after the collision in Cenozoic (Faure and Natal'n, 1992). Despite of this complicated tectonic history, the peridotite xenoliths are strikingly uniform in lithology, anhydrous spinel lherzolite (Nezuka, 1998; Yamamoto et al., 2004) (Fig. 2). Harzburgites are rarely found from Podgelban (Nezuka, 1998). Hydrous minerals (Ti-pargasite and Ti-phlogopite) were rarely found in lherzolites (Ionov and Hofmann, 1995; Nezuka, 1998). Dunite was rarely found from a few localities (Fevrilska and Ilchanska). The lherzolites mostly exhibit protogranular texture, but tabular equigranular and porphyroclastic textures are also common (Nezuka, 1998).

2.7. Cheju (Jeju) Island, Korea

Cheju (or Jeju) Island is a large volcanic island, composed of a large volcanic edifice (stratovolcano) with numerous parasitic tuff rings and cones (Lee, 1982; Sohn, 1996). Tholeiitic to alkali olivine basalts of intraplate chemical affinity have been active from 1.2 Ma to recent (Choi et al., 2001). There have been a few localities of ultramafic xenoliths reported from Cheju Island (e.g. Yun et al., 1998; Choi et al., 2001). Spinel lherzolite is predominant with minor harzburgite (Fig. 2). No hydrous minerals have been found in peridotite xenoliths from Cheju Island. The lherzolite exhibits protogranular texture. Small amounts of pyroxenites (clinopyroxenite and websterite) were found (Choi et al., 2001).

2.8. Korean Peninsula

Three peridotite xenolith localities, Boun (or Jogokni), Gansung (Ganseong) and Baegryung (Baengnyeong) Island, have been known on and around the Korean Peninsula (Lee, 1996; Choi and Kwon, 2005) (Fig. 1). Boun, Gansung and Baegryung Island are located in the Okcheon belt, Gyeonggi Massif and Imjingang Belt, respectively (Choi and Kwon, 2005). The host rocks of the xenoliths are alkali basalts or basanites forming lava domes or dike (Lee, 1996; Arai et al., 2001a). The host basalt erupted at 11 Ma in Boun (Arai et al., 2001a) and at 4 Ma in Baegryung Island (Choi and Kwon, 2005).

Fertile spinel lherzolite is predominant as mantle peridotite, and harzburgite has been rarely found (Choi and Kwon, 2005) (Fig. 2). Group I xenoliths of dunite and pyroxenites are also rare. Protogranular to weakly porphyroclastic textures are commonly observed in the lherzolite from Korea (Arai et al., 2001a; Choi and Kwon, 2005). The peridotites are totally anhydrous. To be interesting, Group II pyroxenite xenoliths and related megacrysts have not been found from these localities (Arai et al., 2001a; Choi and Kwon, 2005).

2.9. Eastern China

The eastern Eurasian continent is composed of the North China (Sino-Korean) Craton, Yangtze Craton and Cathaysia Block. Alkali basalt and related silica-undersaturated magmas of Cenozoic age host mantle-derived xenoliths at many localities on eastern China (Fig. 1) (Fan and Hooper, 1989). They are distributed on the three blocks, and can provide us with much information on petrological characteristics of the continental lithospheric the mantle, namely on mantle heterogeneity, paleogeotherms, mantle metasomatism, partial melting and mantle dynamics. Several suites of them have been extensively studied (e.g. Xu et al., 2000), and Fan and Hooper (1989) summarize petrographical characteristics of the Chinese mantle peridotite xenoliths. Lithological variations are so large for the peridotite xenoliths from eastern China, from garnet peridotites to spinel peridotites (Fig. 2) via spinel-garnet peridotites (Fan and Hooper, 1989). Garnet lherzolite xenoliths are available mainly from southeastern China (e.g. Xichiang, Minxi and Minqing). Depleted spinel harzburgite xenoliths are also relatively common, sometimes associated with the garnet lherzolite xenoliths (Fan and Hooper, 1989; Zheng et al., 2005). The peridotite xenoliths are mostly anhydrous, but some of spinel lherzolite xenoliths from Nushan contain pargasitic amphiboles (Xu et al., 2000; Xu and Bodinier, 2004). Some of lherzolite xenoliths captured by potassic volcanics from an eastern part of the Central Asian fold belt (Wudalianchi, Erkeshan and Keluo) contain secondary phlogopites (Zhang et al., 2000).

Peridotite xenoliths captured by alkali basalts of Mesozoic age from Xingang are depleted spinel harzburgites (Zheng et al., 2005). Kimberlite pipes of Paleozoic age provide xenoliths and xenocrysts of mantle origin (see the summary of O'Reilly et al. (2001)), but are beyond the scope of this article.

Group II pyroxenite xenoliths are commonly found in Cenozoic basalts from Leizhou Peninsula, south China (Yu et al., 2006). Pyroxenite xenoliths of Group I were reported from Tungchihsu, Penghu Islands at the Taiwan Strait (Ho et al., 2000).

2.10. Luzon–Taiwan arc

There are some arc volcanoes on the Luzon–Taiwan region, which have erupted magmas carrying mantle-derived xenoliths (Richard et al., 1986). Iraya volcano of Batan Island, the main island of the Batanes of the Philippines, between Luzon and Taiwan, has been known as the main locality among them (Fig. 1) (e.g. Richard, 1986; Vidal et al., 1989; Maury et al., 1992). Peridotite and mafic xenoliths (<40 cm across) are abundant in K-rich calc-alkaline andesites of recent age (e.g. Richard, 1986; Arai et al., 1996). Gabbroic to hornblenditic rocks frequently occur as veinlets in peridotites or enclose their clasts, making composite xenoliths (Arai et al., 1996). The former especially encrust the peridotite xenoliths as thin selvages; this mode of occurrence is common to peridotite xenoliths enclosed by calc-alkaline andesite (Arai et al., 1996, 2003a).

The peridotite xenoliths of Iraya volcano can be divided into two types, C-type and F-type (Arai et al., 1996, 2004; Arai and Kida, 2000). The C-type (coarse-grained type) is ordinary mantle peridotite with protogranular to porphyroclastic textures. The F-type is far finer-grained than the C-type and is a kind of cataclasite (Arai et al., 2004). F-type is transitional to C-type in texture (Arai et al., 1996; Arai and Kida, 2000).

Harzburgite, which is predominant over other peridotites as C-type (Fig. 2), mainly shows protogranular texture, having small amounts of anhedral chromian spinel and clinopyroxene (Arai et al., 2004). Metasomatic formation of secondary orthopyroxene at the expense of olivine is characteristic of the Iraya peridotite xenoliths, especially of F-type (Arai and Kida, 2000). It is sometimes associated with production of pargasite and phlogopite (Arai et al., 2004).

3. Mineral chemical characteristics

3.1. Major element chemistry

The olivine-spinel compositional relationship is a good indicator of petrological characteristics of spinel-bearing peridotites (see Arai, 1994a) (Fig. 3). Fo of olivine is 100 Mg/(Mg+Fe²⁺) atomic ratio, and Cr# of spinel is Cr/(Cr+Al) atomic ratio. It is well correlated with petrographical characteristics, especially with modal ratios of minerals; the peridotite with clinopyroxene/pyroxenes volume ratios lower than 0.1 contains high-Cr# (>ca. 0.5) spinel (Arai, 1994a). The olivine-spinel compositional systematics have an advantage in getting data set of peridotites easily from the literature. We can compare various kinds of peridotites on the same compositional space (Fig. 3). It is noteworthy that the peridotite xenoliths from Avacha volcano, Kamchatka, which may represent the mantle-wedge peridotite beneath a volcanic front, are highly depleted (more depleted than abyssal harzburgite) in term of olivine-

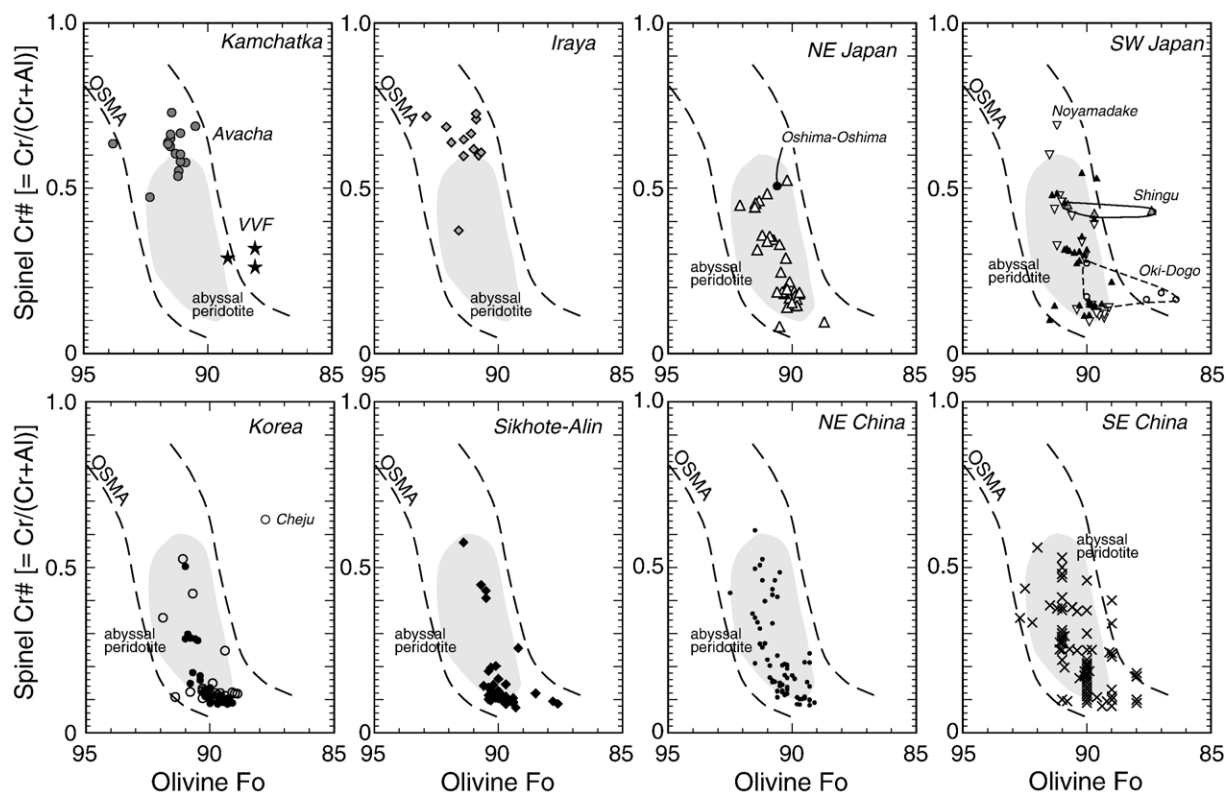


Fig. 3. Relationships between Fo content of olivine and $\text{Cr\#} (= \text{Cr}/(\text{Cr} + \text{Al}))$ atomic ratio of coexisting chromian spinel in spinel peridotite xenoliths from the Western Pacific. OSMA (Olivine-spinel mantle array) is a peridotite resitite trend in the spinel peridotite field (Arai, 1994a). Note that the peridotite on average becomes more fertile from depleted harzburgite in the frontal side of arc (Avacha and Iraya) to fertile lherzolite in continent (Korea, Sikhote-Alin and China) through Japan arcs (see text). Some peridotites plotted off OSMA may be metasomatized ones. Note that Shingu and Oki-Dogo (Fig. 1), and Cheju (Fig. 1), are included in SW Japan and Korea areas, respectively, in this figure. Data source: Abe (1997), Abe et al. (1992, 1995, 2003), Arai et al. (2000, 2001a, 2003a, 2004), Arai and Kida (2000), Choi et al. (2001), Choi and Kwon (2005), Fan and Hooper (1989), Goto and Arai (1987), Hirai (1986), Ishimaru (2004), Kepezhinskis et al. (1995), Kida (1998), Lee (1996), Nezuka (1998), Ninomiya and Arai (1992), Song and Frey (1989), Takahashi (1978b), Xu et al. (1996, 2000), Xu et al. (1998), Xu and Bodinier (2004), and Zhang et al. (2000).

spinel composition (Fig. 3). The peridotite xenoliths from the VVF, northern Kamchatka, are lherzolites more fertile than the Avacha harzburgites (Fig. 3). This may be due to the backarc-side nature of the VVF peridotites (Fig. 1). The peridotite xenoliths from Iraya, Luzon–Taiwan arc, may also represent the sub-volcanic front mantle wedge especially of a young arc, are depleted in terms of olivine-spinel composition (Fig. 3). Relatively fertile lherzolite with low- $\text{Cr\#}$ (ca. 0.1) spinel is predominant in xenoliths from Sikhote-Alin and Korea (Fig. 3). The $\text{Cr\#}$ of spinel is highly variable, from 0.1 to 0.6, in peridotite xenolith suites from eastern China and Japan arcs, although lherzolites with $\text{Cr\#}$ of spinel around 0.1 to 0.2 are dominant (Fig. 3). Some peridotites plotted off the olivine-spinel mantle array from southeastern China and Japan (e.g. some of Shingu and Oki-Dogo ones of Fig. 3) are possibly metasomatized mantle peridotites (see Arai et al., 2000). It is noteworthy that the highly depleted harzburgite with high- $\text{Cr\#}$ (>0.6) spinel is common in the mantle wedge (especially beneath the volcanic front) but is quite rare in the subcontinental mantle (Fig. 3).

Na_2O contents of clinopyroxene at a given $\text{Cr\#}$ of spinel as a measure of degree of partial melting are a good and simple indicator of depth of partial melting (cf. Arai, 1991, 1994a)

because of high pressure-dependence of Na partitioning between clinopyroxene and melt (e.g. Blundy et al., 1995; Putirka et al., 1996). Sodium contents of clinopyroxene cannot be modified during subsolidus conditions (except in metasomatism) because of absence of Na reservoirs in peridotites free of plagioclase and hornblende (pargasite). The peridotite xenolith suites discussed in this article are variable but can be roughly divided into two groups in terms of this relationship (Fig. 4). Almost all the peridotites from eastern China, Sikhote-Alin and Korea have relatively high-Na clinopyroxenes, being comparable to continental-rift and oceanic hotspot peridotites (Arai, 1991). On the other hand, peridotites from the Japan arcs, Avacha volcano and Iraya volcano contain relatively low-Na clinopyroxenes even though we consider their relatively high degrees of partial melting. Their low-Na clinopyroxene is almost comparable to the clinopyroxene in abyssal peridotites (Fig. 4). The Noyamadake peridotite xenoliths from the Southwest Japan have high-Na clinopyroxenes almost similar to those in sub-continental peridotites (Fig. 4). It is noteworthy that the peridotites typically observed in active arcs, which have low-Na clinopyroxenes, is quite rare in the continental region of the Western Pacific (Fig. 4).

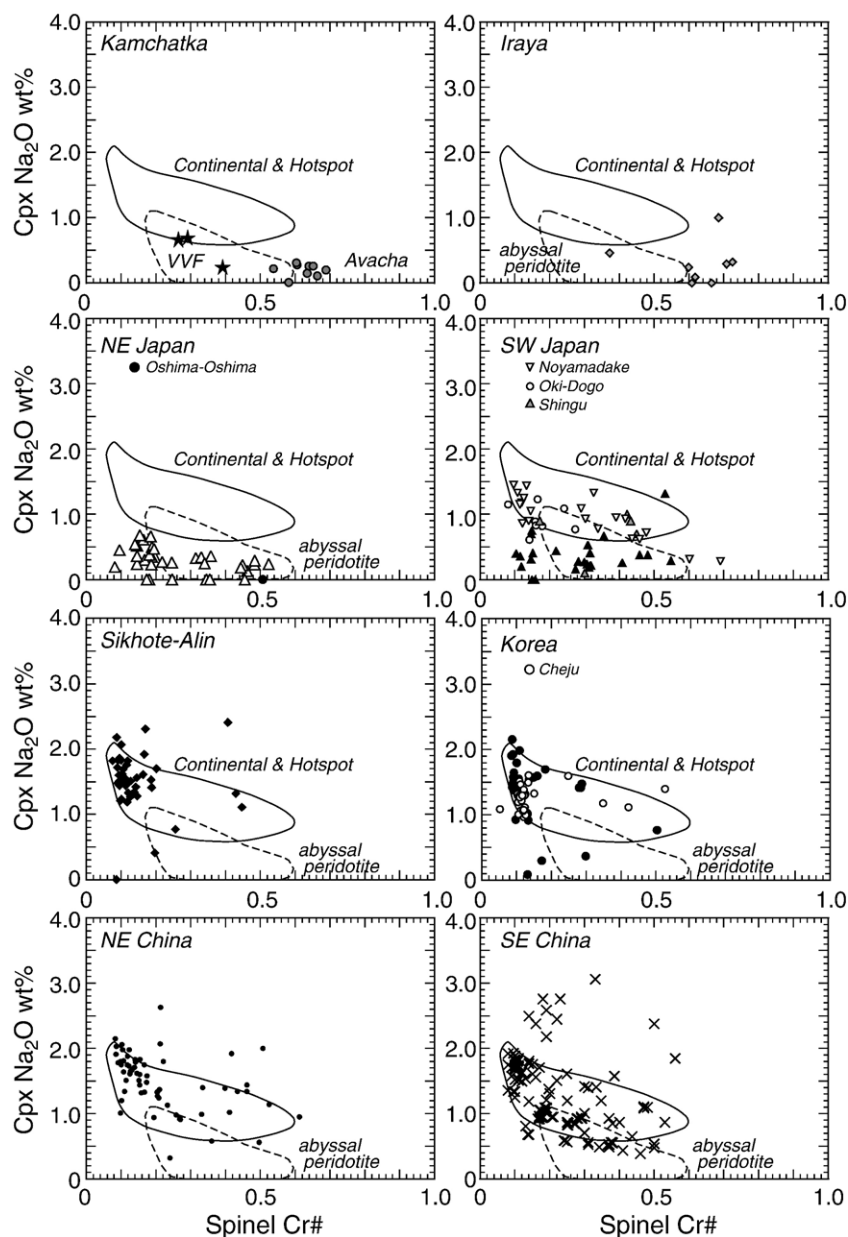


Fig. 4. Relationships between Na_2O content of clinopyroxene and $\text{Cr}\#$ of coexisting chromian spinel in spinel peridotite xenoliths from the Western Pacific. This diagram has been discussed in detail in Arai (1991, 1994a) and Arai et al. (2001a). Peridotites free of plagioclase and amphibole are plotted. The fields of abyssal peridotite and continental/hotspot xenolithic peridotite from Arai (1991) are shown by broken and solid lines, respectively. Note that the peridotite on average gradually changes from low-pressure peridotite with low-Na clinopyroxene in the frontal side of arc (Avacha and Iraya) to high-pressure peridotite with high-Na clinopyroxene in continent (Korea, Sikhote-Alin and China) through Japan arcs (see text). Note that Shingu and Oki-Dogo (Fig. 1), and Cheju (Fig. 1), are included in SW Japan and Korea areas, respectively, in this figure. Data source: Abe (1997), Abe et al. (1992, 1995, 2003), Arai et al. (2000, 2001a, 2003a, 2004), Arai and Kida (2000), Choi et al. (2001), Choi and Kwon (2005), Fan and Hooper (1989), Goto and Arai (1987), Hirai (1986), Ishimaru (2004), Kepezhinskis et al. (1995), Lee (1996), Nezuka (1998), Ninomiya and Arai (1992), Song and Frey (1989), Takahashi (1978b), Xu et al. (1996, 2000), Xu and Bodinier (2004), Xu et al. (1998), and Zhang et al. (2000).

Some of spinel peridotite xenoliths from the Western Pacific contain hydrous minerals. The Megata peridotite suite from the Northeast Japan arc is the most famous example (e.g. Aoki and Shiba, 1973; Arai, 1986). Some of the hydrous minerals replace primary anhydrous minerals, indicating metasomatism (e.g. Arai, 1986; Abe et al., 1992). Note that the TiO_2 content of the hydrous minerals increases, on average, from the frontal side of arc (Avacha and Iraya) to continent (Sikhote-Alin and northeast China) through the backarc side of arc (Megata) (Fig. 5).

3.2. Trace element chemistry of clinopyroxene

In situ trace element analyses of minerals, such as those on clinopyroxene by ion-microprobe (SIMS; secondary ion microspectrometry) and laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS), have become in widespread use for the last decade, and the trace element chemistry of peridotite xenoliths is easily obtainable in the literature now. The trace element chemistry of clinopyroxene in

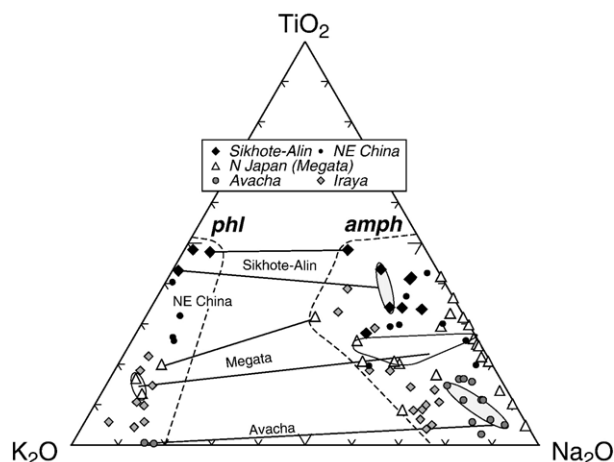


Fig. 5. TiO_2 – K_2O – Na_2O ratios (weight) of secondary hydrous minerals (amphibole and phlogopite) in spinel peridotite xenoliths from the Western Pacific. Coexisting pairs are indicated by solid line. Data source: Abe (1997), Abe et al. (1992, 1995), Arai (1986), Arai et al. (2003a, 2004), Ionov and Hofmann (1995), Ishimaru (2004), Johnson et al. (1996), Nezuka (1998), Xu and Bodinier (2004), and Zhang et al. (2000).

peridotite xenoliths from the Western Pacific is compiled and examined for comparison here. Clinopyroxene is known for the main container of rare earth and some other trace elements in four-phase anhydrous spinel peridotite (Salters and Shimizu, 1988), except for peculiar accessory minerals such as apatite and zircon. The chondrite-normalized REE (rare earth element) pattern of clinopyroxene in lherzolite is nearly identical to that of its whole rock (e.g. Rampone et al., 1991; McDonough et al., 1992). Furthermore, their HREEs (heavy REEs) concentrations vary systematically with the degree of melt extraction of peridotite samples (e.g. Hellebrand et al., 2001).

Clinopyroxenes in the Avacha and Iraya peridotites (C-type) are quite poor in MREEs (middle REEs) to HREEs (heavy REEs) (Ishimaru, 2004). They show LREE (light REE)-depleted and spoon-shaped chondrite-normalized REE patterns with depletion in HREE (Ishimaru, 2004). MREE contents are sometimes less than detection limits (e.g., less than 0.02 ppm for Ce), and HREE contents are slightly higher than detection limits (e.g., 0.04 ppm for Yb). Some of them are also poor in Ti and Zr, 50–170 ppm and around 1.0 ppm, respectively (Fig. 6). Most of the samples from Avacha and Iraya are too depleted in LREEs and HFSEs (high field strength elements) to compare with any other peridotite samples on chemical diagrams. Only a few samples are detectable for trace elements in clinopyroxene by in situ analysis (Fig. 6).

Abe et al. (1998, 2003) and Abe and Arai (2005) reported the trace element chemistry of clinopyroxenes, mainly of Cr-diopside, in Japan-arc peridotite xenoliths obtained by SIMS. The REE patterns of their clinopyroxenes are highly variable even though within the same xenolith suite. They show LREE-depleted convex upward to LREE-enriched, HREE-depleted patterns, and some of them show v-shaped or spoon-shaped patterns with MREE depletion (Abe et al., 1998; Abe and Arai, 2005). The variation of the REE patterns is intimately associated with the variety of microtextural

characteristics and major element chemistry of the samples (Abe et al., 1999).

Abe et al. (1999) distinguished low-T (temperature) and high-T types of peridotite xenoliths with different geochemical characteristics from the Southwest Japan arc. Peridotite xenoliths from On-yama and Kurose belong to the low-T type (Abe et al., 1999). As in the case of the major element mineral chemistry, the On-yama lherzolites are relatively homogeneous with respect to chondrite-normalized REE pattern (Abe et al., 1998), except for one sample. Their chondrite-normalized REE patterns are LREE-depleted convex-upward, except for one sample enriched in LREE. The Ti, Zr and Sr contents are relatively variable, although the Cr# of coexisting spinel is almost constant. Ti and Zr content are relatively high, 1003–1400, and around 10 ppm, respectively, although the Sr contents are low, 3.5–12.1 ppm. The chondrite-normalized REE pattern of clinopyroxenes in Kurose peridotite is variable from LREE-enriched to slightly LREE-depleted, being depleted in all REEs. Their Ti/Zr ratio is constant (166–468 ppm), but $(\text{Ce}/\text{Yb})_N$ (suffix N, chondrite-normalized; chondritic abundances after Anders and Grevesse, 1989) varies from 0.2 to 2.0 (Fig. 6).

Peridotite xenoliths from Noyamadake and Kawashimo belong to the high-T type of Abe et al. (1999). In contrast to low-T type ones, abundances of trace elements are variable in high-T type peridotites in accordance with a wide range of the Cr# of coexisting spinel (Abe et al., 2001). The chondrite-normalized REE patterns are variable from relatively flat to LREE enriched/HREE-depleted for the Kawashimo samples (Abe and Arai, 2005). Ce_N and $(\text{Ce}/\text{Yb})_N$ increase from 3.9 to 21 and 0.6 to 5, respectively, and Yb_N , Ti and Zr contents and Ti/Zr weight ratio decrease from 15.8 to 2.3, from 3380 to 500 ppm, from 7.0 to 1.5 ppm, and from 200 to 50, respectively, with an increase of Cr# of coexisting spinel (Fig. 6). Two samples examined from the Noyamadake xenolith suite have completely different clinopyroxene trace element characteristics. The sample OG 104 has a slightly LREE-depleted chondrite-normalized REE pattern although REEs are generally high (Abe and Arai, 2005), whereas the sample OG-103 has a LREE-enriched chondrite-normalized REE pattern with a depletion in HREE. Sr_N in clinopyroxenes from the Noyamadake peridotite is the highest (8.7 and 14.5) of all samples from the Japan arcs (Abe et al., 1999; Abe and Arai, 2005).

Clinopyroxenes in the Megata peridotite are variable in both trace element abundances (Fig. 6) and chondrite-normalized REE patterns (Abe and Arai, 2005). Ti and Zr contents are 230–3635 and 2.9–25.7 ppm, respectively, and Sr_N varies from 0.1 to 7.1. The most hydrated peridotite (I-610) has the clinopyroxene that is the most enriched in Ce, and is enriched with LREEs (Abe and Arai, 2005). The $(\text{Ce}/\text{Yb})_N$ varies greatly from 0.04 to 4.0 and the Ti/Zr ratio varies from 27.5 to 313, but the majority is around 100 (Fig. 6). Generally, Yb_N and Ti and Zr contents decrease and $(\text{Ce}/\text{Yb})_N$ and Sr content increase with an increase of the Cr# of coexisting spinel (Fig. 6).

The REE patterns of clinopyroxene in Boun peridotite xenoliths, Korea, are mostly flat and slightly depleted in LREEs (Arai et al., 2001a). Minerals mostly show inter-grain chemical homogeneity for both trace and major elements (Arai et al.,

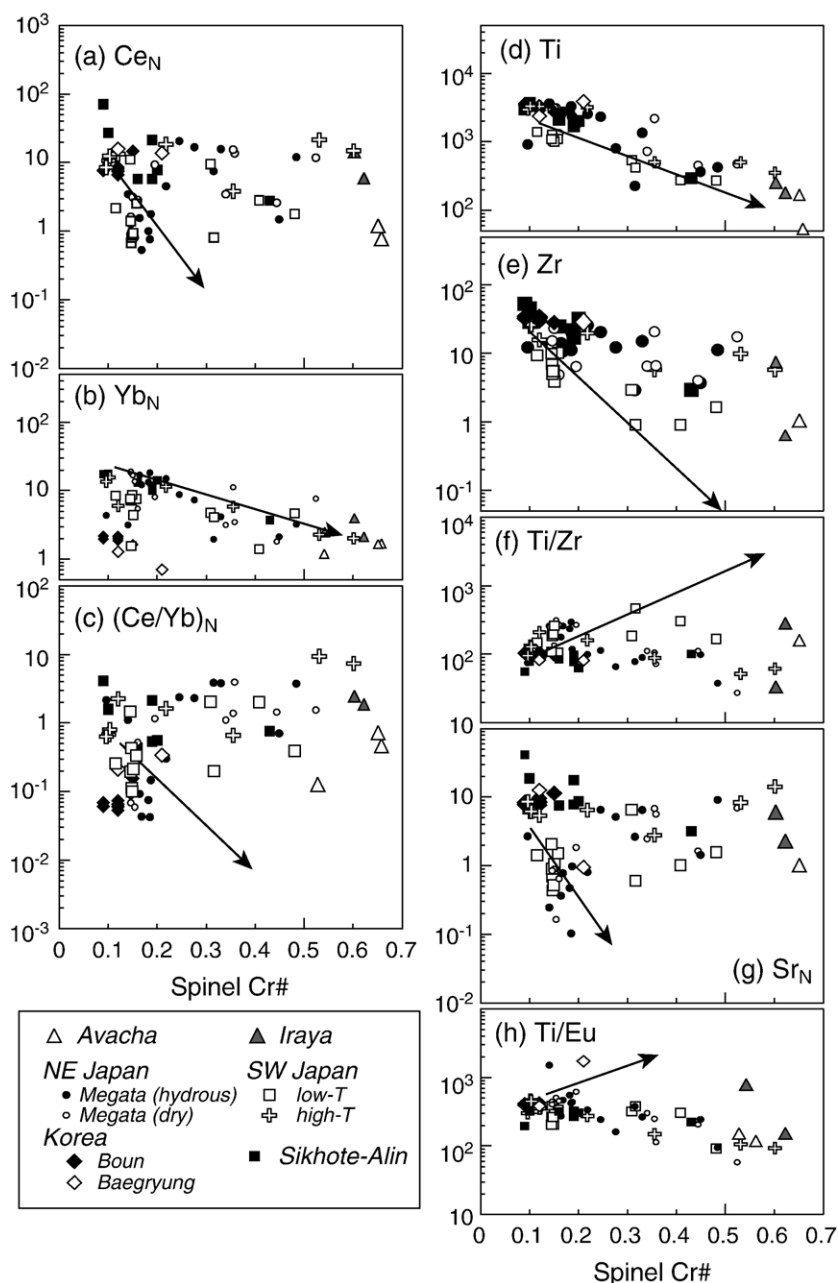


Fig. 6. Correlations between $Cr\#$ ($=Cr/(Cr+Al)$ atomic ratio) of chromian spinel and trace element characters of coexisting clinopyroxene in spinel peridotite xenoliths from the Western Pacific. Suffix N means normalization to chondritic values (Anders and Grevesse, 1989). Lines with arrowhead indicate a trend for abyssal peridotite. Data source: Abe (1997), Abe et al. (1998, 1999, 2003, 2004), Abe and Arai (2005), Arai et al. (2001a), Choi et al. (2001), Ionov et al. (1995), Ishimaru (2004), Xu et al. (2000), Xu et al. (1998), Xu and Bodinier (2004), Zhang et al. (2000), and Zheng et al. (2005).

2001a). The exceptional sample (Bo-19) with LREE-enriched pattern has slightly higher $Cr\#$ of spinel. The Boun peridotites are relatively rich in HFSEs ($Ti > 2700$ ppm, $Zr > 28$ ppm). Two samples from Baegryung (Baengnyeong) Island were analyzed for their trace element chemistry. Their clinopyroxenes show HREE-depleted and slightly LREE-enriched patterns with constant LREE concentrations. Choi et al. (2001) reported the bulk-rock and clinopyroxene geochemical characteristics of Cheju lherzolite xenoliths. Their clinopyroxenes have flat to LREE-enriched REE patterns, being basically the same as the other Korean samples.

Clinopyroxenes in peridotite xenoliths from Sikhote-Alin show slightly LREE-depleted to LREE-enriched trace element patterns (Ionov et al., 1995; Abe et al., 2004). The LREEs/HREEs ratio of clinopyroxene varies largely, while the $Cr\#$ of coexisting spinel is rather constant between 0.08 and 0.45, mostly 0.1–0.2 (Nezuka, 1998).

Clinopyroxenes in spinel peridotite xenoliths from north-east to south-east China (e.g. Zhang et al., 2000; Zheng et al., 2005; Yu et al., 2006) generally have $(Ce/Yb)_N$ ratios higher than unity, which means the samples are more enriched in LREEs than any samples from other localities of

the Western Pacific. Ti/Zr ratio varies widely from 4.7 to 1300 (Fig. 6).

4. Physical conditions recorded by the peridotite

4.1. Pressure–temperature conditions

Garnet-bearing peridotites have been reported only from eastern China in the Western Pacific (e.g. Fan and Hooper, 1989; Xu et al., 2000) in the Western Pacific, indicating a derivation from deeper parts than most of the other peridotites that are garnet-free and spinel-bearing. No meaningful geobarometry is applicable to these peridotites from the spinel-lherzolite stability field. Some lherzolite xenoliths from Megata volcano, the Northeast Japan arc, contain symplectites of colorless spinel and pyroxenes, which are a reaction product of calcic plagioclase and olivine (Takahashi, 1986). This records a transition from the plagioclase-lherzolite field to spinel-lherzolite field on cooling, indicating a derivation from the shallowest part of the upper mantle.

Peridotite xenoliths are important as a recorder of thermal condition of the upper mantle. Two-pyroxene thermometer of Wells (1977) is adopted in this article because it has been widely used in literature, and a comparative study will be much easier here. The equilibrium temperatures of Japanese samples were reported by Arai et al. (1998), Arai et al. (2001b) and Abe and Arai (2005). According to Abe and Arai (2005), the equilibrium temperature of the samples from the Northeast Japan arc (Megata and Oshima–Oshima) is relatively low, between 850 and 1100 °C (average 950 °C) (Fig. 7). Some xenoliths in the Southwest Japan arc (On-yama, Kurose, Takashima, Arato-yama, Shingu) provide temperatures similar to but slightly higher than those from the Northeast Japan arc (900–1150 °C; 1053 °C on average) (Fig. 7). On the contrary, Noyamadake, Kawashimo and Fukuejima in the Southwest Japan arc show quite high equilibrium temperatures, higher than 1100 °C (1100–1250 °C; 1193 °C on average) (Fig. 7). On the other hand, Oki-Dogo samples also have high and relatively uniform equilibrium temperatures (1100–1150 °C) (Fig. 7).

Peridotite xenoliths from Boun (Lee, 1996), Cheju (Jeju) Island (Yun et al., 1998; Choi et al., 2001) and Baegryung Island (Choi and Kwon, 2005) have the equilibrium temperatures similar to those from the Northeast Japan arc (837–1089 °C; 940 °C on average) (Fig. 7).

Ionov et al. (1995) and Nezuka (1998) estimated the equilibrium temperature of peridotite xenoliths from Sikhote-Alin (Fig. 7). The temperature varies from 845 to 1115 °C

(987 °C on average), and 80% of the samples are within a narrow temperature range, 950–1050 °C, in spite of a wide area covered by the xenolith suites (Fig. 1).

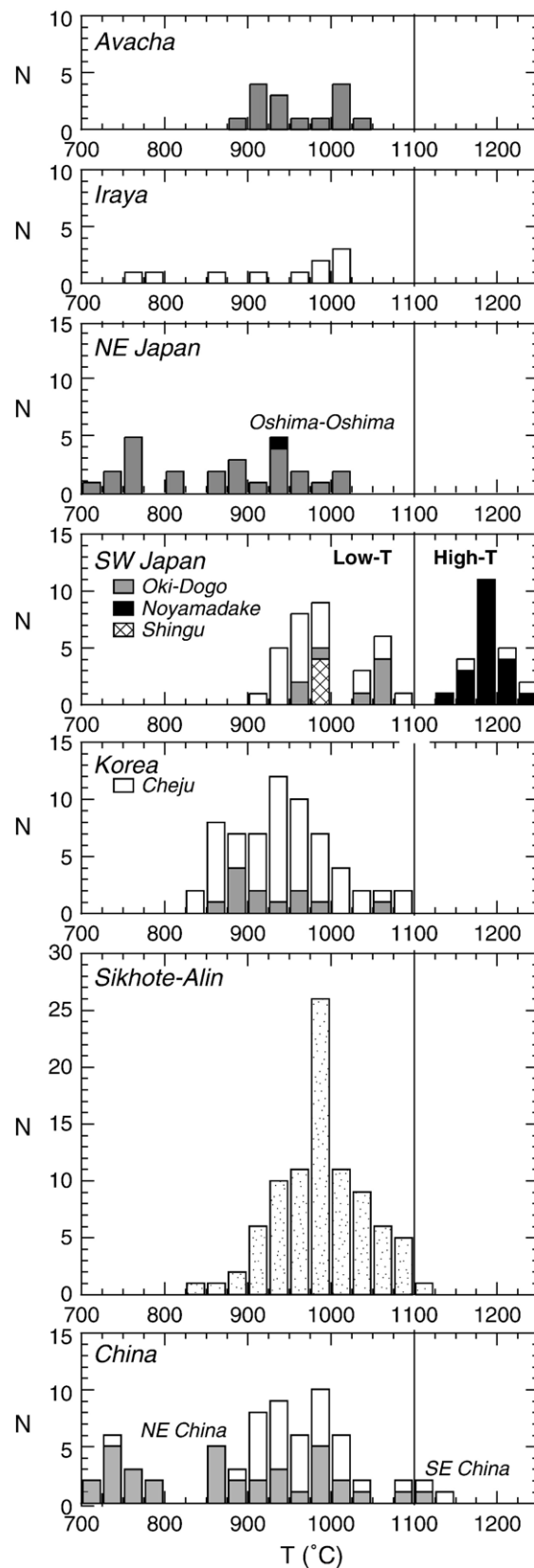


Fig. 7. Histograms of equilibrium temperature of spinel peridotite xenoliths from the Western Pacific. Temperatures by the two-pyroxene thermometer of Wells (1977). N, number of samples. Note that Shingu and Oki-Dogo (Fig. 1), and Cheju (Fig. 1), are included in SW Japan and Korea areas, respectively, in this figure. Data source: Abe (1997), Abe and Arai (2005), Abe et al. (2003), Arai and Kida (2000), Arai et al. (2003a, 2004), Choi et al. (2001), Choi and Kwon (2005), Fan and Hooper (1989), Goto and Arai (1987), Hirai (1986), Ionov et al. (1995), Ishimaru (2004), Lee (1996), Nezuka (1998), Takahashi (1978b), Xu et al. (1996), Xu et al. (1998), Xu and Bodinier (2004), Yun et al. (1998), and Zhang et al. (2000).

Avacha peridotite xenoliths from the Kamchatka arc have equilibrium temperatures as low as those in peridotite xenoliths from the Northeast Japan arc (885–1040 °C; 960 °C on average; Arai et al., 2003a; Ishimaru, 2004) (Fig. 7). Similar to the

Avacha peridotite xenoliths, Iraya peridotite xenoliths have low equilibrium temperatures between 758 and 1024 °C (947 °C on average; Abe, 1997; Arai and Kida, 2000; Arai et al., 2004). The temperatures lower than 800 °C are the lowest of all peridotites described in this paper.

Spinel peridotite xenoliths from eastern China demonstrate relatively low temperatures, being almost equivalent to those from Korea, Sikhote-Alin, Northeast Japan arc and Southwest Japan arc (low-T type) (Fig. 7).

4.2. Oxygen fugacity

Olivine–orthopyroxene–spinel oxygen barometry of Ballhaus et al. (1990) was adopted to examine the redox state of the lithospheric mantle of the Western Pacific. Delta (Δ)FMQ values (oxygen fugacity relative to the FMQ value) were calculated assuming an equilibrium pressure of 1.5 GPa. Arai et al. (2003a) claimed high fO_2 of Avacha peridotite xenoliths, Kamachatka, especially highly metasomatized ones. As shown in Fig. 8, the peridotite xenolith exhibits the highest fO_2 from Avacha and Iraya volcanoes in the Western Pacific. Xenoliths from the continental region (China, Sikhote-Alin and Korea) show relatively high fO_2 values, almost comparable to that of abyssal peridotite (Ballhaus et al., 1991). Mantle peridotites from the Japan arcs have the intermediate fO_2 (Fig. 8). The relatively high fO_2 values recorded by the mantle-wedge peridotite are almost comparable to the values reported from other sub-arc peridotites (Brandon and Draper, 1996; Blatter and Carmichael, 1998; Parkinson and Arculus, 1999).

5. Discussion

5.1. Mantle processes deduced from the peridotite xenoliths

5.1.1. Partial melting

The peridotite is highly various in terms of degree of partial melting in the Western Pacific (Figs. 2 and 3). It is obvious that lherzolite is predominant as mantle peridotite xenolith over harzburgite on the rim of Eurasian continent (China, Korea and Sikhote-Alin) (Fig. 2). In contrast to this, highly depleted

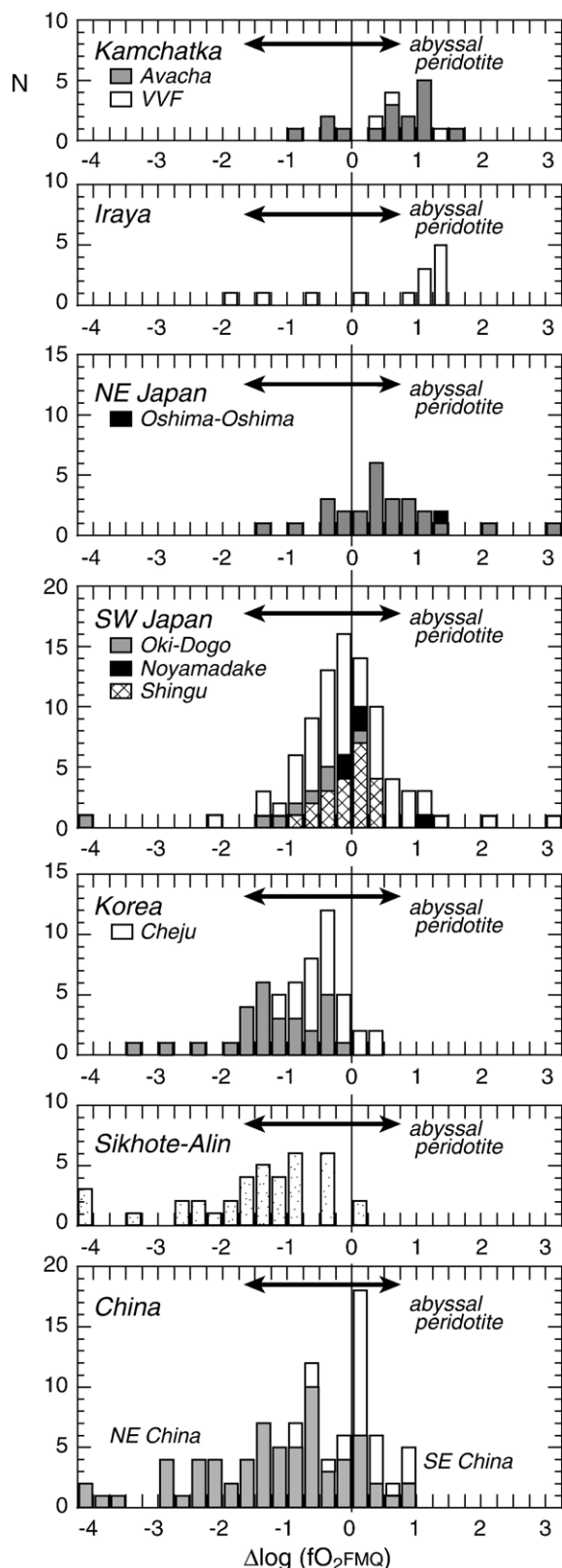


Fig. 8. Histograms of $\log\Delta FMQ$ of peridotite xenoliths from the Western Pacific. The oxygen barometer of Ballhaus et al. (1990) was used for calculation. A pressure of 1.5 GPa was postulated for all peridotites, and the temperature was by the olivine–spinel thermometer of Ballhaus et al. (1990) for the convenience of calculation. The range for abyssal peridotite (Ballhaus et al., 1991) is shown for reference. Zero means the oxygen fugacity of FMQ buffer, plus and minus signs mean oxidation and reduction, respectively, relative to the FMQ buffer. Note the oxygen fugacity decreases on average from depleted harzburgite in the frontal side of arc (Avacha and Iraya) to fertile lherzolite in continent (Korea, Sikhote-Alin and China) through Japan arcs. N, number of samples. Note that Shingu and Oki-Dogo (Fig. 1) and Cheju (Fig. 1) are included in SW Japan and Korea areas, respectively, in this figure. Data source: Abe (1997), Abe et al. (1992, 1995, 2003, 2004), Arai et al. (2001a, 2003a), Arai and Kida (2000), Choi et al. (2001), Choi and Kwon (2005), Fan and Hooper (1989), Goto and Arai (1987), Hirai (1986), Ishimaru (2004), Kepezhinskis et al. (1995), Lee (1996), Nezuka (1998), Ninomiya and Arai (1992), Song and Frey (1989), Takahashi (1978b), Xu et al. (1996), Xu and Bodinier (2004), Xu et al. (1998), and Zhang et al. (2000).

peridotite (harzburgite with high-Cr# (>0.6) spinel) is commonly found from Avacha volcano, Kamchatka, and Iraya volcano, Philippines, both of which are around the volcanic front (Fig. 3). Highly depleted harzburgites, which contain high-Cr# (>0.6) spinel, are rare as xenoliths on the Japan island arcs (e.g. Arai, 1991, 1994a; Abe and Arai, 2005), although they are expected to exist in the upper mantle (cf. Arai, 1994b). Note that some of the depleted spinel harzburgite, frequently associated with garnet lherzolite, from the cratonic areas are restites of high degree of melting within the garnet-lherzolite stability field (Arai, 1993). The degree of partial melting can be high within the mantle wedge because slab-derived aqueous fluids behave as a flux on partial melting (e.g. Kushiro, 1969). The existence of highly depleted peridotite beneath the volcanic front is consistent with the high magma production rate there (e.g. Ui and Aramaki, 1978). This seems to be also consistent with the occurrence of highly depleted peridotite from the fore-arc mantle of oceanic island arcs (e.g. Bloomer, 1983; Parkinson and Pearce, 1989). At some early stage of oceanic

island arc formation, the high degree of partial melting could have been achieved by subduction of then hot oceanic lithosphere, if any (cf. Ishikawa et al., 2002). Aqueous fluids from the slab may be most extensively supplied around the upper corner of the mantle wedge (cf. Tatsumi, 1986), which can be the very locus for high-degree partial melting if the thermal condition is permitted (e.g. Tatsumi and Maruyama, 1989).

Some peridotite xenoliths from the Japan arcs as well as Avacha (Kamchatka) and Iraya (Philippines) xenoliths are restites formed at lower pressures than other continental peridotite xenoliths from Korea, eastern China and Sikhote-Alin because the former contain low-Na clinopyroxene at a given degree of partial melting (Cr# of spinel) (Fig. 4). This is consistent with the thickness of lithosphere, which increases from the trench-arc-backarc region to continental region.

The compiled data in this paper are compared with published data of abyssal peridotites, which are mostly explained as simple residue (Dick, 1989; Johnson et al., 1990) (Fig. 9). Some peridotites from the Japan arcs, Iraya and Kamchatka are

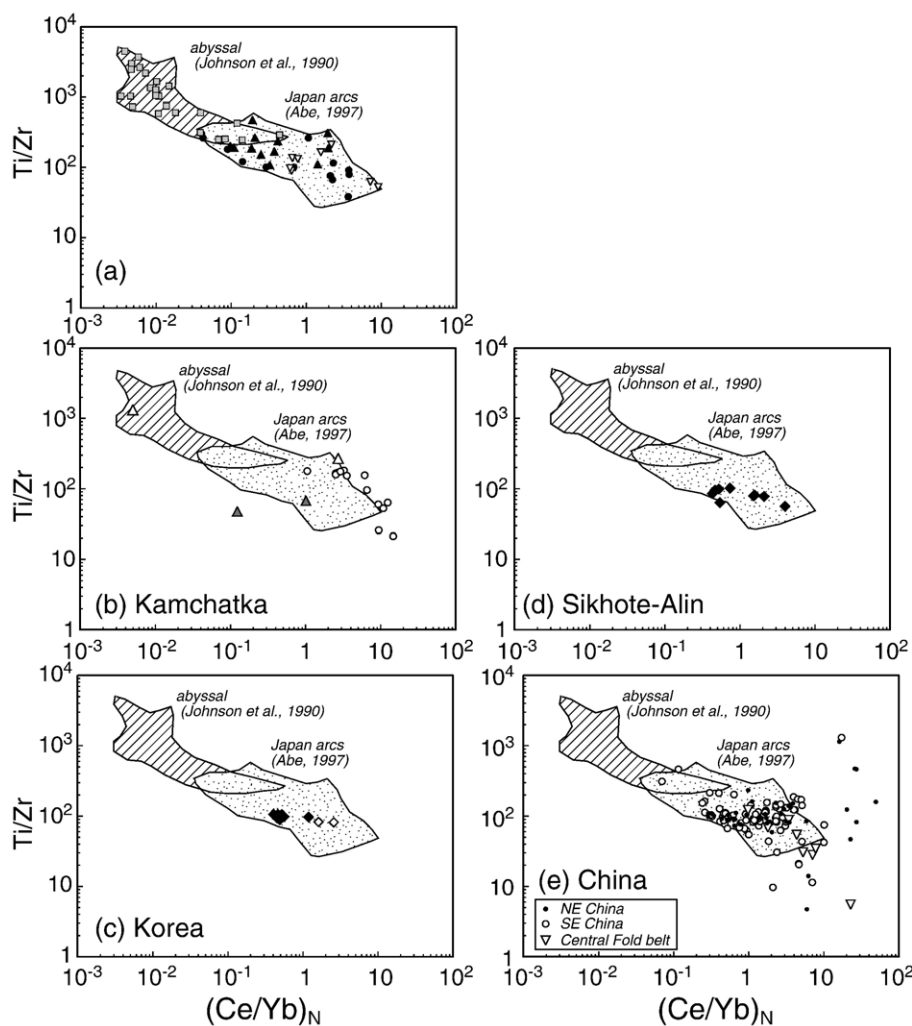


Fig. 9. Relations between Ti/Zr ratio and $(Ce/Yb)_N$ in clinopyroxenes from spinel peridotite xenoliths from the Western Pacific. Suffix N means normalization to chondritic values (Anders and Grevesse, 1989). Fields for abyssal peridotite and Japan-arc peridotite xenoliths are after Abe (1997). Data source: Abe (1997), Abe et al. (1998, 1999, 2003, 2004), Abe and Arai (2005), Arai et al. (2001a), Choi et al. (2001), Ionov et al. (1995), Ishimaru (2004), Xu et al. (2000), Xu et al. (1998), Xu and Bodinier (2004), Zhang et al. (2000), and Zheng et al. (2005).

overlapped in chemistry with the abyssal peridotite, possibly indicating their residual origin after simple melt extraction. Most other samples from the Western Pacific, however, cannot be simple residual materials. If the peridotites were products of simple melt extraction, incompatible elements have to decrease with an increase Cr# of spinel, because the Cr# of spinel is a good measure of degree of melt extraction in mantle peridotite (Dick and Bullen, 1984; Arai, 1994a). Ti, Y and Yb contents of examined clinopyroxene from the arc peridotite decrease with an increase of the Cr# of coexisting spinel (Fig. 6). Ce, Zr and Sr contents of clinopyroxene, however, have no clear correlations with the Cr# of spinel (Fig. 6) in the arc peridotites. The Ce content of clinopyroxene does not decrease with an increase of the Cr# of spinel (Fig. 6a). (Ce/Yb)_N ratios slightly increase rather than decrease with an increase of Cr# of spinel (Fig. 6c). Such a correlation between REE and major element contents in mantle peridotites was first recognized in the peridotite xenoliths by Frey and Green (1974), and has been reported from many peridotite xenoliths and massif peridotites all over the world except for the abyssal peridotites (cf. McDonough and Frey, 1989). Furthermore, the Ti/Zr ratio in clinopyroxene is constant or slightly decreases with an increase of the Cr# of spinel (Fig. 6f). The peridotites from Japan arcs have slightly less volume of clinopyroxene than abyssal peridotites. In terms of their major element chemistry of minerals (cf. Arai, 1994a) and trace element contents of clinopyroxene, however, the fertile samples from the arcs are quite similar to the fertile abyssal peridotite. It is possible, therefore, that the peridotites from the arcs had shared the same source with the abyssal peridotite, but they have evolved through different processes.

5.1.2. Metasomatism 1: hydration

Formation of secondary hydrous minerals has been observed in limited localities of mantle peridotite xenoliths from the Western Pacific, although hydration is widely expected in the mantle-wedge peridotite (e.g. Johnson et al., 1996). Hydration in peridotite has been observed in some peridotite xenoliths derived from mantle wedge in the Western Pacific. The Megata xenolith suite, Northeast Japan arc, is especially famous for hydration (e.g. Aoki and Shiba, 1973; Arai, 1986). To be interesting, amphibole is far more predominant over phlogopite as secondary metasomatic minerals in the mantle peridotite xenoliths from this area. This is ascribed to a kind of fractionation of metasomatic fluids in terms of Na/K ratio within the mantle wedge (Arai, 1986). Phlogopite and amphibole (mainly pargasite) were selectively precipitated in the deeper part (=garnet lherzolite stability field) and in the shallower part (=spinel lherzolite stability field), respectively, within the mantle (e.g. Arai, 1986). To our knowledge, the hydrous minerals that seem to be non-metasomatic and possibly primary have not been documented from the Western Pacific.

Phlogopite and amphibole in the mantle-wedge derived peridotites are characterized by relatively low contents of Ti, one of HFS elements (Fig. 5). This is in a good contrast with relatively Ti-rich character of hydrous minerals from continental lithosphere (e.g. eastern China and Sikhote-Alin) (Fig. 5). The low-Ti character of hydrous minerals from the mantle-

wedge peridotite is consistent with the low HFSE contents of slab-derived fluids/melts (e.g. Keppler, 1996).

The high fO_2 seems to be associated with hydration or aqueous-fluid related metasomatism in peridotite xenoliths (e.g. Parkinson and Arculus, 1999). The peridotite xenoliths from Avacha and Iraya, which have the highest fO_2 values, were metasomatized to various extents by hydrous fluids and/or melts (Vidal et al., 1989; Schiano et al., 1995; Arai et al., 2003a, 2004). This is consistent with the observation that Fe^{3+} content of chromian spinel increases with increasing the amount of metasomatic pargasite in the Ichinomegata peridotite (Abe et al., 1992). Sulfur plays an important role in determination of redox state of magmas and their source mantle (e.g. De Hoog et al., 2004). Sulfides are frequently contained in highly metasomatized peridotites (e.g. Hattori et al., 2002; Arai et al., 2003a). This suggests a role of sulfur species (SO_4^{2-} ion) in metasomatizing fluids derived from slab (De Hoog et al., 2001), which enhanced oxidizing condition by precipitation of sulfides.

5.1.3. Metasomatism 2: Silica enrichment

Silica enrichment of the mantle wedge by slab-derived melts/fluids has been expected by Kelemen (1995). Formation of secondary orthopyroxene at the expense of olivine is observed in the peridotite xenoliths from Iraya volcano, Philippines (Arai and Kida, 2000; Arai et al., 2004) and Avacha volcano, the Kamchatka arc (Arai et al., 2003a). Modal amounts of total orthopyroxenes increase with increasing the degree of this type of metasomatism (Ishimaru, 2004). Similar process has been reported from other peridotite xenoliths derived from the mantle wedge or from the arc-related mantle (e.g. Ertan and Leeman, 1996; Smith et al., 1999; Grégoire et al., 2001; Franz et al., 2002). This type of orthopyroxenite is characterized by scarcity of other associated silicates. Silica-rich fluids derived from the slab or separated from hydrous magma were the agent for this metasomatism (see Arai et al., 2004). The upper mantle peridotite increases in orthopyroxene component through this type of metasomatism (Arai et al., 2003a; Ishimaru, 2004).

Silica-rich melts derived from slab can form plagioclase-quartz (quartz dioritic) rocks with selvage of orthopyroxene at the expense of olivine within the mantle wedge (Arai et al., 2003b; Shimizu et al., 2004). This type of enrichment of mantle in silica is possible in the Western Pacific, because slab melts (=adakites) have erupted or intruded into the crust there (e.g. Tsuchiya and Kanisawa, 1994). Pyroxene-rich xenoliths in adakites and high-Mg andesites are interpreted as their cumulates and/or reaction products between peridotite and slab-derived melts (Tsuchiya et al., 2005).

Alkaline basaltic magmas can enrich mantle peridotite in silica (orthopyroxene) if they were highly fractionated within the mantle (Arai et al., in press). The alkali basaltic melt slightly undersaturated with silica can take the “straddle trend” of Miyashiro (1978) to become silica-oversaturated on fractionation in the upper mantle. Fine-grained orthopyroxenite xenoliths from Takashima, northern Kyushu (Fig. 1) are interpreted to be a reaction product between an evolved magma of alkali basalt affinity (=trachyte?) and mantle dunite

(Arai et al., in press). Alkaline basalts with slight silica undersaturation of Cenozoic age, related with the Japan-Sea opening, were prevalent in the inner (continent-ward) part of southwest Japan (Takamura, 1973), and such a type of silica enrichment is also common in the uppermost mantle in the Western Pacific.

5.1.4. Shearing

Arai et al. (2004) proposed a possibility of shearing origin of fine-grained type (F-type) peridotite xenoliths found at both Iraya volcano, Luzon–Taiwan arc, and Avacha volcano, Kamchatka arc. The shearing is due to strike-slip movement of overlying wedge during oblique subduction (Fitch, 1972). The occurrence of the F-type peridotite xenolith exclusively from the on-front volcanoes seems to be consistent with the prediction of Fitch (1972) that the strike-slip faults appear around the volcanic front. The sinistral NE–SW trending strike-slip fault systems in East Asia (e.g. Xu et al., 1989; Lee, 1999) may be accumulative surface manifestation of NE-trending movement of the eastern tip of the Eurasia plate.

5.2. Petrological model of the upper mantle of the Western Pacific

The petrological model of the upper mantle beneath the Western Pacific region may not be simple, being reflected by its complicated geological history (Fig. 10). At the eastern front of the Eurasian continent, the mantle wedge has been evolved through addition of materials from slab as well as subtraction of melt components as arc magmas. Opening of back-arc basins, such as the Sea of Japan (Japan Basin) and South China Basin, at the Tertiary time (e.g. Karig, 1971; Tamaki and Honza, 1991) has greatly modified the upper mantle structure by large-scale upwelling of asthenospheric mantle (e.g. Miyashiro, 1986; Iwamori, 1991). Arai et al. (2000) presented a petrological model of upper mantle beneath the Western Pacific; the mantle peridotite has been metasomatized, to various degrees, by the melt that produced Group II pyroxenites. The melt was ascribed to a large-scale asthenospheric upwelling for the Japan-Sea

opening (Uto, 1990; Iwamori, 1991). This model is, therefore, applicable widely to the Western Pacific, which has backarc basins of Tertiary age (Tamaki and Honza, 1991). Yu et al. (2006) also discussed detailed metasomatism of mantle peridotite by the melt that precipitated Group II pyroxenites (Al-augite pyroxenites) from South China. This metasomatism and formation of Group II rocks were related to the opening of the South China Basin (Yu et al., 2006).

The almost absence of the arc-type mantle, i.e. low-pressure peridotites with low-Na clinopyroxene and sometimes with high-Cr# spinel, in the continental area is noteworthy. If the accretion of arc is one of the important elements of continental growth (cf. Faure and Natal'n, 1992), this type of peridotite is expected to exist beneath the continental margin. Arai et al. (2001a) briefly discussed a possibility of its replacement by high-pressure more fertile lherzolites due to upwelling of asthenospheric mantle behind the arc. This may be related with a counter-flow of deep asthenospheric mantle towards mantle wedge along with slab descent (Fig. 10).

Lithospheric mantle peridotites sampled by Cenozoic basalts from eastern China, Sikhote-Alin and Korea (continental margin) are mostly fertile spinel lherzolites (Song and Frey, 1989; Xu et al., 1996, 1998; Yu et al., 2006), decoupled with overlying cratonic continental crust. A large number of geochemical and petrological studies of the mantle xenoliths from northeast to southeast China (Xu et al., 1998, 1996, 2000; Zhang et al., 2000; Chen et al., 2001; Zheng et al., 2005) confirm the existence of a thick (~200 km) cratonic lithosphere with a cold geotherm before the Paleozoic (Griffin et al., 1998), which has been transformed into a thin lithosphere (80–110 km) with a hot geotherm in the Cenozoic (e.g. Chen et al., 2001). The young lithospheric mantle is quite different from the Paleozoic one deduced from xenocrysts and xenoliths in kimberlites, which was depleted in harmony with the thick continental crust (Xu et al., 2000; O'Reilly et al., 2001). A seismic tomography profile across the North China Craton along latitude 36°N clearly reveals the presence of isolated high-Vp zones dispersed within a region with generally low Vp at depths of 100 km (see Zheng

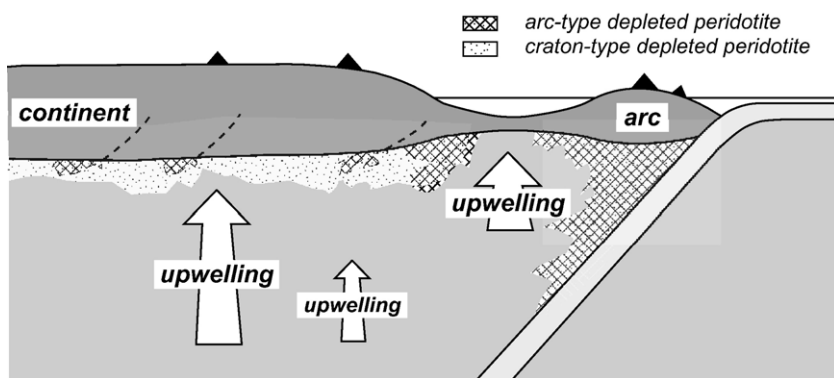


Fig. 10. A cartoon to show the petrological constitution and evolution of the upper mantle of the Western Pacific. Highly depleted spinel peridotite had been formed beneath both cratonic areas (cf. Takahashi, 1990; Arai, 1993) and arc areas (cf. Arai, 1994b). Arc-type depleted peridotite may have existed in the sub-continental mantle if accretion of arcs have contributed to continental growth. These depleted peridotites have been replaced with upwelling fertile lherzolite (O'Reilly et al., 2001). See also Arai et al. (2001a).

et al., 2005). Interpretation of this profile has led to a “mushroom cloud” model, which envisages thinning of the lithosphere beneath the North China craton during the late Mesozoic as a result of extension of the ancient mantle root and mixing with the upwelling asthenosphere (e.g. Griffin et al., 1998). Large-scale asthenospheric upwelling caused replacement of the old depleted mantle peridotites of Precambrian age with young fertile spinel peridotites (Xu et al., 2000; O'Reilly et al., 2001). The asthenospheric upwelling has been frequent in the Western Pacific, and some of the mantle diapirs impacted the continental margin to produce backarc basins at Tertiary (cf. Miyashiro, 1986; Iwamori, 1991). Densely populated strike-slip faults, which have been active since the Jurassic (e.g. Xu et al., 1989), possibly facilitated their upwelling in the Western Pacific.

The high-T type peridotite xenoliths from Noyamadake, Kawashimo and Fukuejima, the Southwest Japan arc, show extremely high equilibrium temperatures almost equivalent to the asthenosphere–lithosphere boundary (~1250–1300 °C). These temperatures are too high to be on the same geotherm with low-T type peridotite xenoliths to the Southwest Japan arc because both types of peridotite are from almost the same depth, i.e., the spinel peridotite stability field. In addition to this, Noyamadake and Kawashimo clinopyroxenes have flat to enriched REE patterns suggesting their fertility. These peridotite xenoliths are probably asthenospheric materials most recently underplated in the West Pacific widely.

The LREE/HREE ratio of clinopyroxene in Boun, Baegryung and Cheju peridotite xenoliths is higher than unity, which suggests that the xenoliths are relatively fertile to enriched in REE, especially in LREE. They are similar to the high-T type peridotite xenoliths of the Southwest Japan arc in spite of their low equilibrium temperature (Fig. 7). The trace element chemistry suggests that the lithospheric mantle beneath Korean Peninsula is fertile as indicated by major element mineral chemistry and modal compositions. These data imply that the lithosphere had been completely replaced by asthenospheric mantle at some time earlier than the high-T type peridotites in the Southwest Japan arc. The asthenospheric peridotite then has been cooled down.

Many samples have clinopyroxenes with high LREE/HREE ratios (higher (Ce/Yb)_N ratio than unity; Figs. 6 and 9). Most of them coexist with high-Cr# spinel, which means the peridotites are depleted in melt components in terms of spinel chemistry. This is the absolute example of the “REE paradox”; the more depleted sample in terms of melt component is more enriched in incompatible elements relative to compatible ones (e.g. Frey and Prinz, 1978; O'Reilly and Griffin, 1988). Such characteristics of the “REE paradox” are particularly found in peridotite xenolith suites from east China, Korea, Sikhote-Alin and Southwest Japan arc (high-T type).

6. Summary and conclusions

1. Mantle peridotites obtained as xenoliths from the Western Pacific vary in lithology and geochemistry from the frontal part of arc inward to continent.

2. Depleted spinel harzburgites and fertile spinel lherzolites are predominant in the leading edge of sub-arc mantle wedge and in the sub-continental mantle, respectively. Spinel peridotites with intermediate characters are distributed at the backarc side of arc in between.
3. Depleted spinel harzburgites had been present beneath the continent both as residue counterpart of cratonic crust and as accreted sub-arc mantle materials. They may have been replaced with fertile lherzolite derived from subsequently upwelling asthenospheric mantle. Some of the mantle diapirs were responsible for backarc basin opening.
4. The lithospheric mantle has been modified by melts derived from the upwelling asthenosphere, which produced Group II pyroxenites and chemically metasomatized the pre-existing lithospheric peridotite.
5. The high temperature lherzolite (high-T type) of Southwest Japan is due to younger upwelling of asthenosphere than the low temperature lherzolite.

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