Petrological feature of spinel lherzolite xenolith from Oki-Dogo Island: An implication for variety of the upper mantle peridotite beneath southwestern Japan

Thematic Article

Petrological feature of spinel lherzolite xenolith from Oki-Dogo Island: An implication for variety of the upper mantle peridotite beneath southwestern Japan

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Abstract   Spinel lherzolite is a minor component of the deep-seated xenolith suite in the Oki-Dogo alkaline basalts, whereas other types of ultramafic (e.g. pyroxenite and dunite) and mafic (e.g. granulite and gabbro) xenoliths are abundant. All spinel lherzolite xenoliths have spinel with a low Cr number (Cr#; < 0.26). They are anhydrous and are free of modal metasomatism. Their mineral assemblages and microtextures, combined with the high NiO content in olivine, suggest that they are of residual origin. But the Mg numbers of silicate minerals are lower (e.g. down to Fo_{86}) in some spinel lherzolites than in typical upper mantle residual peridotites. The clinopyroxene in the spinel lherzolite shows U-shaped chondrite-normalized rare-earth element (REE) patterns. The abundance of Fe-rich ultramafic and mafic cumulate xenoliths in Oki-Dogo alkali basalts suggests that the later formation of those Fe-rich cumulates from alkaline magma was the cause of Fe- and light REE (LREE)-enrichment in residual peridotite. The similar REE patterns are observed in spinel peridotite xenoliths from Kurose and also in those from the South-west Japan arc, which are non-metasomatized in terms of major-element chemistry (e.g. Fo > 89), and are rarely associated with Fe-rich cumulus mafic and ultramafic xenoliths. This indicates that the LREE-enrichment in mantle rocks has been more prominent and prevalent than Fe and other major-element enrichment during the metasomatism.

Key words: Fe-enriched peridotite, Japan Sea, LREE enrichment, mantle metasomatism, Oki-Dogo Island, spinel lherzolite xenoliths.

INTRODUCTION

Takahashi (1978a) proposed that the upper mantle beneath the South-west Japan arc is dry and has a higher geotherm than that beneath the North-east Japan arc on the basis of petrologic studies on the mafic and ultramafic xenoliths from Oki-Dogo Island, southwestern Japan and Megata volcano, north-eastern Japan. Recent studies on mantle xenoliths from many other localities in the Japan arcs are consistent with this conclusion (Abe 1997; Arai *et al*. 1998, 2000). Arai *et al*. (1998, 2000) proposed that the variety of mantle peridotite beneath the South-west Japan arc depends on the variety of the degree of metasomatism by Fe-rich melts superimposed on the primary residual characteristics.

Oki-Dogo Island is very important for the xenolith study because it is the most continent-ward locality of the mantle peridotite xenoliths in the South-west Japan arc, approximately 60 km off shore of the Honshu Island (Fig. 1). Large amounts of mafic and ultramafic xenoliths including the residual mantle peridotite have been
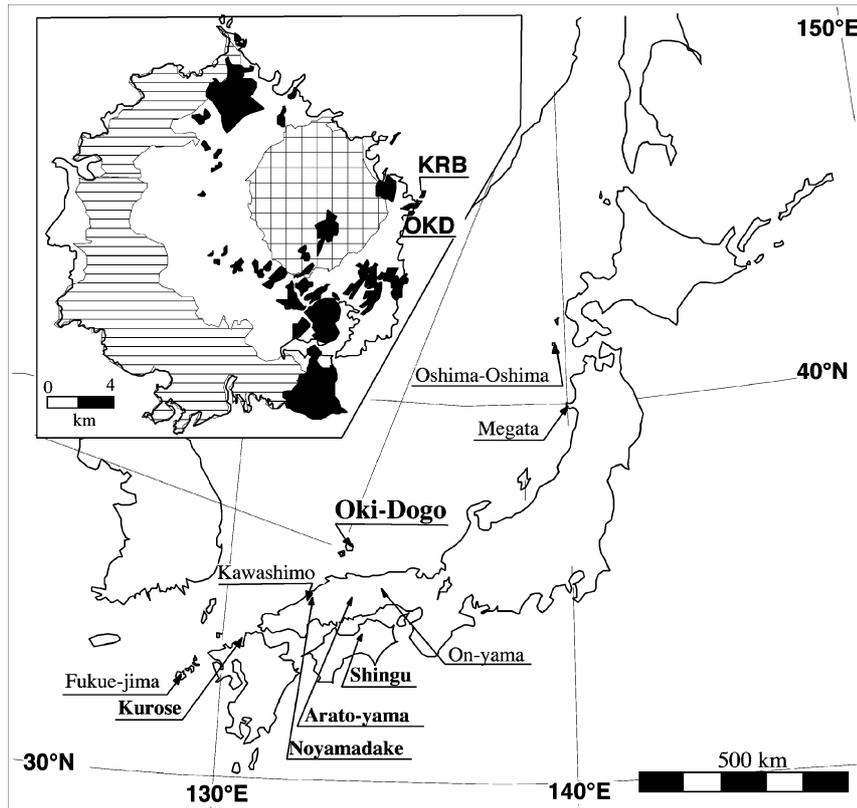
Fig. 1 Locality map of the mantle xenoliths in Oki-Dogo (Kuroshima basalt and OKD volcanic neck). Distribution of Plio-Pleistocene alkali basalt, and Miocene-Pliocene alkali rhyolite and basement gneiss complex are taken from Takahashi (1978a) and Uchimizu (1966). Selective localities of mantle xenoliths from the South-west and North-east Japan arc are shown. KRB, Kuroshima basalt; OKD, OKD volcanic neck. (■), alkali basalt; (⊟), alkali rhyolite; (▢), gneiss.

reported (Takahashi 1975, 1978a,b). Kaneoka *et al.* (1978) and Nagao and Takahashi (1993) reported the Ar and Sr isotope geochemistry and noble gas geochemistry of the ultramafic xenoliths, respectively, both from Oki-Dogo Island and Ichinomegata volcano. Many petrological and geochemical studies on the residual peridotite xenoliths in the Japan arcs and the Japan Sea have been performed (cf. Arai *et al.* 1998). But no detailed studies have been performed on the spinel lherzolite group xenoliths from Oki-Dogo Island, which are the residual mantle, since the work of Takahashi (1978a,b).

In the current paper we present the new petrology and mineral chemistry data, especially the trace-element chemistry, of spinel lherzolite xenoliths from Oki-Dogo. The preliminary data were reported by Abe *et al.* (1999). We then discuss the upper mantle processes beneath the Japan arcs and the Japan Sea, involving the petrological data of the residual peridotite xenoliths from other localities, and the trace element data of the clinopyroxene in the peridotite xenoliths from Kurose, which is also located in the Japan Sea coast in the South-west Japan arc (Fig. 1; Abe *et al.* 1998; Arai *et al.* 2001). Particular emphasis is placed on the mantle metasomatism induced by

invasions of evolved melts beneath the South-west Japan arc and the degree of melting in the upper mantle during the Japan Sea opening.

OKI-DOGO ISLAND AND ITS DEEP-SEATED ROCK XENOLITHS

Oki-Dogo Island is located in the Japan Sea (Fig. 1) and on a shelf that leads to Oki Bank from Shimane Peninsula. It has a basement of an old metamorphic complex mainly composed of a variety of gneiss. The metamorphic ages of the basement complex have been determined to be *ca* 2000 Ma by the Sm–Nd isochron method (Tanaka & Hoshino 1987) and by the Pb–Pb method on zircon (Yamashita & Yanagi 1994). The alkaline basalts in question erupted in the Pliocene–Pleistocene (from 4.38 ± 0.23 to 0.55 ± 0.09 Ma; Uto *et al.* 1994) after the opening of the Japan Sea, which took place during the Oligocene–Miocene (28–18 Ma; Tamaki *et al.* 1992). All basalts are monogenetic (Takahashi 1978a,b), and they are divided into three groups: Omine basalt group (OBG), Saigo basalt group (SBG) and Misaki basalt group (MBG) in chronological order (Uchimizu 1966; Xu 1988), and their K–Ar ages are $4.38 \pm 0.23 – 2.35 \pm 0.13$ Ma, 1.29 ± 0.05 on average
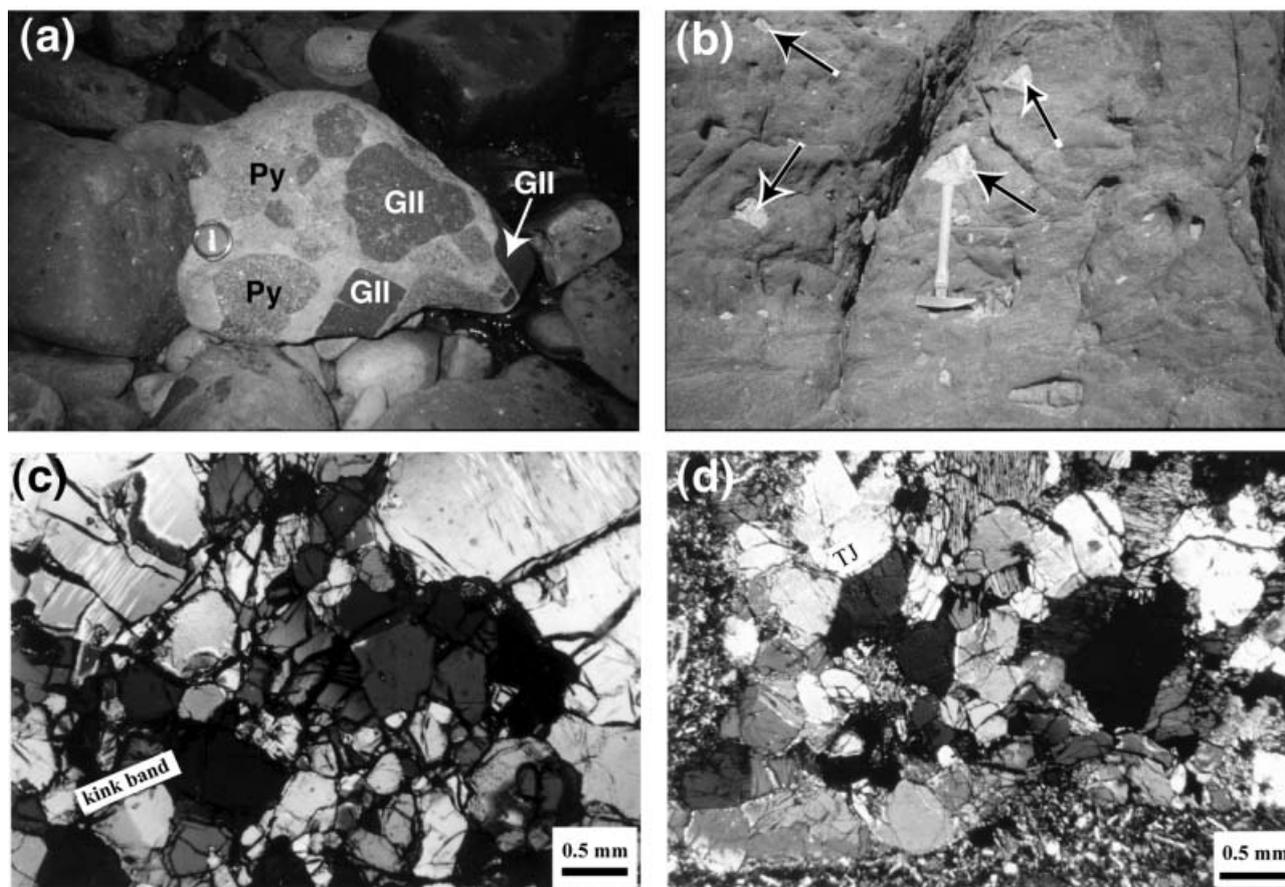
Fig. 2 (a) Boulder including a lot of ultramafic xenoliths at the outcrop of OKD volcanic neck. (b) Outcrop of Kuroshima alkali basalt. Arrows point to the ultramafic xenoliths. (c) Photomicrograph of spinel lherzolite xenoliths (KRB t-1). Crossed-polarized light. TJ, Triple junction. (d) Photomicrograph of spinel lherzolite included in alkali basalt (KRB 4–2). Crossed-polarized light.

and 1.29 ± 0.09 Ma on average, respectively (Uto *et al.* 1994).

According to Takahashi (1978a,b), five basalt lava flows that belong to the OBG contain abundant ultramafic and mafic xenoliths including mantle-derived spinel lherzolite. These basalts contain 2–15% of normative nepheline, and their SiO_2 content and FeO/MgO ratio range from 45.0 to 49.1 wt% and 0.60–1.15, respectively (Uto *et al.* 1994). Takahashi (1978a) described approximately 70 ultramafic and mafic xenoliths in detail and divided them into five groups on the basis of mineral assemblages and microtextures. It is noteworthy that the large amounts of angular xenoliths of ultramafic and mafic rocks are densely packed (Fig. 2a) in a lava, the dyke exposed in Oku village (OKD) volcanic neck by Takahashi (1975). Kuroshima basalt is a small reef-like rock approximately 100 m off the coast intruded by OKD. Relative proportions of xenolith rock types from Kuroshima alkali basalt (KRB) and OKD along

with those of other localities in the South-west Japan arc are shown in Fig. 3. The KRB is the most abundant in spinel lherzolite of the five lavas (Takahashi 1978a).

The five xenoliths groups classified by Takahashi (1978b) are: (1) spinel lherzolite; (2) banded spinel peridotite; (3) banded plagioclase peridotite; (4) gabbro; and (5) granulite. The banded spinel and plagioclase peridotite groups contain dunite, lherzolite, wehrlite, pyroxenite and/or harzburgite. Spinel lherzolite xenoliths are up to 10 cm in diameter and most of them are approximately 7 cm (Fig. 2a). Spinel lherzolite is the major xenolith type in KRB, while it is only subordinate in amount or absent in the other alkali basalt lavas in Oki-Dogo. Takahashi (1978b) considered that the banded spinel and plagioclase peridotite groups are cumulates crystallized from anhydrous basaltic magmas because of their microstructure and chemical compositions (Fe, Mn, Ti-rich; Ni, Cr, Mg-poor compared to the spinel lherzolite). They
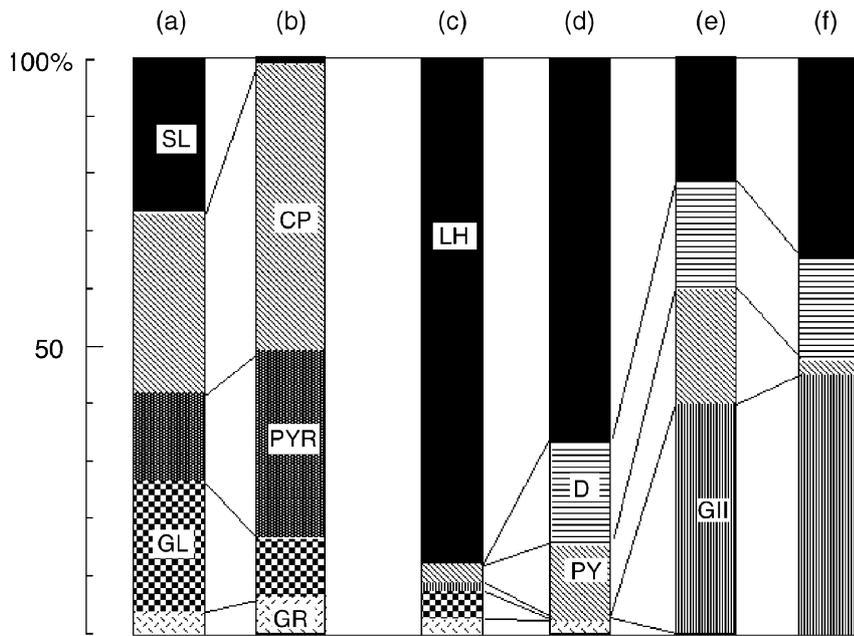
Fig. 3 Frequency diagrams of xenoliths rock species from several localities in southwestern Japan. Data from Takahashi (1978a) for (a) Kuroshima basalt (KRB) and (b) OKD volcanic neck (OKD), and Arai *et al.* (2000) for (c) Kurose, (d) Noyamadake, (e) Arato-yama and (f) Shingu. SL, spinel lherzolite; GL, granulite; CP, cumulus peridotite; PYR, pyroxenite from Oki-Dogo; GR, granite; LH, lherzolite–harzburgite; D, dunite–wehrlite; PY, pyroxenite; GII, Al-augite series or group II ultramafics in sense of Wilshire and Shervais (1975) or Frey and Prinz (1978), respectively. Takahashi (1978a,b) did not define Al-augite series (or group II) ultramafic xenoliths in Oki-Dogo xenoliths groups, and both cumulus peridotite and pyroxenite are dealt with as the 'Fe-rich ultramafic rocks'.

show, however, metamorphic deformation and recrystallizing texture. Original cumulus textures were probably obliterated through subsolidus recrystallization under upper mantle conditions. All spinel lherzolite xenoliths described here are from KRB.

PETROGRAPHY OF SPINEL LHERZOLITE

Spinel lherzolite in KRB occurs only as discrete xenoliths (Fig. 2b). Any composite xenoliths of spinel lherzolite and other rock types have not been found in KRB. Some composite xenoliths, pyroxenite cut into wehrlite and dunite, are found in OKD lava. The spinel lherzolite is Cr-diopside series (Wilshire & Shervais 1975) or group I (Frey & Prinz 1978) ultramafic xenoliths. Spinel lherzolite shows mosaic to slightly porphyroclastic textures (Fig. 2c,d). Olivine grains commonly have kink bands (Fig. 2c,d). Triple junctions are observed mainly among olivine grains (Fig. 2c,d). All the orthopyroxene porphyroclasts have clinopyroxene exsolution lamellae and some grains are kinked. Orthopyroxene adjacent to the host rock always reacts with the magma and is changed to very fine-grained aggregates of olivine, clinopyroxene and glass. Clinopyroxene has spinel exsolution lamellae and are usually fine-grained (<2 mm; Fig. 2c). Spinel grains are holly leaf in shape and always exist interstitially in pyroxene-

rich portion. They are sometimes surrounded by small grains of pyroxenes, typically of orthopyroxene.

The Oki-Dogo spinel lherzolites are rather poor in clinopyroxene (Table 1; Fig. 4). The clinopyroxene/pyroxenes volume ratio is approximately 0.1 in most samples (Fig. 4). The Oki-Dogo lherzolite has the typical residual peridotite texture and the modal compositions.

According to Takahashi (1978a,b), the other ultramafic xenolith groups from Oki-Dogo show a strongly banded structure. The banded spinel peridotite contains an abundance of aluminous spinel (3–15 vol%). Some banded plagioclase ultramafic xenoliths contain kaersutitic hornblende, although the ultramafic and mafic xenoliths from Oki-Dogo Island are characteristically anhydrous. The spinel lherzolite group is clearly distinct from those banded peridotites of the other groups in terms of texture and mineral assemblage (Takahashi 1978b). Similar peridotite xenoliths abundant in aluminous spinel with a banded structure have been found from the Kurose xenolith suite (Arai *et al.* 2001).

MINERAL CHEMISTRY

MAJOR ELEMENTS

Major-element analyses of olivine, orthopyroxene, clinopyroxene and spinel were performed with a 4

Table 1 Modal compositions of spinel lherzolite xenoliths from Oki-Dogo

	Ol	Opx	Cpx	Sp	Fo	Cr#	T (Wells)	T (S & S)
KRB 2	60.4	30.2	4.0	2.4	86.8	0.065	1054	1032
KRB 3	54.8	37.5	6.8	1.2	87.2	0.260	1017	1099
KRB 4–1	82.5	15.3	0.7	1.4	86.4	0.158	1050	1088
KRB 4–2	71.7	17.2	1.9	9.2	89.7	0.141	1057	1115
KRB 5	62.8	27.6	6.6	3.1	89.8	0.192	1046	1092
KRB 6	58.8	28.6	9.7	2.9	88.9	0.190	1032	1145
KRB 9	48.9	45.0	3.5	2.4	87.0	0.178	1060	1193
KRB t-1	46.2	42.6	8.4	2.8	87.6	0.160	1066	1196
KRB t-2	80.1	10.9	8.7	0.3	88.5	0.186	1034	1068
KRB t-3	50.2	44.2	4.1	1.3	87.9	0.187	1040	1179

Average Fo content of olivine (Fo) and Cr/(Cr + Al) atomic ratio (Cr#) in each sample are shown. The equilibrium temperatures (°C) are calculated by Wells (1977) two pyroxene geothermometer and Sachtleben and Seck (1981) Al in Opx geothermometer for T (Wells) and T (S & S), respectively. Ol, olivine; Opx, orthopyroxene; Cpx, clinopyroxene, Sp, spinel.
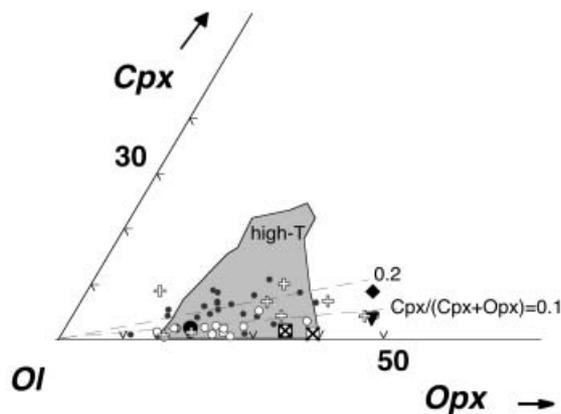

Fig. 4 Modal compositions of olivine, orthopyroxene and clinopyroxene in the samples. As a comparison, the data of subarc mantle xenoliths (data from Abe 1997) and highly metasomatized peridotite from Ichinomegata, North-east Japan arc (Abe *et al.* 1992) are shown. Oki-Dogo spinel lherzolite has a small amount of clinopyroxene compared with high-temperature-type peridotite xenoliths from South-west Japan arc (shaded area; data from Abe 1997). (⊠), Megata highly metasomatized (amph. > 10 vol%); (●), megata (others); (○) Kurose; (●), KRB-4-2; (▼), KRB-9; (◆), KRB-t-1; (⊕), Oki-Dogo (others).

Fig. 5 Relationships between the Fo content of olivine and the Cr/(Cr + Al) atomic ratio (Cr#) of spinel from Oki-Dogo spinel lherzolite xenoliths. Spinel and plagioclase peridotites data are from Takahashi (1978a) and Abe *et al.* (1999). The data of other peridotite xenoliths from Japan arcs (Abe 1997; Arai *et al.* 2000), highly metasomatized peridotite xenoliths from Ichinomegata (Abe *et al.* 1992) and harzburgite from Oshima-Oshima (Ninomiya & Arai 1992) and the Japan Sea floor (Ishii 1987) are shown for comparison. Olivine–spinel mantle array (OSMA) is a spinel peridotite restite trend after Arai (1987, 1994a). (◆), Oshima-Oshima; (★), Japan Sea; (⊠), Megata highly metasomatized (amph. > 10 vol%); (△), Megata (harz. (harzburgite) with hornblendite veinlet); (●), Megata (others); (●), KRB-4-2; (▼), KRB-9; (◆), KRB-t-1; (⊕), Oki-Dogo (others).

spectrometer JEOL 8800 superprobe at Tokyo Institute of Technology, using a focused beam, and an accelerating voltage of 15 KeV and a beam current of 12 nA on all phases. The structural formula of spinel was calculated assuming the spinel stoichiometry after subtracting all Ti as an ulvospinel component (Fe_2TiO_4). Total Fe in silicate analysis was assumed to be Fe^{2+}. Selected microprobe analyses are listed in Table 2.

The Fo content of olivine ranges from 86.5 to 89.8, and is lower than that in most other mantle xenoliths from the Japan arcs (Fig. 5). The NiO content of olivine is, however, rather constant, being approximately 0.3 wt% (0.25–0.36) and has a
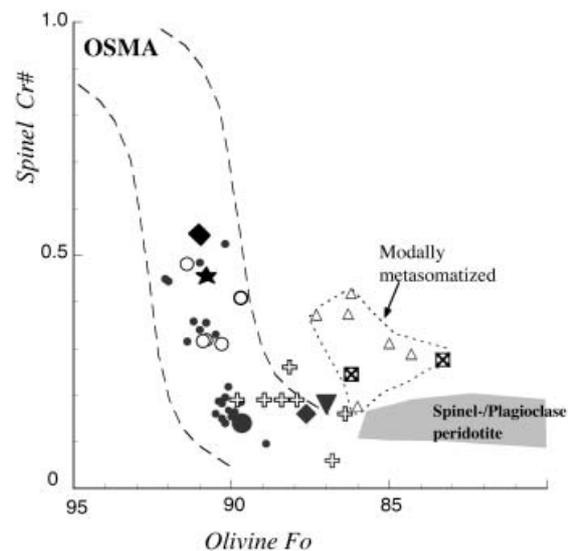
slightly but distinctly positive correlation with Fo content (Table 2).

The Cr# (= Cr/(Cr + Al)) of spinel is low (0.06–0.26; Fig. 5) and the Mg# (= Mg/(Mg + Fe^{2+})) of spinel has a negative correlation with the Cr#. The TiO_2 content in spinel is slightly higher than that in abyssal spinel peridotite at a given Cr# (cf. Dick & Bullen 1984). The Fe^{3+}/(Cr + Al + Fe^{3+}) ratio is <0.1

Table 2 Selected microprobe analyses of olivine, orthopyroxene, clinopyroxene and spinel in selected samples

	KRB 4-1				KRB 4-2				KRB 9				KRB t-1			
	Ol	Opx	Cpx	Sp	Ol	Opx	Cpx	Sp	Ol	Opx	Cpx	Sp	Ol	Opx	Cpx	Sp
SiO_2	40.88	54.89	52.44		41.26	55.57	51.89		40.99	55.71	53.00		41.27	56.13	52.65	0.08
TiO_2	0.02	0.04	0.28	0.11	0.04	0.02	0.18	0.15	0.04	0.10	0.23	0.16	0.00	0.02	0.13	0.27
Al_2O_3	0.03	4.55	5.60	51.34	0.05	4.56	5.10	53.26	0.02	4.50	5.30	49.29	0.01	4.38	5.33	48.51
Cr_2O_3	0.00	0.48	0.70	14.41	0.00	0.41	0.77	13.05	0.03	0.37	0.84	15.90	0.00	0.57	0.94	13.78
FeO^*	12.71	7.93	4.27	13.29	9.79	6.25	3.22	11.38	12.07	7.61	4.18	14.89	11.61	7.26	3.69	14.81
MnO	0.14	0.15	0.11	0.15	0.11	0.13	0.05	0.15	0.18	0.13	0.14	0.13	0.18	0.16	0.12	0.14
MgO	45.40	30.37	15.58	18.76	48.06	31.44	16.14	20.01	45.41	30.02	15.46	18.10	46.06	30.27	15.82	18.43
CaO	0.18	1.22	19.90		0.11	1.02	20.48		0.10	1.19	19.95		0.09	1.06	19.86	0.00
Na_2O	0.01	0.06	0.89		0.02	0.06	0.61		0.04	0.10	0.82		0.02	0.06	0.83	0.00
K_2O	0.00	0.00	0.00		0.00	0.00	0.02		0.01	0.00	0.02		0.00	0.00	0.00	0.01
NiO	0.32	0.11	0.03	0.33	0.36	0.14	0.04	0.26	0.24	0.10	0.05	0.25	0.33	0.07	0.02	0.34
Total	99.68	99.81	99.79	98.39	99.78	99.60	98.50	98.28	99.08	99.84	99.99	98.71	99.56	99.96	99.38	98.99
Mg#	0.864	0.872	0.867	0.757	0.897	0.900	0.899	0.798	0.870	0.876	0.868	0.737	0.876	0.881	0.884	0.767
Cr#		0.066	0.077	0.158		0.057	0.091	0.141		0.053	0.096	0.178		0.081	0.106	0.160
Cr/Y				0.154				0.138				0.172				0.152
Al/Y				0.819				0.839				0.793				0.798
Fe^{3+}/Y				0.027				0.023				0.035				0.050
Al^{VI}		0.088	0.088				0.089				0.084				0.085	
Al^{IV}		0.151	0.151				0.132				0.142				0.143	
Al^{IV}/Al^{VI}		0.585	0.585				0.672				0.595				0.594	

Fe*, total Fe; Mg#, Mg/(Mg + Fe*) atomic ratio for silicates and Mg/(Mg + Fe^{2+}) for spinel; Cr#, Cr/(Cr + Al) atomic ratio; Y, total trivalent cation (= Al + Cr + Fe^{3+}); Al^{IV}, 4-coodination aluminum; Al^{VI}, 6-coordination aluminum cations based on 6 oxygens. The cation ratios of spinel were calculated assuming spinel stoichiometry after subtracting all Ti as an ulvospinel molecule (Fe$_2$TiO$_4$). Ol olivine; Opx, orthopyroxene; Cpx, clinopyroxene; Sp, spinel.
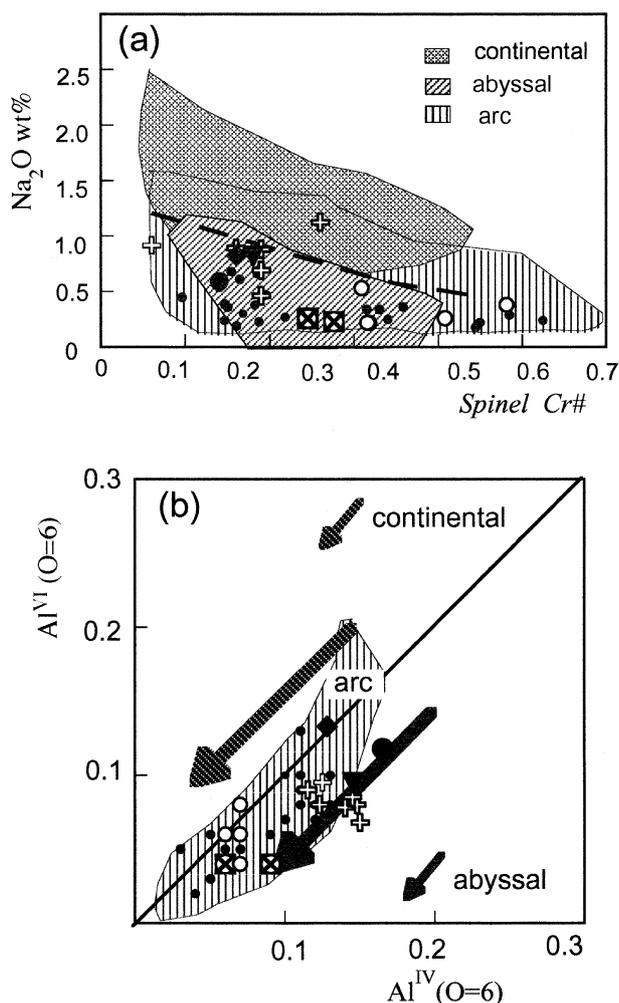
Fig. 6 (a) The relationships between Na_2O content of clinopyroxene and Cr# of spinel from Oki-Dogo spinel lherzolite xenoliths. The regions for (⊠) continental and (⊿) abyssal areas are from Arai (1991); (Ⅲ) arc area is from Abe (1997). Clinopyroxene in Oki-Dogo spinel lherzolite xenoliths is low in Na, the same as other arc peridotite xenoliths. (b) The relationships between Al^{VI} and Al^{IV} in clinopyroxene in Oki-Dogo spinel lherzolite xenoliths. Al^{VI}/Al^{IV} ratio in clinopyroxene in all samples is lower than 1. The regions for continental and abyssal areas are from Seyler and Bonatti (1994). The arrows show the melting trends of subcontinental and suboceanic mantle peridotites (Seyler & Bonatti 1994). Symbols as in Fig. 5.
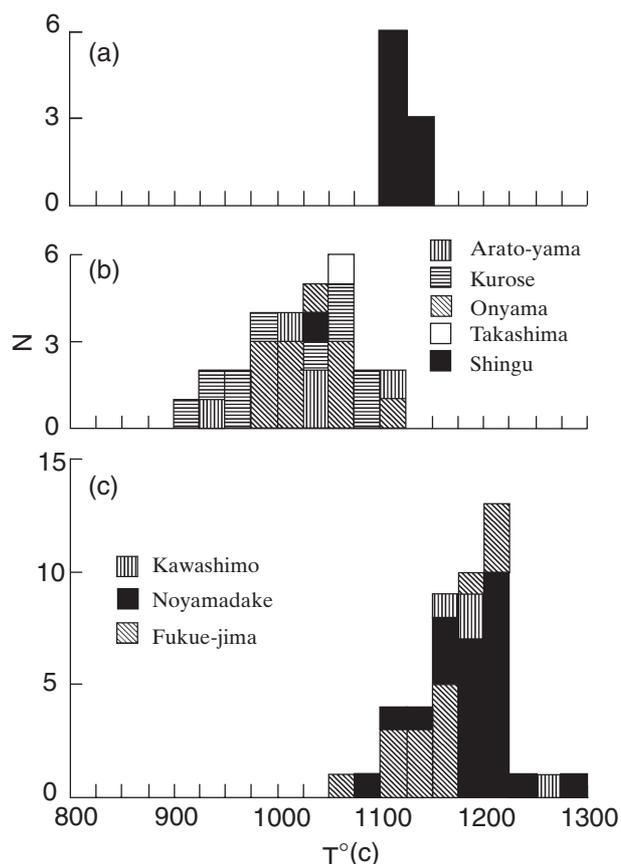

Fig. 7 (a) Equilibrium temperatures (Wells 1977) of spinel lherzolite xenoliths from Oki-Dogo Island. As a comparison, the data of mantle xenoliths from South-west Japan arc are shown: (b) low temperature (Ⅲ, Aratoyama; ⊟, Kurose; ⊠, Onyama; □, Takashima; ■, Shingu) and (c) high temperature (Ⅲ, Kawashimo; ■, Noyamadake; ⊠, Fukue-jima). Data of Fukue-jima are from Umino and Yoshizawa (1996) and others are from Abe (1997) and Arai *et al.* (2000).

(Table 2). Spinel in the Oki-Dogo lherzolite has the mantle spinel characteristics defined by Dick and Bullen (1984).

Orthopyroxene is enstatite with $En_{85.1-88.4}$, and contains a moderate amount of CaO (1.0–1.2 wt%) and Al_2O_3 (4.0–5.0 wt%). Clinopyroxene is Cr-diopside to augite or Mg-rich augite with 0.5–1.0 wt% of Cr_2O_3. The Al_2O_3 and CaO contents in clinopyroxene vary from 4.7 to 6.6 wt% and from 19.6 to 21.3 wt%, respectively. All the clinopyroxene has a low Na_2O content (<1.2 wt%) and a low Al^{VI}/Al^{IV} ratio (0.54–0.73), which are different from those of

the subcontinental mantle peridotites (Fig. 6a,b; Arai 1991; Seyler & Bonatti 1994).

The equilibrium temperatures were calculated from the two-pyroxene thermometer of Wells (1977) and the Al-Opx thermometer of Sachtleben and Seck (1981), which yield 1017–1066°C and 1032–1196°C, respectively (Table 1; Fig. 7). These temperatures are between the average temperatures of the low-temperature type (low-T type) and the high-temperature type (high-T type) peridotite xenoliths from South-west Japan arc (Arai *et al.* 1998).

TRACE ELEMENTS IN CLINOPYROXENE

In situ trace-element analyses of clinopyroxenes were conducted on polished thin sections for three spinel lherzolite samples with a Cameca IMS-3f secondary ion mass spectrometer (SIMS) installed

at Tokyo Institute of Technology. The primary ion beam was mass filtered $^{16}O^-$-accelerated to 12.5 KeV, adjusted for a beam current of approximately 20 nA and focused to a spot diameter of 25 μm. Kinetic energy filtering was achieved by offsetting the sample accelerating voltage (–60 V for rare-earth elements (REE) and –100 V for Ti, Zr, Sr and Y) while keeping the setting of the electrostatic analyzer voltage and the width and position of the energy slit constant. Other analytical and instrumental conditions were similar to those employed by Yurimoto *et al.* (1989) and Wang and Yurimoto (1993). Analytical techniques were the same as those used by Abe *et al.* (1998) for mantle xenoliths from the Japanese Island arcs.

The concentrations of REE, Sr, Zr, Y and Ti in clinopyroxenes are shown in Table 3. The REE concentrations of three samples of pyroxene megacrysts, which were measured by the same method with the lherzolite clinopyroxenes, are listed for comparison. The chondrite-normalized REE patterns are shown in Fig. 8(a). For comparison, the REE patterns of clinopyroxene in several peridotite xenoliths from Kurose, the South-west Japan arc, are shown in Fig. 8(b).

The patterns of KRB lherzolite clinopyroxene are U-shaped with middle REE (MREE)-depletion and light REE (LREE)-enrichment (Fig. 8a). The LREE-enriched patterns are similar to those for the Kurose peridotites (Fig. 8b).

The clinopyroxenes are enriched in LREE (up to 4.5 p.p.m. Ce) and Sr (up to 50.3 p.p.m), and poor in MREE (<0.3 p.p.m. Eu; Table 3; Fig. 8a). The ratio of the chondrite-normalized Ce and Yb abundances (= (Ce/Yb)n) of the clinopyroxene is <1.12. The Ti/Zr ratio varies from 149 to 516. The correlations between Ti and Zr concentrations, and between Ti/Zr ratio and (Ce/Yb)n are shown in Fig. 9. They are plotted between abyssal, subarc and subcontinental areas, which were compiled by Abe (1997).

DISCUSSION

Fe-ENRICHMENT AS MANTLE METASOMATISM

The spinel lherzolite from Oki-Dogo Island is Fe-rich relative to common mantle peridotite xenoliths in alkaline basalts (Fig. 5). There are several localities of such Fe-rich (Fo < 88) Cr-diopside series peridotite in the world; for example NSW, Australia (Wilkinson & Binns 1977), British Columbia, USA (Fujii & Scarfe 1982; Brearly *et al.* 1984), Oahu, Hawaii (Sen & Leeman 1991) and
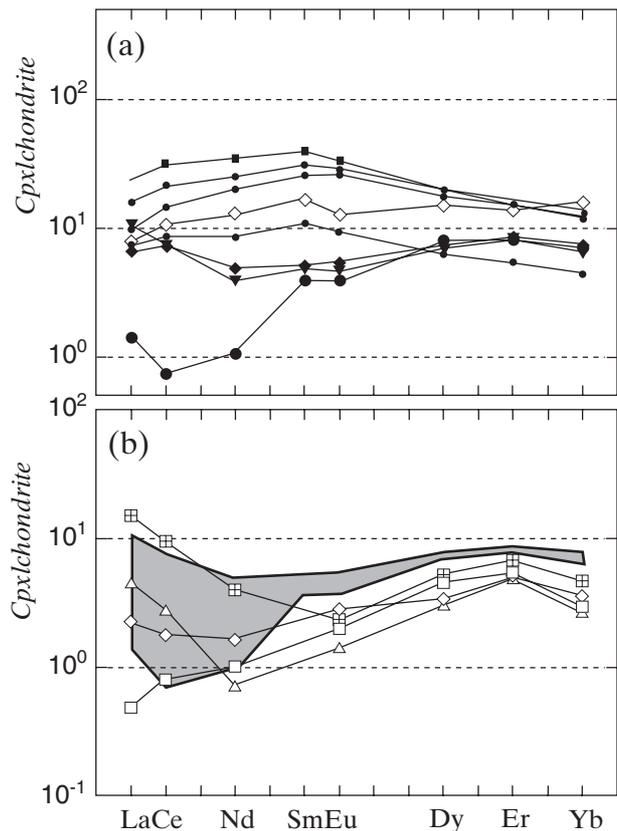

Fig. 8 (a) Chondrite normalized rare-earth element (REE) patterns of clinopyroxenes in spinel lherzolite (▼, KRB-9; ◆, KRB-t-1; ●, KRB-4-2) and Al-augite megacryst (○, KRB; □, OKD) from Oki-Dogo. (◇), primitive Cpx; clinopyroxene in primitive mantle, the value calculated from the primitive mantle value (Sun & McDonough 1989) and the distribution coefficients between clinopyroxene and melt (Johnson *et al.* 1990). Chondrite compositions used for normalization are after Anders and Grevesse (1989). (b) Chondrite-normalized REE patterns in clinopyroxene of Kurose peridotite xenoliths (△, KR-50; ◇, KR-379; ⊞, KR-350; □, KR-392). Data from Abe *et al.* (1998). The concentrations of middle rare earth element (MREE) to heavy rare earth element (HREE) in Kurose clinopyroxene are slightly lower than those in Oki-Dogo clinopyroxene (shaded area).

southwestern Japan (Arato-yama (Fujiwara & Arai 1982) and Shingu (Goto & Arai 1987)).

Other Fe-rich lherzolite xenoliths, which are modally metasomatized and contain phlogopite, have been found associated with ordinary Mg-rich ones from Salt Lake, Hawaii (Goto & Yokoyama 1988). Some peridotite xenoliths from Megata volcano (Ichinomegata and Ninomegata craters) are also Fe-rich (down to $Fo_{84.5}$; Fig. 5), and they are strongly metasomatized and contain more than 10 vol% of sparsely distributed amphibole or hornblendite veinlets (Abe *et al.* 1992).

In contrast, the Fe-rich peridotite xenoliths from Arato-yama (Fujiwara & Arai 1982) and Shingu (Goto & Arai 1987) as well as those from

Table 3 Rare earth and other trace element concentrations (in p.p.m) in clinopyroxene of Oki-Dogo spinel lherzolite and Al-augite megacryst measured by SIMS

p.p.m.	Lherzolite				Megacryst	
	KRB4-2	KRB-9	KRB t-1	OKD	KRB-a	KRB-b
La	0.33	2.47	1.56	5.60	1.76	2.32
Ce	0.46	4.52	4.52	19.10	5.31	8.98
Nd	0.48	1.77	2.24	15.87	3.94	9.14
Sm	0.71	0.83	1.29	5.74	1.54	4.19
Eu	0.25	0.23	0.33	1.97	0.54	1.46
Dy	1.95	1.70	1.80	4.88	1.54	0.67
Er	1.30	1.32	1.38	2.68	0.87	4.10
Yb	1.12	1.04	1.19	2.19	0.71	4.35
Lu	0.17	0.16	0.18	0.28	0.11	0.82
Ti	1224	1379	1405			
Sr	5.63	50.25	42.42			
Y	15.23	13.84	15.49			
Zr	2.37	9.23	3.97			
$(Ce/Yb)n$	0.11	1.12	0.98	2.25	1.93	1.17
Ti/Zr	516	149	354			

$(Ce/Yb)n$, the ratio of chondrite normalized Ce and Yb values. The chondrite values are from Anders and Grevesse (1989). SIMS, secondary ion mass spectrometer.

Oki-Dogo, southwestern Japan, do not contain any hydrous phases and show no evidence of modal mantle metasomatism (Arai *et al.* 2000). All Cr-diopside series ultramafic xenoliths from the South-west Japan arc are anhydrous, although some composite xenoliths that are Cr-diopside series harzburgite with kaersutite-bearing Al-augite series rock were found in Shingu (Goto & Arai 1987). Arai *et al.* (2000) proposed that the Fe-rich peridotites (Cr-diopside series) were invaded in the upper mantle by Fe-rich cumulates and/or Fe-rich ultramafic rocks (Al-augite series), because they are exclusively found in the localities where Al-augite series and/or Fe-rich ultramafic xenoliths are abundant (Fig. 3).

Furthermore, the Cr content of pyroxene and spinel in the metasomatized peridotite either decreases or increases depending on the Al/Cr relation between the wall-rock peridotite and the melt, so that the spinel Cr# in the wall rock becomes similar to that in associated later-formed rock types. The Cr# of spinel in Megata harzburgite with metasomatic veinlet decreases towards the metasomatic veinlet, which contains lower-Mg# silicates as well as low-Cr# spinel (Abe *et al.* 1992). According to Kempton (1987), Al contents of the pyroxene and spinel in the wall-rock lherzolite increase slightly towards the boundary with Al-augite series vein in composite xenoliths from the Geronimo volcanic field. Their wall rock phases are also enriched in Ti and Fe. Contrary to this, the spinel composition in two lherzolite xenoliths from Dish Hill, California show Cr-enrichment towards metasomatic hydrous veinlet (McGuire *et al.* 1991).

In the Oki-Dogo xenoliths, Fe-rich ultramafic rocks have a quite low Cr# of spinel (Fig. 5), so that pyroxenes and spinel in the spinel peridotite probably became richer in Al_2O_3 before Fe-enrichment had occurred.

LIGHT RARE-EARTH ELEMENT ENRICHMENT

The spinel lherzolite xenoliths from Oki-Dogo Island have relatively low-Mg# silicates and low-Cr# (<0.2; Fig. 4) spinel as compared with primitive mantle. These compositions suggest that these lherzolites are as fertile as primitive mantle in terms of major element chemistry of minerals. They are, however, poor in modal clinopyroxene (Table 1; Fig. 3), so that they are Ca-poor in bulk rock composition. The also have lower heavy rare earth element (HREE) concentrations in clinopyroxene than those in the primitive mantle (Fig. 8a). The bulk rock chemistry and trace element chemistry of clinopyroxene, however, suggest that the Oki-Dogo lherzolites are not primeval mantle such as 'pyrolite'.

The clinopyroxenes in Oki-Dogo spinel lherzolites have U-shaped (MREE-depleted) patterns (Fig. 8a). In contrast, clinopyroxenes in peridotite xenoliths from most other localities of the Southwest Japan arc exhibit LREE-depleted convex-upward or flat to LREE-enriched patterns except for the Kurose residual peridotites (Fig. 8b; Abe
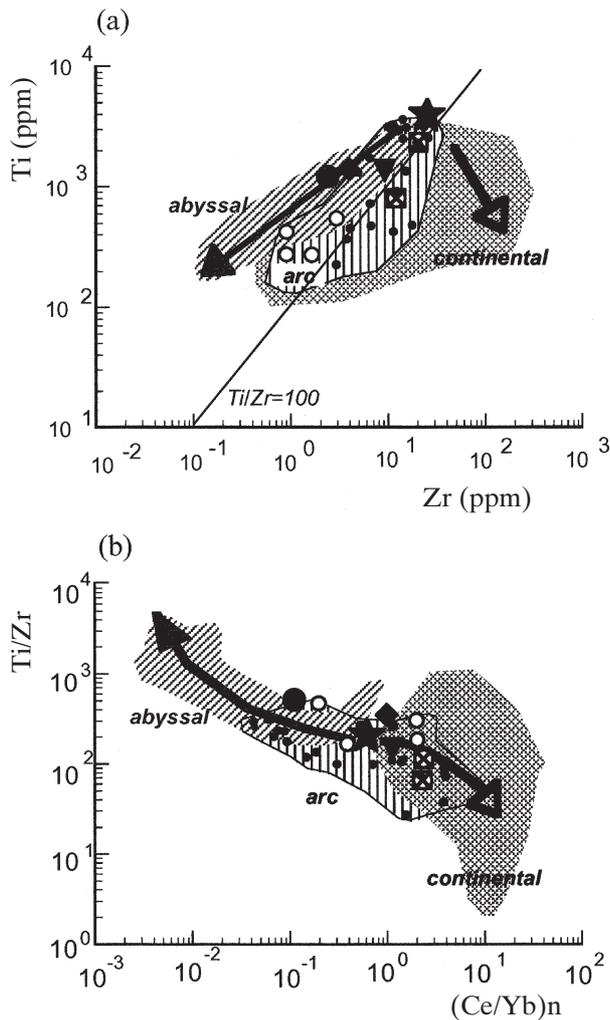
Fig. 9 (a) Relationship between Ti and Zr concentrations in clinopyroxenes in Oki-Dogo spinel lherzolite xenoliths. (b) Relationships between Ti/Zr ratio and (Ce/Yb)n in clinopyroxene in Oki-Dogo spinel lherzolite xenoliths. The abyssal data are from Johnson *et al.* (1990) and the arc data are from Abe (1997). The data for young continental peridotite xenoliths were compiled by Abe (1997). (★), primitive mantle clinopyroxene calculated from Sun and McDonough (1989). (✐), melt extraction; (⬂), effect of influx (metasomatic trend). Symbols as in Fig. 5.

somatic phases. Instead, Fe-rich and Al-augite series ultramafic xenoliths are associated with those residual mantle peridotite xenoliths in both localities, although they are rare in the Kurose xenolith suite (Fig. 3). Those clinopyroxenes in Fe-rich and Al-augite series pyroxenes have higher REE contents than that in the residual peridotite. As shown in Fig. 8(a), the REE concentrations are much higher in the Al-augite megacrysts from Oki-Dogo alkali basalt, which are considered to be precipitated from alkaline basalt and have the same origin as that of the Fe-rich pyroxenite than in clinopyroxenes in spinel lherzolite. Therefore, it is consistent with the estimation that the metasomatic agent was derived from the melt forming these Fe-rich rocks during and/or after their formation.

Fe-enrichment is the dominant mantle process beneath the Oki-Dogo Island, but all of the lherzolite and harzburgite xenoliths from Kurose have preserved their Mg-rich (Fo > 89) composition after LREE-enrichment. It means that the Fe-enrichment, which is prominent on the Oki-Dogo lherzolite, was not so pervasive in the upper mantle beneath Kurose. The mobility of REE through the metasomatic agent (fluid and/or melt) is greater than that of major elements such as Mg and Fe (Eggler 1987), whereas the diffusivity of REE in mantle minerals is much smaller than that of major elements. For example the Fe–Mg exchange diffusion coefficient in olivine is around 10^{-14} m^2/s at 900°C and 3–9 GPa (Jaoul *et al.* 1995) and that of REE in clinopyroxene is 10^{-18}–10^{-19} m^2/s at 1350°C and 1.5 GPa in clinopyroxene (Van Orman *et al.* 2001). Those data suggest that REE can reach over the distance of meters in the upper mantle condition in the order of 1 billion years, while 1 million years would be necessary for the Mg–Fe equilibration over the same dimension. Therefore, Fe-enrichment has been caused by an element exchange mechanism through diffusion with Fe-rich cumulus rock in solid state. In contrast, LREE-enrichment has been caused by infiltration of the metasomatic agent all through the wall-rock, a mechanism that is suggested by several authors (Navon & Stolper 1987; Vasseur *et al.* 1991). The metasomatic agent, which is rich in REE, was released from the melt that formed Fe-rich mafic and ultramafic rocks within the mantle, and that was capable of being the REE carrier throughout the distance. The trace-element characteristics (U-shaped REE pattern) of mantle peridotite from Oki-Dogo Island and Kurose have been most probably caused by a highly mobile

1997). Ozawa and Shimizu (1995) proposed an open-system melting (influx melting) model based on the data from the Hayachine-Miyamori peridotite massif, north-eastern Japan. Ozawa and Shimizu (1995) showed that the U-shaped patterns can be formed by trapped melt crystallization after the melt extraction, or by mantle metasomatism after the melting. The REE patterns of Oki-Dogo and Kurose mantle clinopyroxenes were modified by metasomatism after melt extraction. Neither the spinel lherzolite from Oki-Dogo nor the residual peridotite from Kurose contain meta-

metasomatic melt and/or fluid impregnations. This LREE-enrichment metasomatism is relevant to Fe-rich cumulus ultramafic rock formation in the upper mantle beneath the Oki-Dogo, but is apparently irrelevant in Kurose mantle.

THE JAPAN SEA OPENING

Taking the location and the eruption age (Pliocene) of the alkaline basalts with the mantle xenoliths into account, the upper mantle beneath the Oki-Dogo Island is a possible mantle residue formed during the opening of the Japan Sea in the middle of the Tertiary. In plagioclase-free spinel peridotite samples from oceanic and continental areas, the composition of spinel varies systematically as a function of the degree of bulk rock major element depletion and, thus, the spinel Cr# is commonly considered to be a good indicator of the degree of melting (Dick & Bullen 1984). Melting experiments of peridotitic material have shown a trend of increasing spinel Cr# of the residual peridotite with increasing proportions of coexisting melt (Jaques & Green 1980). Arai (1994b) suggested therefore, by using the olivine–spinel chemical relation in volcanics, that the source peridotite for the back-arc-basin basalt had experienced extraction of high-degree partial melt including high-Cr# of spinel (0.4–0.5). In fact, we obtained the depleted mantle peridotites from the following two localities in the northern part of the Japan Sea. One is the harzburgite xenolith (Cr# of spinel = 0.5) from Oshima-Oshima, which is included in calc-alkaline andesite (Ninomiya & Arai 1992), and the other is also the harzburgite xenolith (Cr# of spinel = 0.45) found in alkaline basalt by the abyssal dredging in the Japan Sea (38°12.2′N, 132°34.7′E; Ishii 1987). The Cr# of spinel is, however, much lower in Oki-Dogo spinel lherzolite (0.06–0.26) than in those harzburgites (Fig. 5). Even though we discussed in the former section the possibility of Al-enrichment during Fe-metasomatism in the mantle beneath the Oki-Dogo Island, it is unlikely that the spinel lherzolite was originally harzburgite representative of the Japan arc mantle.

In contrast, Hirai (1986) concluded that the upper mantle peridotite xenolith from Kurose is the residue after back-arc-basin basalt formation beneath the Japan Sea. The Kurose peridotites have higher Cr# of spinel (0.27–0.55) than the Oki-Dogo spinel lherzolite. The Cr# of spinel is, however, lower in most Kurose peridotites (approx.

0.3) than in harzburgites from the Japan Sea floor and from Oshima-Oshima. Tamaki *et al.* (1992) considered that the northern part of the Japan Sea was formed by the sea-floor spreading with volcanism, while crustal thinning was the main mechanism for the southern part, as determined during two cruises of the Ocean Drilling Program on the Japan Sea (Leg 127 & 128). In other words, the degree of melting in the upper mantle beneath the northern part of the Japan Sea is higher than in that beneath the southern part. The variation of spinel Cr# in the mantle peridotites from the Japan Sea and the coast supports this estimation of melting degree in the upper mantle.

CONCLUSIONS

The spinel lherzolite xenoliths from Oki-Dogo Island are slightly more Fe-rich than other mantle peridotite xenoliths in the world. Their microtexture, modal compositions and the high NiO content in olivine, suggest that they are Cr-diopside series residual mantle peridotite. The low Mg# of their silicate minerals was affected by the formation of abundant Fe-rich cumulative ultramafic rocks found as xenoliths in the same lava flow.

The clinopyroxene has LREE-enriched U-shaped patterns. These patterns can be formed by REE-enrichment metasomatism after depletion by melt extraction. The metasomatic agent was released from the melt that had precipitated Fe-rich ultramafic rocks into the upper mantle peridotite.

A similar REE-pattern is found in Kurose peridotite xenoliths, despite their rare association with Fe-rich ultramafic xenoliths. The similarity of REE patterns between Oki-Dogo and Kurose and the disparities in the volume of Fe-rich xenoliths and the Mg# are due to the large difference of the diffusion rate and the mobility between major and trace elements.

Mantle peridotite xenoliths from Oki-Dogo and Kurose are the residue after the opening of the Japan Sea, although they show a relatively low degree of partial melting. This is consistent with the tectonic model of the opening of the Japan Sea.

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