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Os, Nd, and Sr isotopic and chemical compositions of ultramafic xenoliths from Kurose, SW Japan: Implications for contribution of slab-derived material to wedge mantle

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Abstract

We examined seven ultramafic xenoliths from 1~3 Ma alkali olivine basalt reefs near the Eurasian continent and one sample of the host alkali basalt to identify the mantle wedge material and to constrain the origin and evolution of mantle beneath SW Japan. Six xenoliths are from Kurose and one xenolith is from Takashima, northern part of the Kyushu islands, SW Japan. The Sr and Nd isotopic ratios vary from 0.70416 to 0.70773 and from 0.51228 to 0.51283, respectively. The Kurose and Takashima xenoliths have higher Sr isotopic ratios and lower Nd isotopic ratios than those of the peridotite xenoliths from the other arc settings such as Simcoe and NE Japan.

The Kurose xenoliths have less radiogenic Os isotopic ratios ($^{187}Os/^{188}Os = 0.123–0.129$) than the primitive upper mantle (PUM) estimate and limited variation compared to the other arc xenoliths. Their Os isotope compositions are rather similar to the ultramafic xenoliths from NE and east China. In addition, the samples of the Kurose and Takashima xenoliths plot along a mixing line between ultramafic xenoliths from SE and NE China and a slab component in Sr–Nd–Os isotopic space. Our results suggest that fragments of continental lithospheric mantle from the China craton may exist beneath Kurose and Takashima after the Sea of Japan expansion when the Japanese islands were rifted away from the Eurasian continent during Miocene. Later magmatism due to subduction of the Philippine Sea Plate beneath the SW Japan arc around 15 Ma ago may have introduced fluids or melts derived from slab component, interpreted to be oceanic sediments rather than altered oceanic crust, that possibly modified the original composition of the lithospheric mantle sampled by the peridotite xenoliths from Kurose and Takashima.

Keywords: Ultramafic xenoliths; Os isotope ratio; Nd isotope ratio; Lithospheric mantle; Subduction zone

1. Introduction

The contribution of slab-derived material to island arc volcanism is poorly understood. In a subduction zone, various materials such as subducted oceanic crusts,

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sediments, fluids, and mantle wedge materials are closely associated and various mechanisms, such as dehydration, melting and magma mixing, and crustal contamination, make the interpretation of the origin of arc rocks complicated. Studies especially to unravel the effects from subducted slabs using arc volcanic rocks were done with varying results. For example, Shibata and Nakamura (1997) measured Sr, Nd and Pb isotopic ratios of volcanic basalts from NE Japan arc. They explained that the compositions of the basalts could be reproduced by addition of fluids from subducted slab to MORB mantle in mantle wedge. They proposed that the fluid derived from slab materials originated from a mixture of 15% oceanic sediments and 85% altered MORB. Elliott et al. (1997) examined the Th–U isotopic disequilibrium of volcanic rocks from the Mariana Islands and found out that these volcanic rocks form two isochrons, 30 ka and 110 ka. They interpreted that these two isochrons represent two discrete slab additions and variable addition of the slab components to sub-arc mantle. If the sub-arc mantle is heterogeneous, it is highly possible that the different chemical composition of magma depends on where melting happens. One of the ways to know the chemical composition of the melting locality is to analyze xenoliths sampled by volcanic rocks. Xenoliths derived from depth provide information on the composition of upper mantle and/or the lower crust beneath the continent. In addition, ultramafic xenoliths are most likely to be directly related to either magmas or mantle that has been affected by extensive arc volcanism. Thus, geochemical studies of xenoliths can possibly provide key information on subduction processes.

The purpose of this study is to estimate the influence of the slab material on mantle wedge and to know what components are present in the mantle wedge. For this purpose, we sampled ultramafic xenoliths from the SW Japan arc and measured the major element abundances and Sr, Nd and Os isotopic ratios. We also discuss the relationships of mantle wedge with the neighbor continent.

The Japanese islands and related subduction zones are now located at the eastern margin of the Eurasian continent, which is presently the largest on earth (Fig. 1). Originally, they were parts of and lay at the eastern edge of the Eurasian continent while the Izanagi and Farallon plate were subducting beneath SE Asia (Maruyama et al., 1989). The Japanese islands were then separated from the continent during the Sea of Japan expansion in Miocene (20–15 Ma) (Otofuji and Matsuda, 1984; Okino et al., 1994). Before the Sea of Japan expansion, the SW Japan sliver was located at the margin of the Yangtze craton and rotated to its present position when the Philippine Sea plate began subducting beneath it around 15 Ma ago. These geologic events may have imprinted their signature on the geochemical features of volcanic rocks and xenoliths in SW Japan. Thus, the geochemical study of the xenoliths and related volcanic rocks can also provide some information on the relationship between subcontinental lithosphere and the mantle wedge beneath Japan and similar continental arcs.

The Os isotopic composition of peridotite xenoliths can place effective constraints on the history that peridotite xenoliths record. Osmium is a highly compatible element and is concentrated in the mantle rather than in the crust unlike the case of Sr and Nd isotope systems. The difference between the partition coefficients of parent Re and daughter Os makes Os isotope ratio lower in the mantle materials and higher in the crustal materials by age effects. The Os concentration of ultramafic xenoliths derived from upper mantle is several hundred ppt to ppb level. In subduction systems, the oceanic crust (MORB) has higher Re concentrations (MORB: 0.5–2 ppb, e.g., Shirey and Walker, 1998) than Os concentrations (MORB: 0.01–0.5 ppb, e.g., Shirey and Walker, 1998). They give a Re/Os ratio as high as 650 (e.g., Shirey and Walker, 1998), so that the Os isotope in MORB is elevated rapidly because of radioactive decay of ^{187}Re. The arc volcanic rocks and xenoliths yield higher Os isotope ratios, which were possibly affected by slab-derived metasomatism, than those from other tectonic settings (e.g., Brandon et al., 1996, 1999; Widom et al., 2003). Lassiter and Luhr (2001) indicated that the Os isotope systems of arc volcanic rocks might reflect an input of slab-derived fluids or melts in the source magma region. They suggested that the study of arc-related peridotite and pyroxenite xenoliths are more likely to provide direct constraints on Os transport in the mantle during subduction. The mantle xenoliths from subduction zones sometimes have radiogenic Os isotope ratios, which are explained by the mobility of Os into slab fluids (Brandon et al., 1996; Peslier et al., 2000a,b; Widom et al., 2003). Parkinson et al. (1998) analyzed the Os isotope compositions of Izu–Bonin–Mariana forearc peridotites and suggested that the low Os isotope ratios of some peridotites show a vestige of ancient depleted mantle. Thus, the study of Re–Os isotope system of ultramafic xenoliths derived from mantle beneath arc can provide information for better understanding of the interaction between mantle and subduction material.

2. Geological settings and samples

A large number of Cenozoic alkali basalts are distributed in a wide area from the Korean peninsula and eastern China to the southern part of Siberia, which has been called a “hot region” (Miyashiro, 1986). These

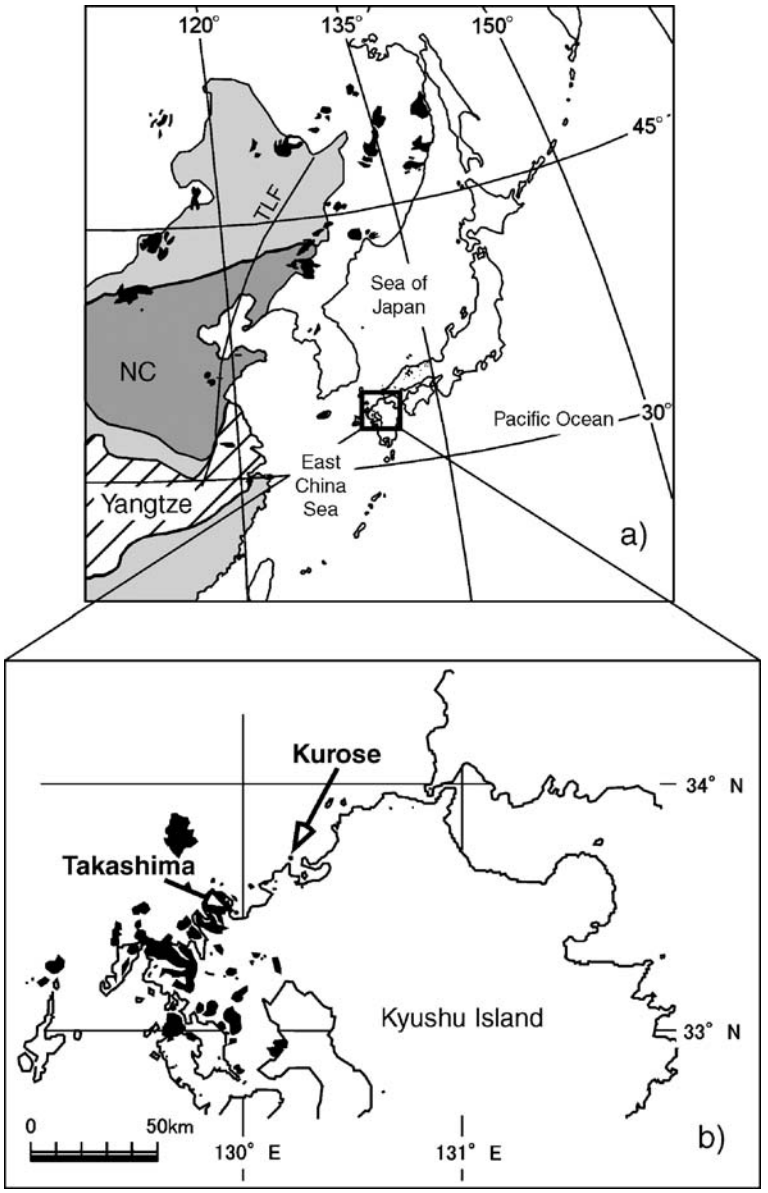

Fig. 1. Location map of Kurose and Takashima. (a) NC: North China craton, Yangtze: Yangtze craton, TLF: Tan–Lu fault. The black areas show the distribution of Cenozoic basalts in the eastern part of Asia. Data are from Aoki (1959), Kurasawa (1967), Takamura (1973), and Nakamura et al. (1986). (b) The northern part of Kyushu islands (inset in (a)).

alkali basalts contain various types of xenoliths, which may help to constrain the structure and composition of the deeper parts of the crust and upper mantle. Recently, many isotopic studies of xenoliths from the North China and the Yangtze (Zhao et al., 2000, 2001) cratons forming the eastern part of the Eurasian continent have been performed to clarify their origin. For example, Gao et al. (2002) suggested that Archean lithosphere exists beneath the eastern block of the North China craton. Xu (2002) showed that the pyroxenites in Cenozoic basalts from Hannuoba, North China craton, were generated from mixing between an asthenospheric melt and variable amounts of continental crust components. In Japan, many alkali basalts also erupted in late Cenozoic time from the Chugoku area to the northwestern parts of the Kyushu islands, near China. Some of these volcanic rocks contain xenoliths derived from the lower crust and upper mantle. Studies of these xenoliths have mainly focused on mineralogy and major element concentrations (e.g., Takahashi, 1978; Kobayashi and Arai, 1981;

Arai and Hirai, 1983). Trace element concentrations, Sr and Nd isotope ratios and/or noble gas isotopes have also been analyzed to clarify the origin of the material beneath Japan (e.g., Abe et al., 1998; Abe and Yamamoto, 1999; Kagami et al., 1999; Ikeda et al., 2001).

A notable location for xenoliths in Japan is Kurose, which comprises small alkali basalt reefs located in northern Kyushu, near the Eurasian continent (Fig. 1). The age of the alkali basalts here is 1.13±0.12 Ma (K–Ar dating: Uto et al., 1993), which is younger than the eruption ages of similar alkali basalts distributed from northern Kyushu to Chugoku area (mostly ca. 3 Ma). On the basis of a study of alkali basalts from the northern part of Kyushu, Hoang and Uto (2003) suggested that the mantle beneath most of northern Kyushu is geochemically and isotopically similar to that beneath the Sea of Japan, and represents a spectrum of compositions from depleted MORB-EM1 (DUPAL like) hybrids to shallow level EM2-type enriched components.

Various kinds of xenoliths, including ultramafic rocks and mafic granulites, were brought from depth to the surface by the Kurose alkali basalts. The xenoliths are mainly ultramafic rocks derived from upper mantle, with granulite xenoliths derived from lower crust comprising less than 10 vol.% (Arai et al., 2000). These xenoliths and the host alkali basalts have been intensively studied petrologically and geochemically (e.g., Arai and Kobayashi, 1981; Arai and Hirai, 1983; Abe et al., 1998; Arai et al., 2000). From a petrological viewpoint, Arai et al. (2000) suggested that the structure beneath Kurose consists of layered upper mantle devoid of metasomatism by Fe-rich melt, and lower crust layer. Kagami et al. (1999) examined the Sr isotopic ratios and Sm–Nd whole-rock-mineral isochron age of mafic granulite xenoliths from Kurose and Takashima and concluded that they were cumulate and/or residues of differentiated products from mafic magmas associated with late Cretaceous to early Tertiary volcanic magmas. Ikeda et al. (2001) analyzed the Sr, Nd and noble gas isotopic compositions of phenocrysts, megacrysts, and ultramafic xenoliths from SW Japan including Kurose. They concluded that the source mantle of the vast majority of these rocks likely possesses the signature of old subducted oceanic crust and sediments, and that some were products of mixing between depleted mantle and these recycled materials.

We sampled six peridotite xenoliths and one host alkali basalt from Kurose. Five of the peridotite xenoliths are harzburgites with rare clinopyroxene, and the sixth is a dunite. They show porphyroclastic textures and are mainly composed of 70–85 vol.% olivine (maximum 2 mm across) and 10–20 vol.% orthopyroxene (maximum 1.5 mm across). Clinopyroxene grains are small and are in trace amounts compared with olivine and orthopyroxene porphyroclasts. Cr-spinel is less than 2 vol.% and exists as inclusions or as interstitial minerals. Two pyroxene geothermometers for most of Kurose peridotite xenoliths are uniform (1000 to 1100 °C; Arai et al., 2000, based on Wells, 1977). The host alkali basalt is a holocrystalline basalt with olivine and clinopyroxene phenocrysts.

Another xenolith locality is Takashima, a small island about 1 km in diameter 30 km southwest of Kurose (Fig. 1). In Takashima, the biotite granites and hornblende-biotite granodiorites are covered by alkali olivine basalts. Nakamura et al. (1986) reported that the alkali olivine basalts erupted at 3.00±0.04 Ma (K–Ar dating), which is similar to the age of other alkali basalts in the northern Kyushu and Chugoku area. This alkali olivine basalt contains various types of xenoliths (Yamaguchi, 1964; Ishibashi, 1970; Kobayashi and Arai, 1981). In addition, a lot of big boulders of host alkali olivine basalts are found on the shore, and from one of which we sampled a dunite xenolith. The dunite shows porphyroclastic texture and is mainly composed of euhedral olivine and chromite, with small amount of clinopyroxene and orthopyroxene. The host alkali basalt of Takashima is geochemically similar to the Kurose alkali basalt (Arai et al., 2005).

3. Analytical methods

The samples were crushed to 1–2 cm size chips and washed several times with distilled–deionized water in an ultrasonic bath. Large phenocrysts of olivine and clinopyroxene were removed from the alkali basalts by hand picking after the samples were crushed. The rock chips were further reduced using a stamp mill, and powdered in both agate mortar and agate ball mill. Concentrations of Rb, Sr, Nd, and Sm were determined using isotope dilution. For the determination of Rb, Sr, Nd, and Sm concentrations, and Sr and Nd isotope ratios, powdered samples (about 0.5 g) were decomposed using HF and $HClO_4$, and the elements of interest were separated from major elements by passing the dissolved sample through cation exchange columns with HCl and 2-methyllactic acid (Tanaka and Masuda, 1982). Isotope analysis was performed using TI-MS (VG Sector 54-30 for natural isotope ratios and Finnigan MAT-THQ for isotope dilution) at Nagoya University. The average $^{87}Sr/^{86}Sr$ ratio of NIST-SRM987 was 0.710237±17 (2σ, n=72), and $^{143}Nd/^{144}Nd$ ratio of the JNdi-1 standard solution was 0.512108±10 (2σ, n=18) during the course of this study. The Rb, Sr, Nd, and Sm

Table 1
Major element composition of the ultramafic xenoliths from Kurose and Takashima

		SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Mg#
Ultramafic xenolith												
Kurose												
K-1	Harzburgite	43.9	0.02	1.6	8.7	0.13	41.9	1.76	n.d.	0.01	0.004	0.905
K-2	Harzburgite	43.6	0.03	1.4	9.0	0.14	42.2	1.83	n.d.	0	0.005	0.903
K-3	Harzburgite	43.1	0.03	1.2	8.5	0.13	43.1	1.57	n.d.	n.d.	0.006	0.909
K-4-1	Harzburgite	42.7	0.02	1.2	9.3	0.14	44.4	1.11	n.d.	n.d.	0.004	0.904
K-4-2	Dunite	40.2	0.02	0.3	9.0	0.13	49.3	0.32	n.d.	n.d.	0.006	0.915
K-5	Harzburgite	43.9	0.04	1.4	8.8	0.13	43.6	1.34	0.03	0.06	0.010	0.907
Takashima												
TW-3	Dunite	39.9	0.03	0.5	12.1	0.16	45.3	0.75	n.d.	n.d.	0.006	0.881
Alkali basalt												
K-host		46.3	2.54	14.8	10.9	0.17	7.7	8.46	4.38	0.91	0.721	

Concentrations are in wt.%. The n.d. means under detection limit. Mg# are calculated on atomic ratio.
* Total Fe given as Fe_2O_3.

blanks were 0.5 ng, 2.3 ng, 0.014 ng, and 0.2 ng, respectively.

Rhenium and Os concentrations were determined by isotope dilution method with ^{185}Re and ^{190}Os spike solutions. Osmium concentration was analyzed at the same time as Os isotope ratio. Sample powders were digested by the Carius tube method (Shirey and Walker, 1995). Approximately 0.1–0.5 g of fine sample powder was dissolved in inverse aqua regia at 220 °C for 12–24 h. After digestion, osmium was separated from the acid solution by CCl_4 extraction (Cohen and Waters, 1996) to organic phase. Then osmium was again back-extracted into HBr from CCl_4 and further purified by micro distillation (Roy-Barman, 1993; Roy-Barman and Allègre, 1995; Birck et al., 1997). Rhenium was separated from the acid solution after Os extraction using anion exchange column chemistry (Pearson et al., 1995) with anion exchange resin (Bio-Rad, AG-1X8). Rhenium and Os were loaded individually on Pt-filaments and

Table 2
Major elements of olivine, orthppyroxene, clinopyroxene, and Cr-spinel in the ultramafic xenoliths from Kurose (K-2 and K-5)

	K-2				K-5			
	ol	opx	cpx	sp	ol	opx	cpx	sp
SiO_2	41.0	56.1	53.2	0.08	41.0	56.0	53.1	0.13
TiO_2	0.01	0.05	0.10	0.08	0.01	0.02	0.09	0.12
Al_2O_3	0.02	3.25	3.20	42.41	0.02	2.77	2.88	36.71
FeO*	9.27	5.82	2.56	12.49	8.93	5.58	2.50	13.56
MnO	0.16	0.14	0.07	0.17	0.14	0.13	0.09	0.19
MgO	49.0	33.1	17.3	18.4	49.9	33.8	17.7	17.6
CaO	0.08	0.93	22.3	0.02	0.09	0.93	22.1	0.01
Na_2O	0.02	0.03	0.24	0.01	0.01	0.02	0.28	0.00
K_2O	0.01	0.01	0.01	0.00	0.01	0.02	0.01	0.01
Cr_2O_3	0.07	0.53	0.68	25.42	0.02	0.55	0.75	31.20
Total	99.56	99.93	99.64	99.05	100.06	99.81	99.52	99.58
Mg#	0.91	0.92	0.93		0.92	0.92	0.93	
Cr#		0.06	0.08	0.19		0.07	0.09	0.25

ol: olivine; opx: orthopyroxene; cpx: clinopyroxene; sp: Cr spinel. FeO*: total iron as FeO; Mg#: Mg/(Mg+total Fe) atomic ratio of silicates; Cr#: Cr/(Cr+Al) atomic ratio.

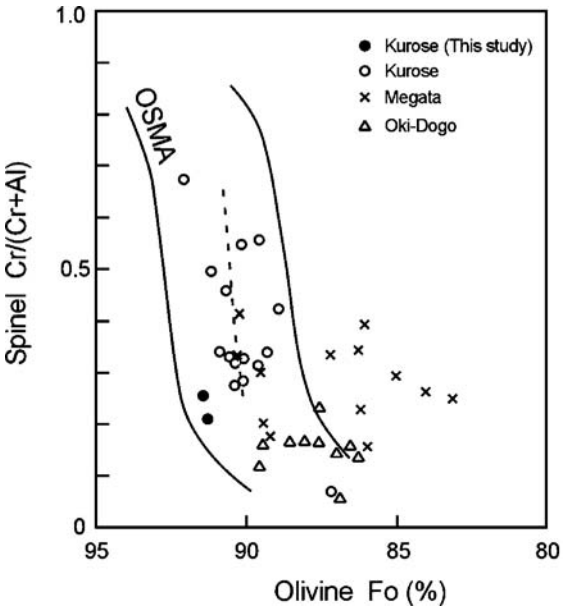

Fig. 2. Relationship between olivine Fo content and Cr# (=Cr/(Cr+Al)) of chromian spinel in the mantle peridotite xenoliths from Japan. OSMA is the olivine-spinel mantle array, a possible spinel peridotite restite trend (Arai, 1987; 1994). The data of peridotite xenoliths for Kurose, Megata, and Oki-Dogo from Abe et al. (1998), Abe and Yamamoto (1999), and Abe et al. (2003) are also shown for comparison.

Table 3
Sr, Nd, and Os isotopic compositions and Rb, Sr, Nd, Sm, Re, and Os concentrations for ultramafic xenoliths and their host alkali basalt

	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Nd	Sm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ϵ_{Nd}	Re	Os	$^{187}Re/^{188}Os$	$^{187}Os/^{188}Os$	T_{RD} (Ga) *
Ultramafic xenolith														
Kurose														
K-1	0.21	2.25	0.265±2	0.70473±3	0.097	0.028	0.179±10	0.512516±24	−2.4	0.20	1.29	0.72±1	0.1270±5	0.35
K-2	0.20	2.15	0.262±10	0.70470±3	0.117	0.028	0.154±12	0.512495±14	−2.8	0.25	1.12	1.04±1	0.1266±6	0.42
K-3	0.12	1.63	0.208±6	0.70435±14	0.089	0.027	0.195±16	0.512563±33	−1.5	0.35	0.96	1.71±4	0.1289±34	0.09
K-4-1	0.18	3.54	0.143±2	0.70665±1	0.048	0.012	0.162±21	0.512280±14	−7.0	0.29	1.26	1.08±8	0.1244±9	0.71
K-4-2	0.16	4.72	0.095±2	0.70773±2	0.100	0.020	0.125±6	0.512426±28	−4.1	0.37	0.45	3.88±5	0.1231±26	0.89
K-5	0.97	5.67	0.484±11	0.70416±2	0.256	0.049	0.122±2	0.512832±12	3.8	0.30	1.66	0.84±3	0.1229±6	0.92
Takashima														
TW-3	0.33	4.29	0.216±8	0.70583±1	0.165	0.044	0.166±2	0.512451±11	−3.6					
Alkali basalt														
K-host	3.90	237	0.046±1	0.70379±2	12.44	2.47	0.125±7	0.512839±6	3.9	0.35	0.10	16.4±7	0.1268±11	

The abundances of Rb, Sr, Nd, and Sm are in ppm and Re and Os are in ppb. All errors are 2σ.
* Parameters for calculating T_{RD} model ages are from depleted mantle in SE China $^{187}Os/^{188}Os = 0.1296$ (Meisel et al., 2001) and $^{187}Re/^{188}Os = 0.433$ (Gao et al., 2002).

measured using NTI-MS (VG Sector 54-30 at Nagoya University) as oxides. The average $^{187}Os/^{188}Os$ ratio of our Os standard solution (diluted Osmium plasma standard solution, Specpure, Alfa Aesar) was 0.10643± 11 (2σ, $n=35$). The average $^{187}Os/^{188}Os$ ratio of repeated analysis of the standard rock sample JP-1 (peridotite, geochemical reference samples from Geological Survey of Japan) is 0.12085±42 (2σ, $n=5$), which agrees within the analytical uncertainties with the previously reported data (Suzuki and Tatsumi, 2001). Rhenium and Os blanks were 6 pg and 7 pg, respectively. These blank levels are negligible relative to high Re and Os contents of the samples analyzed in the present study. Detailed procedures are described in Senda et al. (2006).

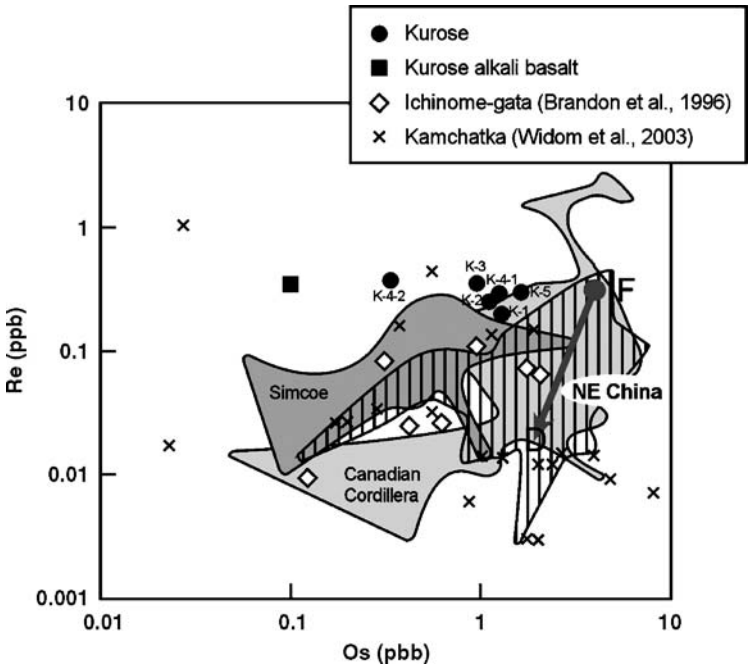

Fig. 3. Re and Os concentrations for peridotite xenoliths from Japan in comparison with those of other arcs and China. Downward dark grey arrow extending from F (fertile) to D (depleted) mantle is from Morgan (1986). Data for Canadian Cordillera, Ichinome-gata, Kamchatka, NE and east China, and Simcoe are from Brandon et al. (1996, 1999), Widom et al. (2003), Peslier et al. (2000a,b), Gao et al. (2002), Wu et al. (2003), and Reisberg et al. (2005).

Major elements were analyzed using X-ray fluorescence (XRF) spectrometry following the procedure of Sugisaki et al. (1977). The mineral components of the samples K-2 and K-5 were determined by electron microprobe (JEOL JRX8800R) at Nagoya University.

4. Results

The major element concentrations of the harzburgites from Kurose (Table 1) are almost homogeneous. Mineralogical constituents of K-2 and K-5 are homogeneous in each thin section, but differ between samples, e.g., olivine has relatively high MgO contents in K-2 and spinel of K-5 contains high Cr_2O_3 (Table 2). The Mg numbers of K-2 and K-5 olivines are around 0.91. The olivine Fo contents and spinel Cr/(Cr+Al) values of K-2 and K-5 are similar to other xenoliths from Kurose (Abe et al., 1998; Abe and Yamamoto, 1999; Arai et al., 2000), and in the range of OSMA (olivine-spinel mantle array; Arai, 1987, 1994) defined as a mantle peridotite residual trend (Fig. 2). The Kurose data plot near a lengthwise straight line shown by a broken line in Fig. 2. The scatter

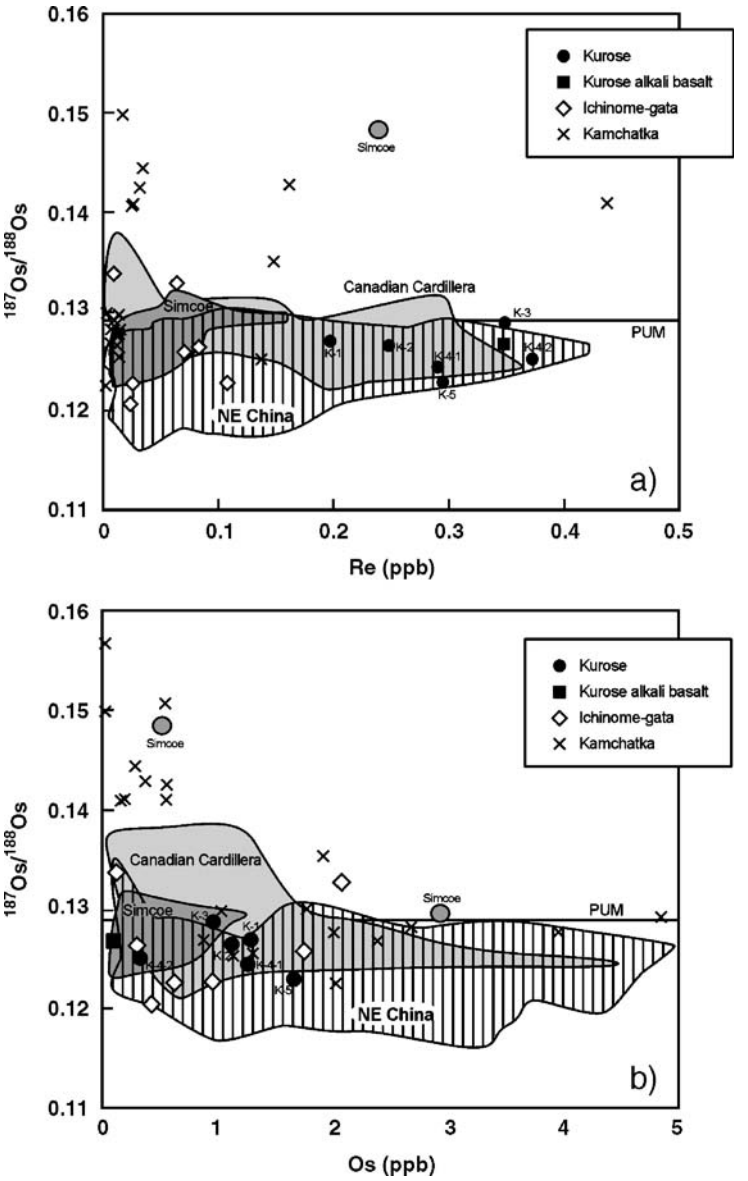

Fig. 4. Variation in $^{187}Os/^{188}Os$ vs. Re (a) and Os (b) concentrations for the Kurose ultramafic xenoliths and alkali basalt, together with the NE and east China xenoliths. The PUM (Primitive Upper Mantle) line is $^{187}Os/^{188}Os$ ratio (0.1296) from Meisel et al. (2001). The data sources are the same as in Fig. 3.

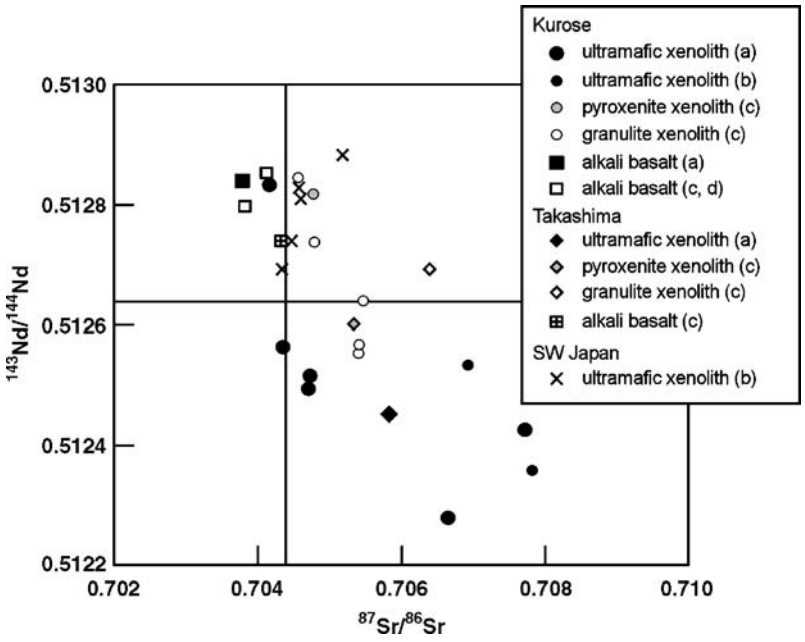

Fig. 5. Nd and Sr isotopic ratios of Kurose and Takashima xenoliths with alkali basalts. The data are from (a) this study, (b) Ikeda et al. (2001), (c) Kagami et al. (1999), and (d) Hoang and Uto (2003).

of Cr/(Cr+Al) values of Kurose xenoliths suggests that they underwent several different conditions during partial melting of mantle peridotites (Arai, 1994).

Rubidium and Sr concentrations of Kurose and Takashima ultramafic xenoliths range from 0.12 to 0.33 ppm and from 1.63 to 4.72 ppm, respectively, except for K-5 (Rb: 0.97 ppm; Sr: 5.67 ppm) as shown in Table 3. Examination of thin sections shows that sample K-5 has slightly more abundant clinopyroxene than the other samples from Kurose. As clinopyroxene is generally rich in incompatible elements, a generous amount of clinopyroxene in K-5 is consistent with the relatively high concentrations of Rb and Sr. The Sr isotopic ratios of the xenoliths in this study range from 0.70416 to 0.70773, within the range of those previously reported for spinel lherzolite xenoliths (0.70342–0.70446; Abe and Yamamoto, 1999) and for harzburgite xenoliths from Kurose (0.70693–0.70783; Ikeda et al., 2001).

The Kurose and Takashima xenoliths exhibit Nd and Sm concentrations (0.048–0.256 ppm and 0.012–0.049 ppm, respectively) that are an order of magnitude lower than the concentrations in ultramafic xenoliths from Ichinome-gata, NE Japan (Nd: 0.035–2.58 ppm, Sm: 0.34–1.53 ppm; Tanaka and Aoki, 1981; Brandon et al., 1996). The Sm/Nd ratios of the Kurose and Takashima xenoliths range from 0.193 to 0.309. The Nd isotope ratios from this study ($^{143}Nd/^{144}Nd$=0.51228–0.51256) show agreement with those of harzburgite xenoliths ($^{143}Nd/^{144}Nd$=0.51236–0.51253) from Kurose previously reported by Ikeda et al. (2001), with the exception of K-5 ($^{143}Nd/^{144}Nd$=0.51283).

Rhenium concentrations of the Kurose xenoliths are similar to those of the fertile mantle, whereas Os contents are lower than fertile mantle (Fig. 3). The Os isotopic ratios ($^{187}Os/^{188}Os$=0.123–129) of all the Kurose xenoliths as well as alkali basalts are lower than that of the PUM estimate (Primitive Upper Mantle: 0.1296; Meisel et al., 2001), and fall within the range reported for arc xenoliths from elsewhere and China (Fig. 4). Dunite K-4-2 has higher Re and lower Os concentrations than the harzburgites from Kurose. Peridotite xenoliths from other arcs such as NE Japan (Ichinome-gata) have variable Re and Os concentrations without any relationship with rock types (Fig. 3).

Major element concentrations and Sr and Nd isotopic ratios of the alkali basalt from Kurose obtained in this study are identical with those reported in previous studies (e.g., Uto et al., 1993; Kagami et al., 1999; Hoang and Uto, 2003; shown in Fig. 5). The Kurose alkali basalts may be homogeneous in composition.

5. Discussions

5.1. Continental lithospheric mantle as a source of the Kurose xenoliths

Not only ultramafic xenoliths from upper mantle but also mafic granulite xenoliths from lower crust are found

in the host alkali basalt of Kurose. Kagami et al. (1999) reported the Sr and Nd isotopic ratios of the mafic granulites and concluded that the origin of the mafic granulite xenoliths was associated with late Cretaceous felsic igneous rocks distributed in SW Japan and southern Korean Peninsula. The Sr and Nd isotopic ratios of the mafic granulites plot in a different field from those of the ultramafic xenoliths of Kurose except for K-5 (Fig. 5). The $^{147}Sm/^{144}Nd$ ratios of the ultramafic xenoliths, ~ 0.15, are lower than the ratios of mafic granulites, ~ 0.2 (Kagami et al., 1999). If the ultramafic xenoliths were associated with the granulite xenoliths, more mafic phases (ultramafic xenolith) would be relatively enriched in Sm. The Sm/Nd ratios of the Kurose xenoliths, however, do not show such a tendency. These geochemical features argue against any relationship between the ultramafic xenoliths and mafic granulites in Kurose. Thus, it is more likely that the origin of the ultramafic xenoliths was not closely related with that of the mafic granulites.

The Os concentrations of the Kurose ultramafic xenoliths lie near the fields defined by ultramafic xenoliths from other arcs, including the Canadian Cordillera and Kamchatka (Fig. 3). On the other hand, Os isotopic ratios are also similar to those of xenoliths from other arcs (Fig. 4), but do not extend to radiogenic values. According to Brandon et al. (1996) and Widom et al. (2003), the radiogenic Os isotopic ratios of arc-derived xenoliths can be explained by metasomatism with hydrous slab fluids or melts which were transported from the subducted slab into the mantle wedge. As shown in Fig. 4, the Os isotopic ratios of the Kurose xenoliths range from 0.123 to 0.129, which are less variable compared to other arc xenoliths with Os isotopic ratios ranging from 0.12 to 0.16 (Fig. 4). It seems that the Os isotopic compositions of the xenoliths from Kurose were less influenced by hydrous slab fluids or melts compared with those of other arcs.

The xenoliths from Kurose possess a Re–Os signature more similar to that of the ultramafic xenoliths from NE and east China (Fig. 4). Rudnick et al. (2004) suggested that the ultramafic xenoliths of NE China are derived from continental lithospheric mantle based on petrological and geochemical studies. The xenoliths sampled by Cenozoic alkali basalts in east China are considered to have originated from the lithospheric mantle and have Os isotopic ratios of 0.1140–0.1391 (Suzuki et al., 2004). Reisberg et al. (2005) reported the Os isotope ratios for Cenozoic basalts-borne xenoliths from Subei basin (0.1177–0.1345) and suggested that their Re–Os signature is related to Mesozoic or Cenozoic lithosphere thinning in eastern China. Qixia peridotite xenoliths from eastern China have been linked with Jurassic to Cretaceous lithosphere in the North China craton ($^{187}Os/^{188}Os = 0.1199–0.1299$), whereas the Hannuoba peridotite xenoliths from northern China yield an early Proterozoic age based on the whole rock isochron and possess slightly lower Os isotopic ratios than Qixia's ($^{187}Os/^{188}Os = 0.1166–0.1282$, Gao et al., 2002). The T_{RD} ages, the minimum Re depletion age (Walker et al., 1989), of the Kurose xenoliths (Table 3) are similar to most of the peridotite xenoliths from NE and east China (0.13–0.89 Ga, Gao et al., 2002; Reisberg et al., 2005). The Os isotopic compositions of the Kurose xenoliths, as well as their Re and Os concentrations, fall mostly within the fields defined by these xenoliths from NE and east China lithospheric mantle (Fig. 4). Thus, the Kurose xenoliths may be related to the continental lithospheric mantle beneath China.

The possibility that some fragments of continental lithospheric mantle beneath China remain beneath the region where Kurose and Takashima islands are located is consistent with SW Japan arc being once part of the eastern margin of the Eurasian continent. The SW Japan arc sliver rotated 40–50° clockwise and terminated rotation at around 15 Ma (Otofuji et al., 1991) in response to the opening of the Sea of Japan and the major episode of rifting of the Sea of Japan back-arc basin. The southward drift of the SW Japan arc, caused by the clockwise rotation of the arc sliver, most likely resulted from the start of subduction of the very young (15–27 Ma; Tamaki et al., 1992; Okino et al., 1994) oceanic crust of the Philippine Sea plate beneath the SW Japan arc (Tatsumi and Maruyama, 1989). The eruption age of the Kurose alkali basalt (1 Ma; Uto et al., 1993) indicates that the Kurose xenoliths were not sampled before the Sea of Japan expansion. Likewise, the alkali basalt of Takashima also erupted after the Sea of Japan expansion (3 Ma; Nakamura et al., 1986). Our Os isotopic data suggest that a piece of the lithospheric mantle of the eastern China continent exists beneath Kurose even after the opening of the Sea of Japan. Nakajima et al. (1995) reported that the volcanic rocks of NE Japan possess the isotopic composition of the continental lithospheric mantle beneath the Sea of Japan after its opening. These observations suggest that the China continental lithospheric mantle itself or its slivers existed beneath the Japanese islands after the Sea of Japan expansion.

5.2. Contamination of subducted slab materials

The Re concentrations of Kurose xenoliths are similar to fertile mantle, but Os concentrations are lower than fertile mantle (Fig. 3). Similarly, the arc peridotites from Kamchatka (Valovayam, Bakening; Widom et al., 2003),

NE Japan and Cascade (Ichinome-gata and Simcoe; Brandon et al., 1996, 1999) have lower Os concentrations than fertile mantle (Fig. 3) although some arc peridotites which have Os concentrations similar to fertile mantle are also reported from Kamchatka (Avachinsky; Widom et al., 2003) and Papua New Guinea (Lihir; McInnes et al., 1999). Brandon et al. (1996) explained that the low Os concentrations of arc peridotites were affected by Cl-rich slab fluids. Widom et al. (2003) suggested that the mantle Os scavenged and exchanged with oxidized slab melts during interaction with the wedge mantle. The Os isotopic ratio of the slab material is very high compared with that of the mantle. For example, oceanic sediments are mainly composed of continental crust-derived components, which have extremely high $^{187}Os/^{188}Os$ of 1.0–1.4 (Peucker-Ehrenbrink and Jahn, 2001; Hattori et al., 2003) and oceanic sediments are thus expected to have high Os isotopic compositions. Oceanic crust also possesses high Os isotopic compositions, because of the low Os content of MORB (0.001–0.05 ppb, e.g., Shirey and Walker, 1998) and the consequent high Re/Os ratio, which leads to an elevation of $^{187}Os/^{188}Os$ ratio with time.

One of the explanations for the origin of arc xenoliths is offered by Brandon et al. (1996) for the Nd and Os isotope ratios of peridotite xenoliths from Simcoe, Cascade arc and Ichinome-gata, NE Japan arc. For Simcoe xenoliths, they claimed that the Nd and Os isotope ratios can be reproduced by mixing 7 to 15% mass of subduction component composed of 5–10% sediment and 95–90% subducted basalt (MORB) with depleted peridotite. On the other hand, the radiogenic Os compositions of the Ichinome-gata xenoliths were reproduced by addition of approximately 6% of slab components comprised of 5–20% sediment and 95–80% MORB with depleted peridotite. The Ichinome-gata peridotites may have interacted with slab-derived melts or fluids, as the Al_2O_3 components of the Ichinome-gata xenoliths range from 0 to 15%. The Al_2O_3–Os relations are also consistent with interaction between a slab-derived hydrous fluid and depleted mantle. Widom et al. (2003) also suggested that the Os isotopic compositions and Re concentrations of some of the Kamchatka peridotite xenoliths were also affected by slab-derived melts.

For the Kurose ultramafic xenoliths, the Os concentrations are higher than, whereas the concentrations of Rb, Sr, Nd, and Sm are much lower than, those of crustal materials such as sediment and alkali basalt. Therefore, Sr and Nd isotopic compositions can be expected to be influenced more easily by crustal materials. The $^{143}Nd/^{144}Nd$ ratios of most of the Kurose xenoliths are lower than those of the peridotite xenoliths from SE and NE China, and also those of Ichinome-gata and Simcoe (Figs. 6 and 7). The Kurose xenoliths data fall roughly on a trend toward a low Nd and a high Sr isotopic ratio, suggesting contribution of slab materials. As shown in Fig. 6, the data of the Kurose and Takashima xenoliths plot along a mixing line between slab components and lithospheric mantle (averaged isotopic composition of the peridotite xenoliths from SE and NE China: Sr and Nd data from Xu et al., 2003; Rudnick et al., 2004). In Fig. 7, the Nd and Os isotope ratios of Kurose xenoliths also plot along the mixing line between the same end-members defined in Fig. 6 (Os data from Gao et al., 2002). In the Nd–Os plot (Fig. 7), the first few percent addition of slab material results in large decreases in Nd isotope composition with only a slight change in Os isotope ratio. This reflects the different concentrations of Os and Nd between slab components and lithospheric mantle. It also suggests that the influence of subducted slab component on the Os isotopic composition of the Kurose ultramafic xenoliths is much less compared to their Nd isotope ratios.

The mixing calculation in this model shows that the Sr–Nd–Os isotopic characteristics of the Kurose and Takashima xenoliths can be explained by less than 20% addition of oceanic sediments as fluids or melts, into the lithospheric mantle source. In general, the peridotite xenoliths from arcs are affected by the slab component which is assumed to be a mixing product of altered MORB and oceanic sediments (Brandon et al., 1996, 1999; Widom et al., 2003). However, the Nd isotopic ratios and Nd concentrations of altered MORB are higher than those of the Kurose xenoliths. If we assume various ratios of mixing between altered MORB and oceanic sediments to represent the slab component, the resulting Nd isotope ratios are mostly higher than those of the Kurose xenoliths. Similarly, a mixing model assuming a 2:8 mixture of oceanic sediment and altered MORB (the mixing ratio assumed for NE Japan based on Brandon et al., 1996; open triangle in Fig. 6), cannot explain the Sr–Nd–Os isotopic signatures of the Kurose and Takashima xenoliths.

Based on this mixing model, the Sr–Nd–Os isotopic characteristics of the Kurose and Takashima xenoliths can be explained by less than 20% addition of oceanic sediments into the lithospheric mantle source. This result shows that the contribution of oceanic sediment to the slab component is larger than is considered in NE Japan (Ichinome-gata), Simcoe and Kamchatka (Brandon et al., 1996, 1999; Widom et al., 2003). The difference between the slab materials which affected the mantle beneath SW Japan and other arcs, for example, NE Japan, depends on the chemical and physical signature of

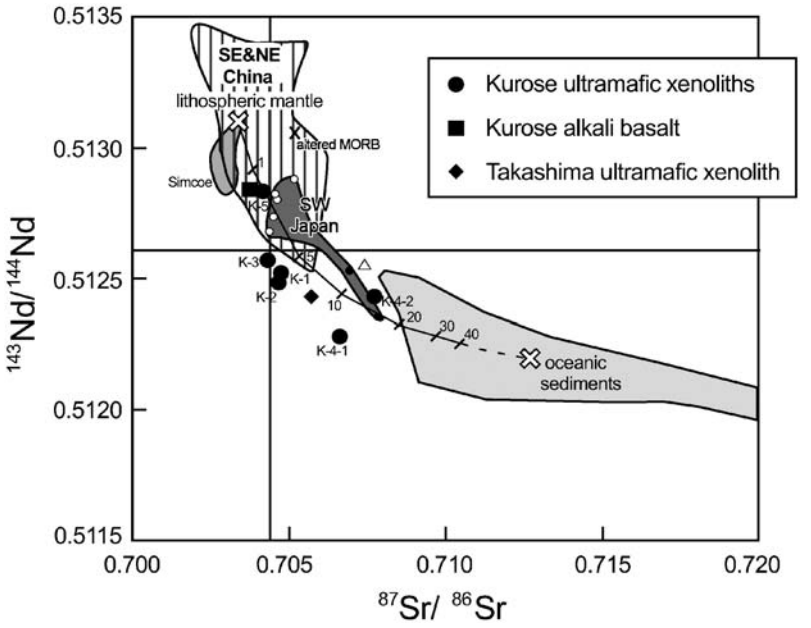

Fig. 6. Nd and Sr isotopic ratios for the Kurose and Takashima ultramafic xenoliths together with the ultramafic xenoliths derived from other arc (Simcoe) and cratons (SE and NE China). The mixing line represents the calculated mixture between an assumed lithospheric mantle ($^{87}Sr/^{86}Sr=0.70336$, Sr: 49.0 ppm, $^{143}Nd/^{144}Nd=0.51310$, Nd: 1.8 ppm; averaged value from Xu et al., 2003 and Rudnick et al., 2004) and an averaged oceanic sediment ($^{87}Sr/^{86}Sr=0.71260$, Sr: 244.5 ppm, $^{143}Nd/^{144}Nd=0.51220$, Nd: 46.84 ppm; averaged value from Othman et al., 1989). The open triangle is a 2:8 mixture ratio of oceanic sediment and altered MORB ($^{87}Sr/^{86}Sr=0.70520$, Sr: 168.7 ppm, $^{143}Nd/^{144}Nd=0.51306$, Nd: 6.7 ppm; Staudigel et al., 1995) defined by Brandon et al. (1996). It cannot explain the variation of Kurose xenoliths. The numbers on the mixing line correspond to the mixing ratio of oceanic sediment. As mixing of an oceanic sediment of more than 40% is not plausible, the mixing line over 40% is indicated by a dashed line. The small circles (small filled circles are from Kurose) and dark grey area are from SW Japan (Ikeda et al., 2001). The Simcoe data are from Brandon et al. (1996, 1999).

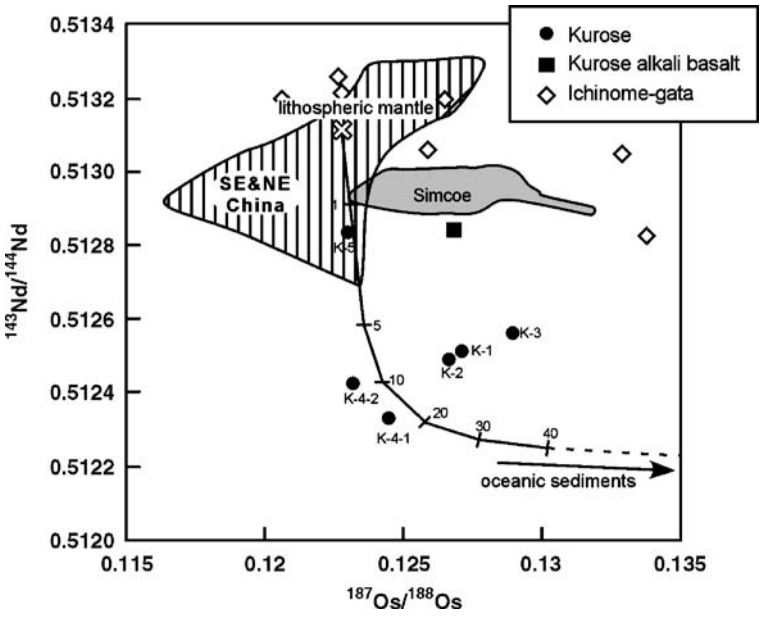

Fig. 7. Nd and Os isotopic ratios for arc-derived peridotite xenoliths. The mixing line extends from lithospheric mantle ($^{143}Nd/^{144}Nd=0.51310$, Nd: 1.8 ppm; $^{187}Os/^{188}Os=0.1231$, Os: 3.6 ppb, averaged value from Gao et al., 2002) to oceanic sediments ($^{143}Nd/^{144}Nd=0.51220$, Nd: 46.84 ppm; Othman et al., 1989, $^{187}Os/^{188}Os=0.6127$, Os: 0.1 ppb; averaged value from Peucker-Ehrenbrink and Jahn, 2001) as a slab component. The numbers on the mixing line indicate the mixing ratio of slab component. As mixing of more than 40% of an oceanic sediment is not plausible, the mixing line over 40% is indicated by a dashed line.

subducted materials. Old and cold plate is subducted beneath NE Japan, whereas young and hence, hot plate, is subducted beneath SW Japan.

In our model, the metasomatic agent which has affected the mantle wedge was not the subducted slab material itself but fluids and/or melts extracted from the slab. As the distribution of elements into a fluid component are not well constrained, the mixing line was calculated assuming simple addition of the slab material itself. The major element compositions of the peridotite xenoliths from Kurose and Takashima (Table 1) are similar to the peridotite xenoliths from SE and NE China (Song and Frey, 1989; Zheng et al., 1998; Rudnick et al., 2004). The xenoliths from Kurose are in the OSMA field, which indicates that the Kurose peridotite xenoliths are residues of partial melting of the original source mantle (Fig. 2). The Rb, Sr, Nd, and Sm concentrations of the peridotite xenoliths from Kurose and Takashima are also in the range of the peridotite xenoliths from SE and NE China (Rudnick et al., 2004). The concentrations of lithophile elements, however, are very low compared with those of the slab materials, such as oceanic sediments and altered MORB, that affected the lithospheric mantle. These facts indicate that contamination of slab material is just "cryptic metasomatism" (Dawson, 1984). The "cryptic metasomatism" may have resulted from open system "incremental batch melting" (Ozawa and Shimizu, 1995; Ozawa, 2001). Using model calculation with trace element contents such as HFSE and REE, Abe and Arai (2005) indicates that the peridotite xenoliths from Kurose were affected by silicate metasomatism (silicate melt or H_2O fluids), which supports the results of the isotope systems obtained in this study. As shown above, the data from Kurose and Takashima fall along the mixing line between lithospheric mantle and oceanic sediments in Sr–Nd–Os isotopic diagrams (Figs. 6 and 7), which suggest that these samples were influenced by the slab materials.

6. Conclusion

The Os concentrations of Kurose ultramafic xenoliths exhibit similar range to those of ultramafic xenoliths from the other arcs such as the Canadian Cordillera, Kamchatka, Ichinome-gata, and Simcoe. The Re concentrations of the Kurose xenoliths are slightly higher than the other arc xenoliths. The Os isotope ratios from Kurose ultramafic xenoliths are similar to or less radiogenic than the isotope ratios of xenoliths derived from other arcs. The Re–Os isotope data for the Kurose ultramafic xenoliths are similar to those of ultramafic xenoliths from China. The Sr–Nd–Os isotopic compositions of some of the Kurose xenoliths fall along a mixing line between lithospheric mantle with similar composition as those of the ultramafic xenoliths from SE and NE China and a slab component mainly composed of oceanic sediments. From these results, the xenoliths from Kurose record two different processes: the first is the signature of continental lithospheric mantle similar to those beneath China; the second is the influence of a certain amount of contaminations from fluids and/or melts derived from the subducted slab. Since the Japanese Islands slivered from Eurasian continent at Miocene time, it is highly probable that a common lithospheric mantle is beneath SW Japan and China. The existence of the similar lithospheric mantle beneath Kurose and China has an important implication for understanding tectonic and geochemical processes at continental margins. In the peridotite xenoliths from Kurose and Takashima, the oceanic sediments much contributed to slab material than altered MORB.

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