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Oxygen Isotopic Ratios for Ultramafic Xenoliths from the Korean Peninsula

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한반도 초염기성 포획암의 산소동위원소 비율

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Abstract: This study examined the geochemical characteristics, equilibrium temperature and pressure conditions, and oxygen isotopic ratios of mantle xenoliths from the various geological sites of the Korean peninsula. The results are as follows: (1) The ultramafic xenoliths from the Korean peninsula mainly consist of typical high magnesium olivine (MgO : 49.12-50.95 wt.%, Mg value: 90.1-92.2), corresponding to worldwide Cenozoic ultramafic xenoliths in chemical compositions. (2) The pressure-temperature conditions of ultramafic xenoliths in the Korean peninsula are from 854 to 1016°C and 4.6 to 24.4 kbar. (3) The oxygen isotopic ratios ($\delta^{18}O$) for olivines in ultramafic xenoliths range from 5.06‰ to 5.51‰, which are relatively uniform oxygen isotopic values and overlapped by the values of N-MORB and upper mantle peridotite ($\delta^{18}O$: 5.2±0.2‰). However, olivines of the ultramafic xenoliths from the Baegdusan and Chejudo have a relatively wide $\delta^{18}O$ values ranging from 5.07 to 5.51‰ and 5.07 to 5.45‰, respectively. Based on the results, this study suggests that the high $\delta^{18}O$ signature of the Baegdusan xenoliths give a hint that ~5% of the oxygen in typical EM2 sources originally derived from recycled sediments.

Keywords: Ultramafic Xenoliths, geochemical characteristics, equilibrium temperature, equilibrium pressure, oxygen isotopic ratios

요 약: 한반도에서 산출되는 초염기성 맨틀포획암의 지화학적 특징과 평형 온도와 압력 조건을 계산하고, 산소동위원소비를 분석하였다. 연구 결과 (1) 한반도 맨틀포획암은 전형적인 초염기성 포획암(MgO: 49.12-50.95 wt.%, Mg값: 90.1-92.2)으로 구성되어 있다. (2) 한반도 맨틀포획암의 평형온도는 854-1016°C이고, 압력은 4.6-24.4 kbar로 얻어졌다. (3) 맨틀포획암을 구성하는 감람석의 산소동위원소비($\delta^{18}O_{ol}$)는 5.06-5.51‰의 균질한 값으로 N-MORB와 상부 맨틀 감람석의 값($\delta^{18}O$: 5.2±0.2‰)과 유사하다. 그러나 백두산과 제주도의 맨틀포획암을 구성하는 감람석의 산소동위원비는 각각 5.07-5.51‰과 5.07-5.45‰로 상대적으로 넓은 범위의 $\delta^{18}O$ 값을 갖고 있다. 이 결과를 바탕으로, 이 연구에서는 백두산 맨틀포획암의 높은 $\delta^{18}O$가 맨틀포획암 물질에 재순환된 퇴적물원 EM2 물질의 혼입 때문일 수 있다는 가능성을 제안하였다.

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주요어: 맨틀포획암, 지화학적 특징, 평형 온도, 평형 압력, 산소동위원소비

Introduction

Investigations of ultramafic xenoliths are important for understanding a complex evolutionary history of the upper mantle. Ultramafic xenoliths are considered to be fragments derived from the upper mantle accidentally brought to the surface by their host alkali basalt volcanism. For this reason ultramafic xenoliths offer important information on the composition, structure and the most direct evidence of the igneous processes that take place in the upper mantle (Choi et al., 2002). Ultramafic xenoliths have been the subject of mineralogical, petrologic, geothermal, geochemical and isotopic studies in mantle geodynamics (Irving, 1980; Cohen et al., 1984; Arai et al., 2001; Choi et al., 2005; Kim et al., 2005; Lee and Walker, 2006; Arai et al., 2007; Chen et al., 2007; Perinelli et al., 2011).

Cenozoic alkali basalts with abundant ultramafic xenoliths are distributed in the Korean peninsula which is located on the southeast continental margin of the Eurasian plate. Ultramafic xenoliths occurred not only in the Chejudo, Baegryeongdo, Jogokri (Boen) and Baegdusan, but Long Quan of Chinese territory as well. Host alkali basalts in the Korean peninsula show OIB geochemical signatures, particularly in REE abundances (Kim et al., 1999). Eruptive ages for the host alkali basalts containing the ultramafic xenoliths range from 21 to 0.1 Ma (Kim et al., 2005).

Nd-Sr isotopic compositions and major- and trace-elemental geochemical characteristics of ultramafic xenoliths in the Korean peninsula have shown the heterogeneity of the mantle composition (e.g., Song and Frey, 1989; Basu et al., 1991; Zhou et al., 2002; Zhang et al., 2004; Choi et al., 2005; Kim et al., 2005). Choi et al. (2005) reported the difference of the end member and local host rock compositions between the Chejudo and Baegryenogdo. Kim et al. (2005) suggested the Baegdusan and Baegryongdo reflect the assimilation of EM2 lithospheric materials. Kil (2007) also suggested the heterogeneous subcontinental lithospheric mantle beneath the Boen area of the mid-Korean peninsula.

Previous geochemical and isotopic investigations on the ultramafic xenoliths have mainly concentrated on the major and trace elements or the Sr-Nd and noble gas isotopic ratios. However, no oxygen isotope compositions to examine the mantle heterogeneity in the upper mantle of the Korean peninsula reported.

Oxygen isotopes could be effectively used to trace crustal components in the source of basaltic magmas because materials precipitated at and/or near Earth's surface, or that have undergone weathering at near-surface conditions, differ greatly from mantle materials (Workman et al., 2008; Gurenko et al., 2011). Widom and Farquhar (2003) suggested the merits of oxygen isotopes to identify the source materials as follows. First, isotopic fractionation is far more significant at low temperatures than at high temperatures, and as a result, crustal material is isotopically heterogeneous compared to mantle material. Second, subduction metamorphism apparently does not have a significant effect on the isotope signature of the crustal material so that distinct crustal sources should remain recognizable. Third, time does not affect the isotope signature of subducted material during aging in the mantle.

Our studies focused on the oxygen isotope compositions of the ultramafic mantle xenoliths to investigate the mantle heterogenity in the upper mantle in the Korean peninsula which is located in the continental margin of the southeastern part of the Eurasian plate. Mineral chemistry was also examined to estimate the equilibrium temperature and pressure of the mantle xenoliths. They lead us to detect the evolutionary history of the upper mantle as well as the possible interactions between crustal and upper mantle materials in the continental margin of the southeast Eurasian plate.

Geological Setting

The Korean peninsula is noted for Tertiary and Quaternary K-series alkali volcanism generated when it was an active continental margin in the past (Kim et al., 2005). Ultramafic xenoliths in the Cenozoic basalts were reported from several locations within and near the Korean peninsula: Chejudo, Jogokri (Boun), Baegryoungdo, Baegdusan and Long Quan (Fig. 1). (Lee, 1996; Choi et al., 2001, 2002, 2005; Kim et al., 2002, 2005; Choi and Kwon, 2005; Kil, 2006, 2007; Chen et al., 2007).

In the case of the Baegdusan and Chejudo areas, which are noted for large scale successive volcanic activities from Miocene to historic time, alkali basaltic volcanism is characterized by voluminous lava with abundunt ultramafic xenoliths. However, the Baegryongdo and Jogokri areas include only small scale intrusions with mantle xenoliths. For comparison, peridotite xenoliths were also collected from the vicinity of a crater lake in the Long Quan volcanic area, east China, ca. 100 km north of the Baegdusan.

Ultramafic xenoliths from the Chejudo are 4 to 10 cm in diameter and are represented by spinel lherzolite with minor spinel harzburgite, clinopyroxenite, wherlite and websteite (Choi et al., 2005). The host basalt has been dated by the K-Ar method yielding ages of 0.1-0.2 Ma (Kim et al., 2005).

Alkali basalt in the Jogokri contains predominantly peridotites and gabbroic xenoliths ranging in size from 0.5 to 30 cm, and a few grass-green olivine and clinopyroxene megacrysts (Kim et al., 2005). The host basalt has been dated by the K-Ar method yielding ages of 11 Ma (Arai et al., 2001; Kim et al., 2005).

Spinel peridotite xenoliths from the Baegryongdo range from 5 to 10 cm in diameter (maximum 30 cm). The host basaltic lava is vesicular with microphenocrysts of olivine and minor clinopyroxene in a groundmass

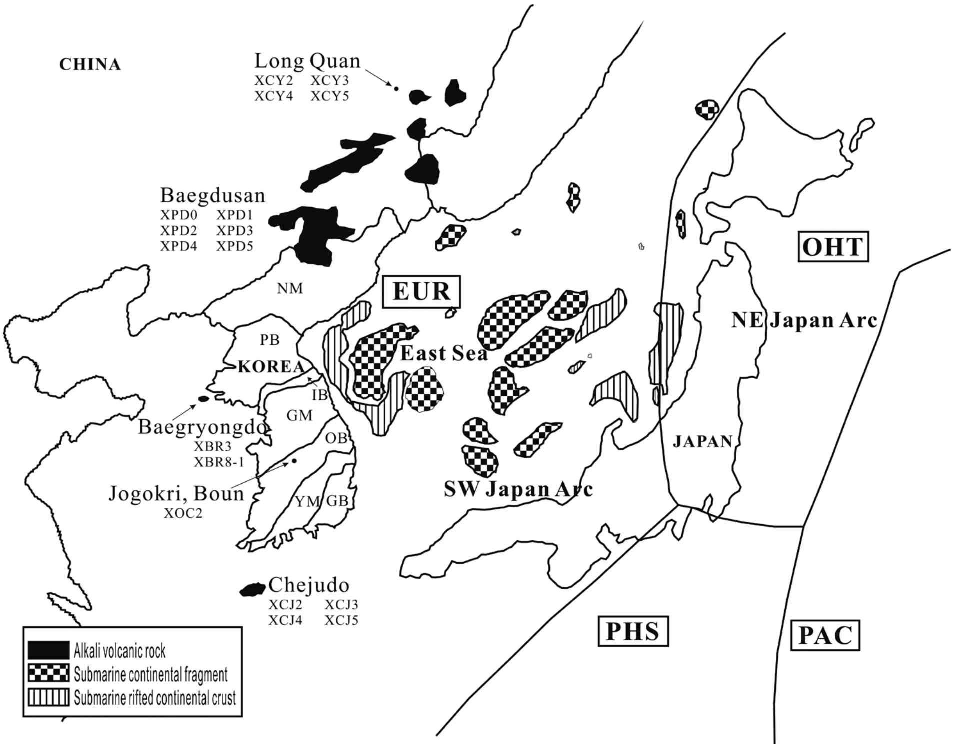

Fig. 1. Distribution of ultramafic xenoliths bearing Cenozoic alkali volcanic rocks in the Korean peninsula of the southeast margin of the Eurasian plate. NM, Nangrim massif; PB, Pyeongnam basin; IB, Imjingang belt; GM, Gyeonggi massif; OB, Ogcheon belt; YM, Yeongnam massif; GB, Gyeongsang basin. EUR, Eurasian plate; OHT, Okhotsk plate; PAC, Pacific plate; PHS, Philippine Sea plate. Sampling sites are included.

of plagioclase, clinopyroxene and magnetite (Choi et al., 2005). Whole rock K-Ar dating of the host basalt from the Baegryongdo yields ages of 6.2 to 7.4 Ma (Kim et al., 2005).

The Baegdusan mantle xenoliths range from 2 to 30 cm in diameter and are comprised of spinel lherzolite consisting mainly of olivine, orthopyroxene, clinopyroxene and chrominm spinel. Whole rock K-Ar ages of the host basalt from Baegdusan range from 18 to 21 Ma (Kim et al., 2005).

Ultramafic xenoliths from the Long Quan, in East China consist mainly of Mg-olivine, clinopyroxene and orthopyroxene minerals. Olivines are thick grass-green megacrysts up to 1 cm in diameter. The K-Ar age of the host basaltic rock was determined to be 0.6 Ma (Kim et al., 2005).

Analytical Methods

Mantle xenoliths were collected from five localities on the Korean peninsula: Chejudo, Jogokri, Baegryoungdo, Baegdusan, and Long Quan. The predominant rock type was spinel lherzolite. More than 18 samples of ultramafic xenoliths were collected. Based on their freshness, each one sample was chosen from five locations for geochemical and isotopical investigation. Thin sections from the five samples were selected. To examine the major-element compositions as well as the equilibrium temperature and pressure conditions, the olivine, clinopyroxene and orthopyroxene minerals on the thin sections were selected.

The major-element compositions of olivine, clinopyroxene and orthopyroxene from ultramafic xenoliths were determined by a JEOL-JXA-8900R electron microprobe at National Center for Inter-University Research Facilities (NCIRF) of Seoul National University. The machine was operated with accelerating voltage of 15 kV, a beam current of 20 nA, a beam diameter of 1 μm and a counting time of 10 seconds.

Accurate measurements of the Ca concentration in olivines were carried out using a special CAMECA analysis program. An accelerating voltage of 20 kV, a beam current of 100 nA and a counting time of 100 s were applied for the Ca analysis.

Mantle xenoliths analyzed in this study are the same samples studied by Kim et al. (2005) for major and trace element abundunces and Sr-Nd isotopic compositions.

Oxygen isotopic ratios were measured in olivines separated from five mantle xenoliths of the Baegdusan (XPD), three of Long Quan (XCY) and Chejudo (XCJ), two of Baegryongdo (XBR), and one of Jogokri (XOC). Three fresh olivine grains of each xenolith sample were selected. Olivine grains were handpicked from crushed and sieved ultramafic xenolith samples and selected under a binocular microscope, in order to eliminate grains that contained inclusions, cracks or alterations. To avoid possible contamination from adhering groundmass of the host basalt or from dust, olivine grains were first ultrasonically cleaned in 2% HNO_3 solution for 15 to 20 minutes, and then rinsed successively by deionized water. The final products were re-examined under a microscope to ensure the absence of foreign materials.

Oxygen isotope compositions were determined by CO_2 laser fluorination at the Korea Polar Research Institute (KOPRI). It has 10.6 μm of wavelength and 20 W of max power (regular power: 10 W). The focal length from the lens to the sample holder inside the reaction chamber is 10.5 cm and the laser beam spot size of 100-500 μm by tuning the focal length, laser beam can be easily switched focused into defocused spot. The preparation line for extraction and purification of O_2 is based on methods described by Kusakabe et al. (2004).

Data for each batch of samples were normalized to the JFB (Juan de Fuca Basalt glass) because JFB is a preferred sample compared with other available standards such as NBS-28 quartz, UWG2 garnet and San Carlos olivine in KOPRI. It is very easily decomposed and does not produce any fluorination (Ahn et al., 2012).

Eighteen CO_2 laser fluorination analyses of JFB made over the course of the study yielded $\delta^{17}O=2.85\pm0.02‰$ (1σ), $\delta^{18}O=5.45\pm0.05‰$ (1σ). These results showed good agreement with previous results using the same system $\delta^{17}O=2.88\pm0.01‰$ (1σ), $\delta^{18}O=5.47\pm0.02‰$ (Ahn, 2009).

Analytical Results

Mineral chemistry

Olivines from the Korean peninsula are characterized by high magnesium ranging from 49.12 (XPD) to 50.95 (XOC) wt.% MgO. The olivines show a very narrow range of Mg numbers (Mg#=Mg/[Mg+ΣFe]×100) of 90.1-92.2. The olivines show a narrow range in SiO_2 (39.11-41.16 wt.%). Oxides of the olivines are Al_2O_3 (0.01-0.03 wt.%), CaO (0.03-0.07 wt.%), K_2O (<0.01 wt.%), P_2O_5 (<0.02 wt.%), and MnO (0.1-0.14 wt.%). XPD, XCJ, XCY, XBR, and XOC samples contain MgO 49.12, 49.89, 50.44, 50.19, and 50.95 wt.%, respectively (Table 1).

Clinopyroxenes of ultramafic xenoliths from the Korean peninsula are characterized by narrow Mg-Fe-Ca ranges from $En_{48.4}$ $Fs_{5.7}Wo_{45.2}$ to $En_{50.9}$ $Fs_{6.9}Wo_{47.4}$. The compositions of clinopyroxene are $En_{48.4}Fs_{6.1}Wo_{47.4}$ from Baegdusan (XPD), $En_{48.6}Fs_{6.9}$ $Wo_{46.7}$ from Chejudo (XCJ), $En_{49.1}Fs_{6.7}$ $Wo_{46.3}$ from Long Quan (XCY), $En_{49.5}Fs_{5.7}$ $Wo_{46.6}$ from Baegryoungdo (XBR), and $En_{50.9}Fs_{5.8}$ $Wo_{45.2}$ from Jogokri (XOC). They have high Mg# between 91.4 (XCJ4) and 93.1 (XOC2).

The orthopyroxene in the ultramafic xenoliths from the Korean peninsula contains a low percentage of TiO_2 (0.02-0.12 wt.%), Al_2O_3 (2.42-2.89 wt.%), MnO (0.12-0.16 wt.%), Na_2O (0.02-0.13 wt.%), K_2O (0-0.01 wt.%), NiO (0.08-0.13 wt.%), P_2O_5 (0-0.01 wt.%), and Cr_2O_3 (0.36-0.56 wt.%).

Most orthopyroxene minerals in the ultramafic xenoliths from the Korean peninsula are characterized by narrow Mg-Fe-Ca compositional ranges from $En_{89.5}Fs_{13.2}Wo_{0.9}$ to $En_{91.2}Fs_{15.3}Wo_{1.6}$. The composition of orthopyroxenes are $En_{89.9}Fs_{15.1}Wo_{1.0}$ from Baegdusan (XPD), $En_{89.5}Fs_{15.3}Wo_{1.2}$ from Cheju (XCJ), $En_{89.6}Fs_{15.1}Wo_{1.3}$ from Long Quan (XCY), $En_{91.2}Fs_{13.2}Wo_{0.9}$ from Baegryoungdo (XBR), and $En_{90.5}Fs_{13.2}Wo_{1.6}$ from Jogokri (XOC).

Temperature-Pressure estimates

Numerous geothermometers for the appropriate mineral assemblages of ultramafic xenoliths have been proposed (Wood and Banno, 1973; Wells, 1977; Bertrand and Mercier, 1985; Brey and Köhler, 1990; Ballhaus et al., 1991). Brey and Köhler (1990) have tested many combinations of geothermobarometers and suggested that the combination of geothermometer of Brey and Köhler (1990) and geobarometer of Köhler and Brey (1990), which gives a reasonable T-P estimation for spinel peridotite. Of existing thermometers, the Brey and Köhler (1990) model of TBK is known as the most precise geothermometer (Putirka, 2008). Putirka (2008) also suggested well-calibrated thermometers and barometers by using a new global regression based on TBK. Putirka's model based on the partitioning of enstatite+ferrosilite ($=Fm_2Si_2O_6$=EnFs; FmO=FeO+MgO+MnO) between clinopyroxene and orthopyroxene increases the degree of precision of the experimental data.

Therefore the equilibrium temperatures of ultramafic xenoliths of the Korean peninsula were calculated using a geothermometer of Brey and Köhler (1990) (TBK). In addition, Putirka's (2008) global regression geothermometer was used. Because Putirka's model is well calibrated based on the Brey and Köhler (1990) model. This model performs best for mafic systems where of $Mg\#_{cpx}>0.75$, and this condition was suitable for the data of this study.

A variety of precise geobarometers for garnet peridotites have been derived in many chemical changes on coexisting minerals which are quite sensitive to pressure and reliable thermodynamic data existed (Choi et al., 2005). However, geobarometry of spinel peridotites proposed by Köhler and Brey (1990) and Adams and Bishop (1986) are unique as they are based on the exchange of equilibrium Ca between olivine and clinopyroxene. In this study, the Köhler and Brey (1990) geobarometer, which is a refined AB geobarometer, is used to obtain pressures of spinel peridotites of the Korean peninsula. In addition, the Putirka's (2008) barometer which was calibrated from

Table 1. Mineral compositions and P-T estimates for ultramafic xenoliths from the Korean peninsula

Location.	BAEGDUSAN			CHEJUDO			LONG QUAN			BAEGRYONGDO			JOGOKRI		
Sample No.	XPD4			XCJ4			XCY5			XBR3			XOC2		
Mineral	OL	CPX	OPX	OL	CPX	OPX	OL	CPX	OPX	OL	CPX	OPX	OL	CPX	OPX
SiO_2 (wt%)	41.01	51.59	52.71	40.88	52.56	55.06	39.11	51.49	52.5	40.7	54.02	57.14	41.6	53.41	57.2
TiO_2	0	0.45	0.11	0	0.39	0.12	0	0.4	0.07	0	0.29	0.07	0	0.07	0.02
Al_2O_3	0.01	6.89	4.89	0.01	5.87	4.51	0.02	6.53	4.88	0.01	3.95	2.48	0.03	2.96	2.42
FeO	9.2	2.29	6.06	9.45	2.63	6	9.86	2.55	6.13	7.6	2.23	5.25	8	2.31	5.28
MnO	0.12	0.08	0.12	0.12	0.08	0.16	0.14	0.06	0.15	0.1	0.07	0.14	0.12	0.09	0.12
MgO	49.12	15.29	34.12	49.89	15.66	33.5	50.44	15.67	34.74	50.19	16.6	34.92	50.95	17.38	34.74
CaO	0.03	20.85	0.51	0.05	20.94	0.65	0.06	20.56	0.69	0.03	21.76	0.5	0.07	21.45	0.84
Na_2O	0	1.87	0.08	0	1.33	0.08	0	1.58	0.13	0	1.35	0.05	0	0.85	0.02
K_2O	0.01	0	0.01	0	0	0.01	0.01	0.01	0.01	0	0	0	0	0.03	0
Cr_2O_3	0.02	0.78	0.38	0	0.69	0.37	0.01	0.78	0.45	0	1.28	0.45	0.02	1.2	0.56
P_2O_5	0	0.01	0.01	0	0.01	0.01	0.01	0.01	0	0	0.02	0	0.02	0.01	0
NiO	0.46	0.1	0.08	0.62	0.04	0.11	0.47	0.03	0.13	0.55	0.02	0.1	0.32	0.09	0.13
Total	99.98	100.19	99.07	101.02	100.2	100.58	100.12	99.66	99.88	99.18	101.57	101.1	101.13	99.83	101.33
	4 oxygens	6 oxygens	6 oxygens	4 oxygens	6 oxygens	6 oxygens	4 oxygens	6 oxygens	6 oxygens	4 oxygens	6 oxygens	6 oxygens	4 oxygens	6 oxygens	6 oxygens
Si	1.003	1.865	1.845	0.993	1.896	1.891	0.964	1.87	1.828	0.998	1.926	1.942	1	1.938	1.942
Ti	0	0.012	0.003	0	0.011	0.003	0	0.011	0.002	0	0.008	0.002	0	0.002	0
Al	0	0.293	0.202	0	0.249	0.183	0.001	0.279	0.2	0	0.166	0.099	0.001	0.126	0.097
Fe	0.188	0.069	0.177	0.192	0.079	0.172	0.203	0.077	0.178	0.156	0.066	0.149	0.161	0.07	0.15
Mn	0.003	0.002	0.003	0.002	0.003	0.005	0.003	0.002	0.004	0.002	0.002	0.004	0.002	0.003	0.003
Mg	1.792	0.824	1.78	1.806	0.842	1.715	1.853	0.848	1.803	1.834	0.882	1.769	1.826	0.94	1.759
Ca	0.001	0.807	0.019	0.001	0.81	0.024	0.002	0.8	0.026	0.001	0.831	0.018	0.002	0.834	0.031
Na	0	0.131	0.005	0	0.093	0.005	0	0.111	0.009	0	0.093	0.003	0	0.06	0.001
K	0	0	0	0	0	0.001	0	0	0.001	0	0	0	0	0.001	0
Cr	0	0.022	0.01	0	0.02	0.01	0	0.022	0.012	0	0.036	0.012	0	0.034	0.015
P	0	0	0	0	0	0	0	0	0	0	0.001	0	0	0	0
Ni	0.009	0.003	0.002	0.012	0.001	0.003	0.009	0.001	0.004	0.011	0	0.003	0.006	0.003	0.003
Mg#	90.5	92.3	90.9	90.4	91.4	90.9	90.1	91.6	91	92.2	93	92.2	91.9	93.1	92.1
En	90.3	48.4	89.9	90.2	48.6	89.5	89.9	49.1	89.6	92	49.5	91.2	91.7	50.9	90.5
Fs	15.9	6.1	15.1	16.1	6.9	15.3	16.5	6.7	15.1	13.3	5.7	13.2	13.7	5.8	13.2
Wo	0	47.4	1	0.1	46.7	1.2	0.1	46.3	1.3	0	46.6	0.9	0.1	45.2	1.6
Ac	0	4.9	0.2	0	3.4	0.2	0	4.1	0.3	0	3.3	0.1	0	2.1	0.1
T_{Pt}	962.8			981.5			1014.5			977.1			1016		
$T_{B\&K}$	854			975.8			936.1			926.3			987.3		
P_{Pt}	12.5			10.8			11.8			10.9			7		
$P_{K\&B}$	14.5			16.6			4.6			24.4			7.3		

Mg#=Mg/[Mg+ΣFe]×100 ol: olivine, cpx: clinopyroxene, opx: orthopyroxene

Temperatures are determined by geothermometers of new regression model of Putirka (2008) (T_{Pt}) and Brey and Köhler (1990) (T_{BK}). Pressures are determined by geobarometer of Putirka (2008) (P_{Pt}) and Köhler and Brey (1990) (P_{KB})

a global regression for inputting Putirka's new regression thermometer model was adapted. This model gives more precise values with a restriction of $Mg\#_{cpx}>0.75$.

Temperature

On the basis of geothermometer of T_{BK} from Brey and Köhler (1990) and T_{Pt} from Putirka (2008), estimated T_{BK} of the Korean peninsula ranges from 854 to 987.3°C. T_{Pt} of our samples ranges from 962.8 to 1016°C (Table 1). Ultramafic xenoliths samples from the Jogokri (XOC2) yielded the highest temperature of T_{BK}=987.3°C and T_{Pt}=1016°C. These results overlap the previous result of the range of 946-1022°C (Lee, 1996). On the other hand, the equilibrium temperatures for Baegdusan xenoliths (XPD4) were obtained to be the lowest T_{BK} (854°C) and T_{Pt} (962.8°C). Temperatures for xenoliths of Chejudo (XCJ4) were 981.5°C for T_{BK} and 975.8°C for T_{Pt}. These results are included the range of the Cheju peridotites 875-1050°C (Choi et al., 2001) and 951-1035°C (Kil et al., 2008). Formation temperatures of ultramafic xenoliths from the Baegryoungdo (XBR8) were 926.3°C for T_{BK} and 977.1°C for T_{Pt}. These values are similar to those of the estimated results for the xenoliths of Baegryoungdo 880-980°C (Choi and Kwon, 2005). Formation temperatures of Long Quan xenoliths (XCY5) were 936.1°C for T_{BK} and 1014.5°C for T_{Pt}.

Pressure

Calculated pressures of the mantle xenoliths in the Korean peninsula range from 4.6 to 24.4 kbar for P_{KB} and 7.0 to 12.5 kbar for P_{Pt} (Table 1). Pressures for xenoliths from the Baegdusan (XPD4) were obtained to be 14.5 kbar for P_{KB} and 12.5 kbar for P_{Pt}. Meanwhile, the pressures for xenoliths of Chejudo (XCJ4) were 16.6 kbar for P_{KB} and 10.8 kbar for P_{Pt}. Choi et al. (2001) reported pressures of spinel peridotite of Chejudo range from 12.9 to 26.3 kbar (46-87 km). Calculated pressures for xenoliths of Baegryongdo (XBR8-1) were 24.4 kbar for P_{KB} and 10.9 kbar for P_{Pt}. These results are included in the similar range to those of the Baegryong peridotites as 4.2-26.6 kbar (Choi and Kwon, 2005). Pressures for xenoliths of Jogokri (XOC2) were 7.3 kbar for P_{KB} and 7.0 kbar for P_{Pt}. These values are included in the range to those of Jogokri peridotites as 3.1-30.0 kbar (Kil, 2007). Pressures for xenoliths from the Long Quan (XCY4) were obtained to be 4.6 kbar for P_{KB} and 11.8 kbar for P_{Pt}.

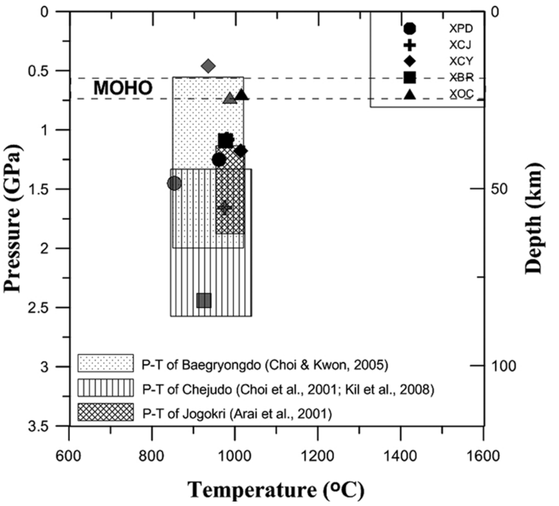

Fig. 2. Pressure and temperature estimates for the ultramafic xenoliths in the Korean peninsula. The Moho depth is after Chang and Baag (2007). Whole black symbols are data from T_{Pt}-P_{Pt}. Partly black symbols are data fromT_{BK}-P_{KB}. XPD; Baegdusan, XCJ; Chejudo, XCY; Long Quan, XBR; Baegryongdo and XOC; Jogokri.

Fig. 2 shows the pressure-temperature conditions estimated for the ultramafic xenoliths of the Korean peninsula. The xenoliths-derived geotherm for the Korean peninsula is from 854 to 1016°C and 4.6 to 24.4 kbar. These values are overlapped to the results of previous studies (Arai et al., 2001; Choi et al., 2001; Choi and Kwon, 2005; Kil et al., 2008). The geotherm constructed for the ultramafic xenoliths from the Korean peninsula is shown in Fig. 3. The Long Quan geothermal gradient is smaller than the others. However, there were no systemic correlations between the locations and the geothermal gradients in the Korean peninsula.

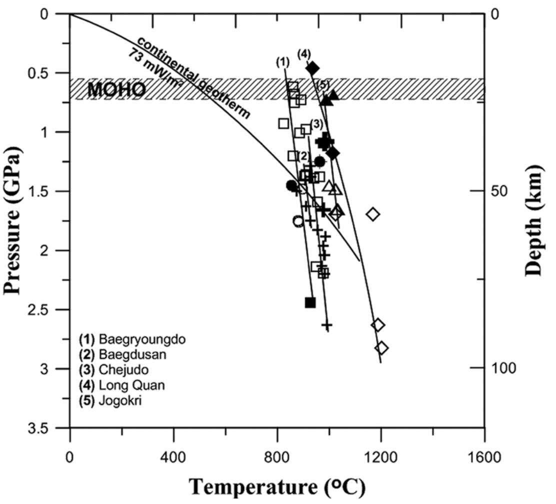

Fig. 3. Temperature and pressure (depth) conditions for spinel peridotite xenoliths from the Korean peninsula. Geothermal gradient are based on 73 mW/m^2 heat flow (Pollack and Chapman, 1977; Han and Keehm, 1997). Filled symbols from this study. Open symbols from previous studies: The data of the Jogokri from Lee (1996); Chejudo from Choi et al. (2001); Baegdusan and Long Quan from Shim (2003); Baegryoungdo from Choi and Kwon (2005).

Oxygen isotope

Oxygen is the most abundant element of planetary mantle and crust that consist mainly of silicates and oxides. Variations of natural isotopic abundance of oxygen have been widely used in the field of stable isotope geochemistry, because the isotopic variations can give information of their origins and processes that they have experienced (Kusakabe et al., 2004).

The range of $\delta^{18}O$ values in olivines from MORBs is extremely narrow (i.e., 5.2±0.2‰, Eiler et al., 1997) and olivines from peridotite xenoliths have $\delta^{18}O$ values consistent with equilibrium with MORB liquids (i.e., 5.19±0.14‰, Mattey et al., 1994: as cited in Eiler et al., 1997). On the other hand, various marine sediments and continental rocks have a wide $\delta^{18}O$ ranges from 0‰ to 40‰ (Eiler, 2001; Workman et al., 2008). The most measured oxygen isotopic ratios for olivines of ultramafic xenoliths from the Korean peninsula range from $\delta^{18}O$=5.06 to 5.51‰ (Table 2). This value is quite similar to that of upper mantle peridotite and MORB olivines (Mattey et al., 1994; Eiler et al., 1997).

Table 2. Oxygen isotopic data of ultramafic mantle xenoliths from the Korean peninsula

Location	Sample No.	$\delta^{18}O$ (‰)
Baegdusan	XPD1	5.07
	XPD2	5.24
	XPD3	5.51
	XPD4	5.33
	XPD5	5.24
Chejudo	XCJ1	5.26
	XCJ3	5.45
	XCJ4	5.07
Long Quan, China	XCY3	5.16
	XCY4	5.23
	XCY5	5.06
Baegryoungdo	XBR3	5.27
	XBR8-1	5.38
Jogokri	XOC2	5.12

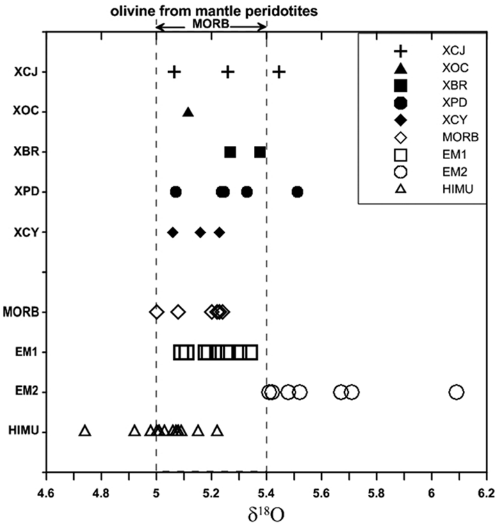

Fig. 4. The $\delta^{18}O$ values for olivine from the ultramafic xenoliths in the Korean peninsula and related peridotites values of $\delta^{18}O$. Eiler et al. (1997) for MORB. Zindler and Hart (1986) and Hart (1988) for EM1, EM2, and HIMU. The vertical dashed lines indicate the range of typical olivine from xenolithic upper mantle peridotites and MORB sources (5.2±0.2‰, Mattey et al., 1994; Eiler et al., 1997; Eiler, 2001).

As shown in Figure 4, most of the values of $\delta^{18}O$ for olivine of the mantle xenoliths from the Korean peninsula are plotted in the range of typical N-MORB type of olivine from xenolithic upper mantle peridotites and MORB sources (5.2±0.2‰). Most samples show uniform oxygen isotopic values and slightly lower than those of upper mantle peridotite and MORB olivines. However, olivines of ultramafic xenoliths from the Baegdusan and Chejudo have a relatively wide $\delta^{18}O$ values ranging from 5.07 to 5.51‰ and 5.07 to 5.45‰, respectively. Furthermore the XCJ3 (5.45±0.01‰) and XPD3 (5.51±0.01‰) show slightly higher values than other values of $\delta^{18}O$ (Fig. 4). These isotopic signatures suggest that the Baegdusan and Chejudo xenoliths allow constraints to be assimilated with recycled sediments and/or to be attributed with the metasomatized mantle.

Discussion

The pressure-temperature conditions of ultramafic xenoliths in the Korean peninsula are from 854 to 1016°C and 4.6 to 24.4 kbar. There were discrepant results of two geobarometer. Although Putirka (2008) suggested well-calibrated thermometers and barometers by using a new global regression based on TBK. The results of this study showed there were disagreements between Putirka's (2008) and Brey and Köhler's (1990). Possible explanations include 1) the strong temperature dependence of the barometer; 2) the Brey and Köhler (1990) geothermometer, which is a two-pyroxene thermometer, predicts temperatures that are 100-200°C above temperatures based on other thermometers, or 3) pooly understood system kinetics, possibly related to rapid diffusion of Ca in olivine whereby the olivine records a different history than pyroxene temperatures (Kil, 2006).

Mantle heterogeneity of the Earth is widely attributed to the temporal and spatial coexistence of isotopically enriched and depleted mantle domains such as DM (depleted mantle), EM1 (enriched mantle of type one), EM2 (enriched mantle of type two), and HIMU (a High U/Pb mantle component) (Zindler and Hart, 1986). This heterogeneity is thought to reflect time-integrated effects of depletion and enrichment caused by the mantle partial melting and crust extraction by subduction, and recycling of the oceanic lithosphere back into the convecting mantle (Widom and Farquhar, 2003; Gurentko et al., 2011).

Nd-Sr-Pb isotope signatures provide the existence in the Earth's mantle of isotopically distinct several reservoirs including MORB, EM1, EM2 and HIMU (Hart et al., 1992). They are most commonly attributed to subduction of oceanic crust. However, it is difficult to relate the radiogenic isotopic variations to crustal contamination. Oxygen isotopes can potentially be an important tracer of distinct types of recycled crustal materials in the Earth's mantle (Eiler et al., 1995; Harmon and Hoefs, 1995; Widom and Farquhar, 2003). Most mantle-derived magmas and ultramafic rocks have well defined $\delta^{18}O$ values of $\delta^{18}O=5.7\pm 0.5$‰ (Eiler et al., 1998). In contrast, altered basaltic and gabbroic rocks of the oceanic crust range from 0 to 12‰, clastic sediments are typically 12 to 20‰, and carbonate and silicate pelagic sediments are typically 20 to 25‰ (Eiler et al., 1998; Eiler, 2001). The extensive survey of oxygen isotopes in oceanic basalt lava and glasses indicates three different types: (1) mantle peridotite and MORB olivine ($\delta^{18}O=5.0$-5.4‰, 5.2±0.2‰, Eiler et al., 1997), (2) EM1 type OIB olivine ($\delta^{18}O=5.09$-5.34‰, 5.21±0.08‰, Eiler et al., 1997), EM2 type OIB olivine ($\delta^{18}O=5.41$-6.09‰, 5.60 ±0.20‰, Eiler et al., 1997), and (3) HIMU-type ($\delta^{18}O$ =4.92-5.09‰, 5.03±0.11‰, Eiler et al., 1997).

The focus of this study is finding the origin of the high $\delta^{18}O$ signature of ultramafic xenoliths in the Korean peninsula. The oxygen isotopic signatures for ultramafic xenoliths can provide us the critical information of the evolutionary history of the upper mantle as well as the possible interactions between crustal and upper mantle materials in the continental margin of the southeast Eurasian plate.

Oxygen isotopic ratios ($\delta^{18}O$) in olivines from ultramafic xenoliths in the Korean peninsula range from 5.06 to 5.51‰, which overlapped those of upper mantle peridotite and MORB. Most mantle-derived magmas span a narrow range in $\delta^{18}O$ values (e.g., $\delta^{18}O_{ol}$ between 5.0 and 5.4‰). It implies that recycled crustal materials are absent in the mantle source area or are less than a few percent (Nardini et al., 2009).

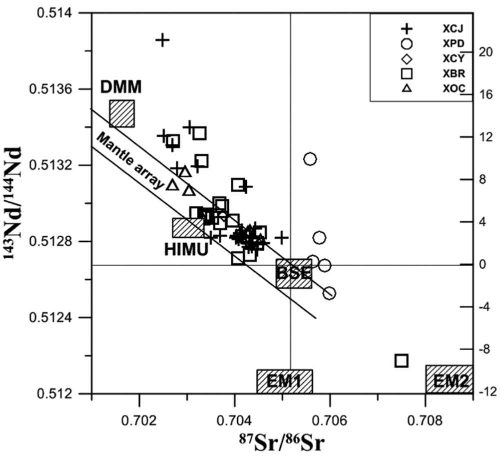

Fig. 5. Sr-Nd isotope correlation diagram for host whole-rocks and ultramafic xenoliths from the Korean peninsula. Shaded areas show the main oceanic mantle reservoirs of Zindler and Hart (1986). Data from Kim et al. (1999); Choi et al. (2002, 2005); Kim et al. (2005); Kil (2006, 2007).

In the case of the Baegdusan and Chejudo xenoliths, the $\delta^{18}O$ values show the relatively large variation ($\delta^{18}O$=5.01-5.51‰) which indicate a slightly deviate from the unmodified mantle composition. The Baegdusan and Chejudo samples that are outside 5.2±0.2‰ require specific explanations for the origin of the isotopically anomalous material in the mantle source region.

Generally isotopic enrichment is likely to be related to subduction, whereby crustal materials are injected into the mantle. According to Eiler (2001) and Eiler et al. (1997), two main processes occurring at mantle conditions may account for the observed high $\delta^{18}O$ values: Crustal contamination and/or containing of EM2 (enriched mantle type two) sources. EM2 has affinities with the upper continental crust and may represent the recycling of continentally derived sediment, continental crust and altered oceanic crust or ocean-island crust (Eiler et al., 1997).

In general, EM2 has low ^{143}Nd/^{144}Nd and high ^{87}Sr/^{86}Sr ratios (Zindler and Hart, 1986). The possibility of containing of EM2 sources in terms of high $\delta^{18}O$ in the ultramafic xenolithic of the Korean peninsula can be supported by Fig. 5 and Fig. 6. In Fig. 5, the Sr and Nd isotope compositions of the Korean peninsula xenoliths show a negative correlation, ranging from the most depleted mid-oceanic ridge basalt (MORB) values to those of the bulk silicate earth along the MORB-oceanic island basalt (OIB) mantle array. However, data from the Baegdusan and one from the Baegryoungdo show enriched isotopic compositions with more extreme ^{87}Sr/^{86}Sr isotopic ratios. Like the observed high $\delta^{18}O$ values, this isotopic enrichment trend could potentially be generated by contamination of upper mantle by the recycled EM2 materials. The xenoliths should have been brought to surface within a short time with the alkali basalt magma. Therefore, it is hard to explain the variable values of $\delta^{18}O$ as a result of crustal contamination only.

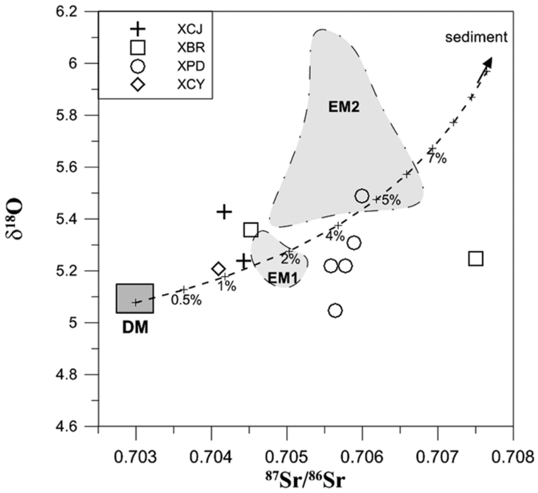

Fig. 6. Plots of $\delta^{18}O$ vs. ^{87}Sr/^{86}Sr for ultramafic xenoliths in the Korean peninsula. The dashed curves mark the range of mixing hyperbolae between depleted mantle (based on data for MORB) and high-$\delta^{18}O$ silicic classic sediments. MORB, EM1 and EM2 data are from Eiler et al. (1997).

Table 3. Concentrations and isotopic compositions of sediments and depleted mantle

	C_{Sr}	^{87}Sr/^{86}Sr	$\delta^{18}O$
Sediments*	300	0.710	15-25
Depleted Mantle*	15	0.703	5.5 (bulk)

*Eiler et al., 1997

Baegdusan samples have an affinity between EM1 and EM2 (Fig. 6). As shown in Figure 5 the Nd-Sr isotopic data from the Baegdusan are plotted between the mantle array of EM1 and EM2. However, it is hard to explain the variable values of the $\delta^{18}O$ for Baegdusan and Chejudo samples. Simple mixing calculations using strontium and oxygen isotopic ratios were carried out to estimate the source materials (Table 3). Mixing curves between a terrigenous sedimentary endmember and depleted mantle indicate that ~ 5% bulk addition of recycled sediments could account for the EM2 signature in the ancient subduction processes (Fig. 6).

Conclusion

The ultramafic xenoliths from the Korean peninsula mainly consist of typical high magnesium olivine (MgO=49.12-50.95 wt.%, Mg#=90.1-92.2), corresponding to worldwide Cenozoic ultramafic xenoliths in chemical compositions. The pressure-temperature conditions of ultramafic xenoliths in the Korean peninsula are from 854 to 1016°C and 4.6 to 24.4 kbar.

The oxygen isotopic ratios ($\delta^{18}O$) for olivines in ultramafic xenoliths of the Korean peninsula range from 5.06 to 5.51‰, which are relatively uniform oxygen isotopic values and overlapped by the values of N-MORB and upper mantle peridotite ($\delta^{18}O=5.2\pm0.2‰$). However, olivines of ultramafic xenoliths from the Baegdusan and Chejudo have a relatively wide $\delta^{18}O$ values ranging from 5.07 to 5.51‰ and 5.07 to 5.45‰, respectively. The high $\delta^{18}O$ signature of the Baegdusan xenoliths gives a hint that ~5% of the oxygen in typical EM2 sources was originally derived from recycled sediments.

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