Sr-Nd-Pb isotopic compositions of submarine alkali basalts recovered from the South Korea Plateau, East Sea

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ABSTRACT: We present geochemical and isotope results (Sr, Nd, Pb) on submarine basalts dredged from the southeastern margin of the South Korea Plateau. The present data are the first geochemical result obtained on submarine basaltic lavas recovered from the Korea Plateau, which is considered to be one of rifted remnants of continent in the East Sea (Sea of Japan) and partially segmented from the Korean Peninsula. The South Korea Plateau basalts (SKPB) show alkali affinities and are characterized by Ocean Island Basalts (OIB)-like trace element compositions relatively enriched in Ba, Nb and Pb. They display relatively flatter [$(Ce/Yb)_n$ = 4.49~5.46] and less fractionated HREE [$(Dy/Yb)_n$ = 1.11~1.29] patterns compared to average OIB, implying that the SKPB were derived from a relatively shallower mantle depth with a larger degree of partial melting. The Sr, Nd and Pb isotopic compositions of the SKPB display a range of values for $^{87}Sr/^{86}Sr$ (0.70378 to 0.70409), $^{143}Nd/^{144}Nd$ (0.512846 to 0.512860) and $^{206}Pb/^{204}Pb$ (17.88–18.44). They show a considerably high range of $^{207}Pb/^{204}Pb$ (15.48–15.62) and $^{208}Pb/^{204}Pb$ (37.86–38.46) values, indicating the involvement of a DUPAL-like MORB source. According to our two-stage magma mixing model, the isotopic compositions of SKPB can be explained by magma source mixing by the addition of an EMII-like mantle component (up to 2%) to the DUPAL-like MORB source embedded with endogenous EMI-like material (about 2%).

Key words: South Korea Plateau, dreged basalt, Sr-Nd-Pb isotope, DUPAL, OIB

1. INTRODUCTION

Late Cenozoic intraplate volcanic activities are recognized from several places in Korea and are believed to post-date opening of the East Sea (Fig. 1). The ages of these alkali rocks vary from 11 Ma to 0.1 Ma (Choi et al., 2006). Several petrological and geochemical studies were carried out for these alkali rocks to address their magma sources and petrogenesis and to discuss deep dynamic processes possibly associated with lithosphere-asthenosphere interaction and lithospheric evoultion (Park and Park, 1996; Kil and Lee, 2005; Choi et al., 2005; Park et al., 2005; Choi et al., 2006; Shin et al., 2006). These rocks all show oceanic island basalt (OIB)-like geochemical characteristics, similar to those of Cenozoic alkaline volcanic products in eastern China (Tatsumoto et al., 1992; Liu, et al., 1994; Liu et al., 2001; Zhang et al., 2002; Liu et al., 2004), East Sea (Japan Sea) region and SW Japan (Tatsumoto and Nakamura, 1991; Uto et al., 2004; Hoang and Uto, 2006). They have been interpreted as the products derived from convectively upwelling asthenosphere and/or thermally activated lithospheric mantle during continental extension (e.g., Uto et al., 2004; Choi et al., 2006). Cenozoic continental extension and mantle upwelling in this region are thought to have been triggered by: 1) the westward subduction of Pacific plate and /or northward indentation of India (Tapponnier et al., 1986; Zou et al., 2000), or 2) plate kinematic adjustments resulting from cessation of the East Sea (Japan Sea) opening (Uto et al., 2004; Hoang and Uto, 2006).

Isotope studies for Cenozoic intraplate basalts from Eastern China (Basu et al., 1991; Zhang et al., 1991; Tu et al., 1992; Zou et al., 2000; Chen et al., 2007) have shown that three different mantle components (DMM, EMI, EMII) were involved in the generation of the magmas, and the DMM-EMI components are dominant in NE china and DMM-EMII components in southeast Asia. Choi et al. (2006) suggested that DMM and an intermediate component between EMI and EMII are required to explain isotopic compositions of the Late Cenozoic Korean alkaline basalts located between the two regions.

During the February 2010 cruise of the R/V Onnuri around the Korea Plateau, many submarine basalts were recovered from the southeastern margin of the South Korea Plateau by dredging (Fig. 2). These samples are the firstly

discovered basalts from the Korea Plateau, which is thought to be one of the continental blocks in the East Sea (Lee et al., 2000). We carried out chemical and isotopic analyses for these dredged samples to investigate geochemical characteristics and to constrain the mantle source components involved in the genesis of the basaltic magma in this region.

2. GEOLOGY AND SAMPLING

The East Sea is one of the typical back-arc basins in West Pacific margin, and composed of the three basins (Japan Basin, Yamato Basin and Ulleung Basin) and the three topographic highs (Korea Plateau, Yamato Bank and Oki Bank) (Fig. 1). These topographic highs are believed to be remnant continental blocks after termination of back-arc opening of the East Sea in the Miocene (Tamaki et al., 1992). Lee et al. (2000) investigated the petrologic and isotopic properties for the granite fragments recovered from the Korea Plateau, and reported that these granites are very similar to Mesozoic Daebo granites which comprise basements of the Korean Peninsula.

The cruise of the R/V Onnuri in February 2010 surveyed the southeastern margin of the Korea Plateau to investigate the tectonic and geochemical evolution of the eastern Korean margin in the East Sea. In the sites A and B of the margins, many basaltic boulders and fragments were recovered by dredging (Fig. 2). The basaltic samples from the site B are highly altered, petrologically heterogeneous and rounded boulders, and are not thought to be in-situ samples, and hence excluded in this study. On the other hand, the samples from the site A are relatively fresh, homogeneous and fragmented basalts. They frequently show elongated vesicles partly filled with phyllosilicates and hydroxides. The dredge for sampling was conducted in the eastern slope of the site A which has 5 to 15° slope angle and 920 to 1,900 m water depth (Fig. 2b).

The fragments from the site A are mostly olivine- and plagioclase-phyric basalts with cryptocrystalline groundmass. Olivine and plagioclase phenocrysts frequently occur as glomeroporphyritic aggregates. The overall optical similarity of them from microscopic observation supports that these basaltic fragments are in site submarine lavas with common occurrence.
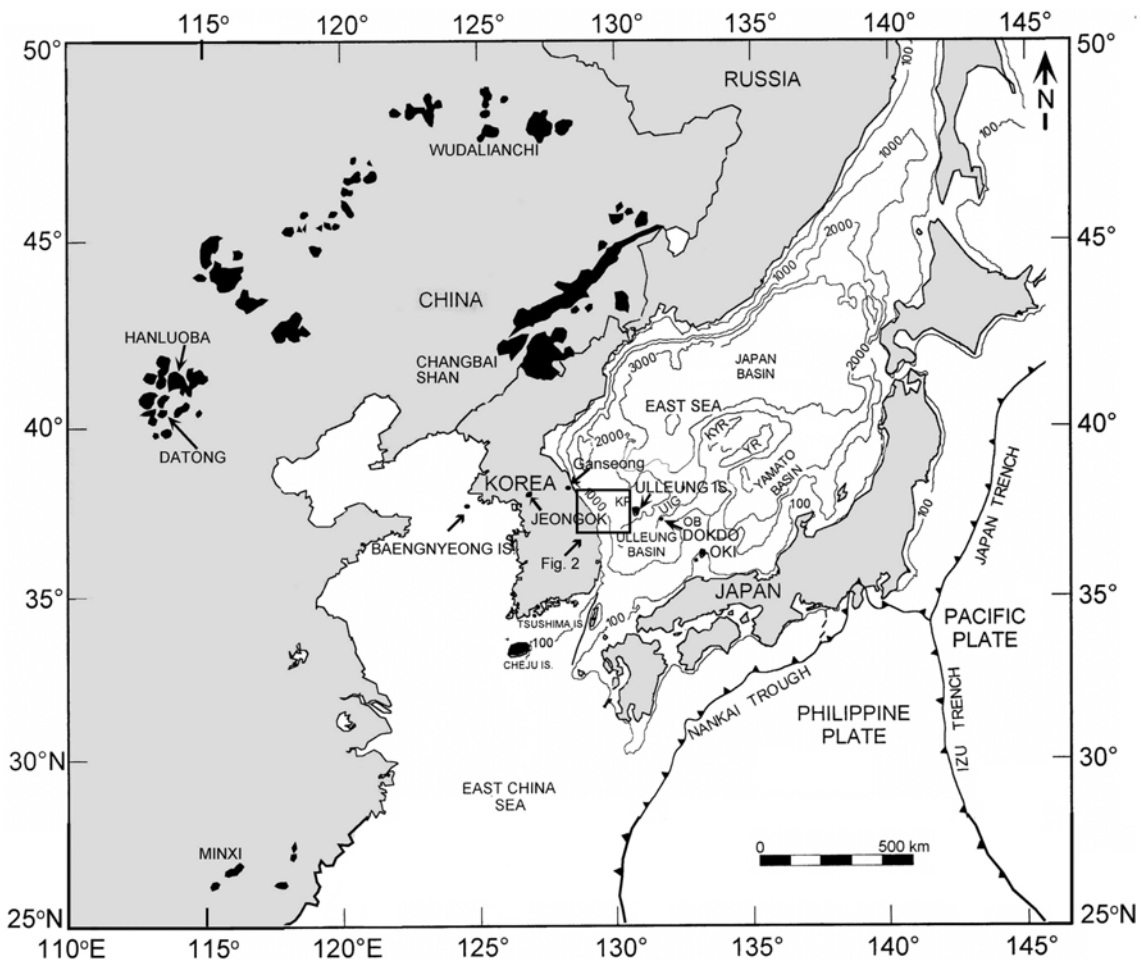
Fig. 1. Physiographic and tectonic map of the East Sea and distribution of Late Cenozoic alkaline volcanic rocks. KP: Korea Plateau, OB: Oki Bank, YR: Yamato Ridge, KYR: Kita-Yamato Ridge. The study area (Fig. 2) is shown as a thick box.
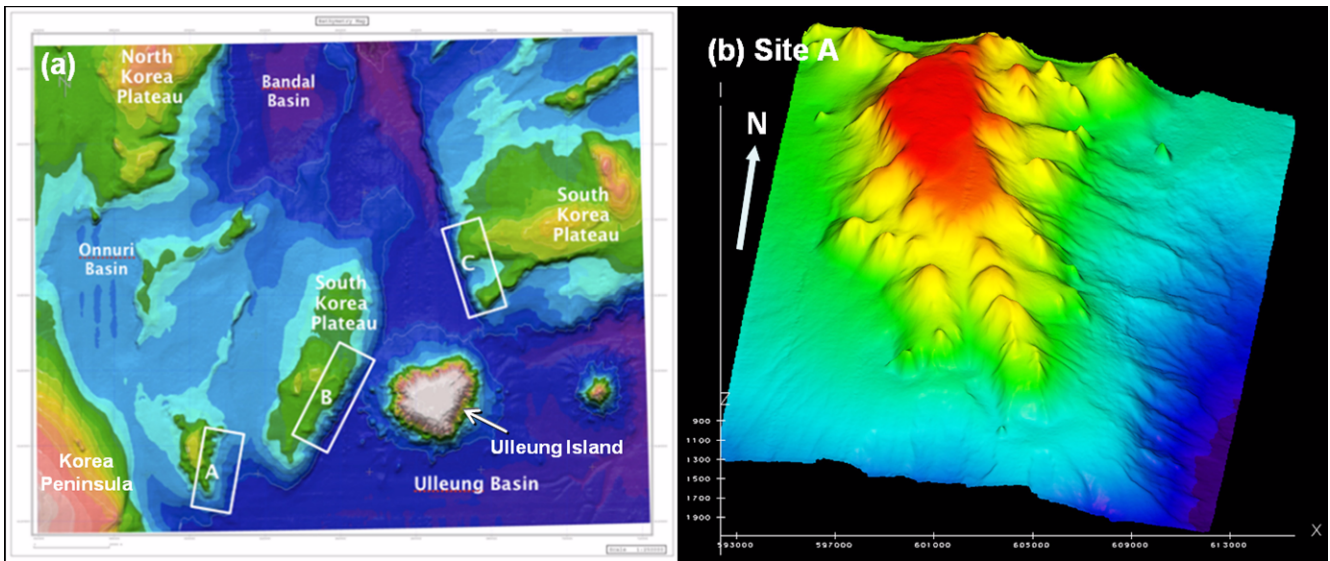
Fig. 2. (a) Bathymetric map around the Korea Plateau. The South Korea Plateau is divided into the western and eastern parts by an NNW-running deep tectonic valley. (b) Bathymetric map of the site A in Figure 2a. The interval of water depth is between 920 m and 1,900 m. There are many small topographic reliefs around the site A, which is thought to be volcanic structures. The dredge for sampling was conducted in the eastern slope which has 5 to 15° slope angle.

3. SAMPLES AND ANALYTICAL PROCEDURES

Fifteen dredged samples from the southeastern margin (A site) of the South Korea Plateau were studied (Fig. 2). Powdered samples for major and trace element analyses were made from relatively fresh parts of rock samples that crushed to <1 cm size and pulverized in an agate ball mill (Retsch PM400).

Major elements were analyzed by X-ray fluorescence (XRF) spectrometry, using a SHIMADZU XRF-1700 at the Cooperative Laboratory Center, Pukyong National University. Trace elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS, Perkin-Elmer, Elan 6100) at Korea Polar Research Institute (KOPRI). Whole rock powders (0.1 g) were dissolved in an HF-HNO_3-$HClO_4$ mixture. Precision was estimated to be within 5% for major elements by XRF and 10% for trace elements by ICP-MS. The results are in Table 1.

Chemical separation and mass spectrometry for Sr, Nd and Pb isotope analyses were performed at KOPRI. Detailed laboratory procedures of this study follow closely those of Kwon (1986). The least altered parts from the representative samples were carefully chosen, and were crushed to small pieces of 1–2 mm in size in a tungsten-carbide mortar. The pieces were washed with 2 N HCl in an ultrasonic bath for 10 min, in order to remove possible contaminants due to sea water alteration, followed by multiple rinses with Milli-Q® water before being ground in an agate mortar.

Sample powders were dissolved in concentrated HF and $HClO_4$. Pb, Sr and Nd were all purified from the same

solution. Pb was separated from other elements using an anion exchange column with HBr medium. Solutions after Pb elution were used for Sr separation by conventional cation column chemistry. Biorad AG50W-X8 (100–200 mesh) cation exchange resin is used to separate Sr from Rare Earth Elements (REEs) as the ion exchange medium. Nd was separated from the bulk REE fraction by the second step cation column chemistry using HDEHP (di-2ethylhexyl-orthophosporic acid)-coated Teflon powder medium.

Mass spectrometric analysis for Sr, Nd and Pb isotopes was performed on a thermal ionization mass spectrometer (TIMS, Thermo Finnigan, TRITON), equipped with nine-adjustable Faraday cups. Sr and Nd isotopic compositions were measured in static mode with relay matrix rotation (the "virtual amplifier" of Finnigan) on a single Ta and double Re filaments, respectively. The data were corrected for mass fractionation by normalizing to $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$, using an exponential law. Replicate analyses of NBS 987 and La Jolla standards gave $^{87}Sr/^{86}Sr = 0.710260 \pm 4$ (N = 20, 2σ) and $^{143}Nd/^{144}Nd = 0.511847 \pm 1$ (N = 17, 2σ). Pb loaded on single Re filament with silica gel and 0.1M H_3PO_4 and the data were corrected for instrumental mass fractionation using the values of Todt et al. (1996) for the NBS981 standard. Replicate analyses of NBS 981 standard gave values of (mean, 2σ, N = 28) 36.486 ± 0.016, 15.422 ± 0.005 and 16.885 ± 0.005 for $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$, respectively. Total blanks averaged are 0.3 ng for Sr, 0.01 ng for Nd and 1 ng for Pb. If we consider that the procedural chemistry blanks in all cases are less than 0.5% of the sample amount, and the isotope ratios of blanks are not sig-

Table 1. Major (wt%) and trace element (ppm) concentrations of the SKPB

Sample No.	AD05-01	AD05-02	AD05-03	AD05-04	AD05-05	AD05-06	AD05-07	AD05-08	AD05-09	AD05-10	AD05-11	AD06-01	AD06-02	AD06-03	AD06-04
SiO_2	52.06	51.16	51.62	51.56	51.54	49.31	49.95	50.01	51.56	51.64	49.35	52.15	50.89	51.17	50.61
TiO_2	1.74	1.69	1.62	1.69	1.72	1.56	1.68	1.67	1.75	1.62	1.78	1.98	1.95	1.89	1.90
Al_2O_3	19.28	18.74	19.07	19.72	18.97	16.88	17.52	17.75	19.46	18.82	17.47	18.97	17.78	17.95	18.17
Fe_2O_3	6.92	6.95	6.84	6.34	6.65	9.94	8.65	8.74	6.86	6.25	9.56	6.62	7.51	7.24	6.84
MnO	0.08	0.08	0.08	0.08	0.08	0.09	0.11	0.11	0.08	0.07	0.12	0.08	0.10	0.10	0.08
MgO	2.14	2.82	2.43	2.82	2.53	3.87	5.52	4.99	2.31	3.30	5.14	2.63	4.44	4.64	2.55
CaO	9.62	9.53	9.60	9.46	9.73	8.16	9.43	9.12	9.22	11.13	9.67	8.75	8.31	8.49	8.17
Na_2O	3.47	3.52	3.23	3.54	3.51	2.42	3.03	3.06	3.48	3.15	3.28	3.64	3.34	3.60	3.76
K_2O	2.11	1.84	1.79	1.66	1.85	1.64	1.67	1.75	1.86	1.66	1.69	1.97	2.13	1.80	2.12
P_2O_5	0.25	0.34	0.31	0.32	0.29	0.31	0.35	0.41	0.46	0.25	0.21	0.41	0.38	0.37	0.49
L.O.I.	2.05	2.93	3.05	2.43	2.80	5.41	1.81	2.15	2.68	1.73	1.25	2.66	2.77	2.42	4.92
Total	99.71	99.60	99.65	99.62	99.67	99.58	99.70	99.77	99.72	99.61	99.52	99.86	99.59	99.68	99.63
Mg#	41.82	48.56	45.21	50.83	46.93	47.58	59.77	57.08	43.94	55.12	55.59	48.07	57.90	59.88	46.47
Ni	18	28	47	42	27	53	72	67	38	31	72	33	40	55	35
Cr	82	82	57	45	81	102	67	132	63	81	100	39	67	53	70
Cu	22	32	29	34	30	32	29	33	30	22	32	32	27	34	33
Zn	92	102	103	88	88	107	86	88	86	75	96	93	82	94	104
Sc	26	26	26	26	26	25	26	27	24	27	26	23	24	23	23
V	204	200	223	190	205	156	213	205	189	246	195	202	186	194	182
Cs	0.82	1.62	1.15	0.77	0.87	2.45	0.26	0.32	0.66	2.40	0.85	1.75	0.28	0.77	1.14
Li	12	11	17	11	9	20	16	14	12	10	8	10	9	9	10
Rb	60	55	44	47	55	60	35	39	37	52	54	53	60	49	62
Sr	499	491	498	517	495	377	555	510	596	504	501	499	492	504	517
Ba	698	711	764	664	790	630	626	650	689	616	636	778	711	719	757
Zr	206	205	196	219	210	133	204	206	220	209	209	232	234	233	244
Hf	5	5	5	5	5	3	5	5	5	5	5	5	5	5	6
Nb	60	60	57	60	59	44	55	57	61	45	52	67	64	63	68
Ta	4.0	4.0	4.0	4.3	3.8	2.6	3.5	3.8	4.0	3.8	3.7	4.3	4.1	4.2	4.3
Th	5.2	5.5	3.8	6.1	5.2	3.8	6.1	4.5	5.0	4.3	5.1	5.7	5.5	5.9	6.6
U	1.9	1.3	0.4	1.4	1.0	4.3	0.9	0.7	1.5	0.8	1.0	0.9	0.6	1.2	1.5
Pb	6.3	5.6	4.0	4.5	3.4	2.8	4.5	2.9	6.0	6.3	4.0	3.9	3.0	3.2	4.6
Y	29.3	29.2	23.1	27.4	27.2	23.2	34.4	25.2	24.9	25.5	28.1	28.5	28.5	29.2	31.7
La	29.7	28.9	22.5	28.1	26.0	22.6	36.3	24.5	25.1	24.8	27.2	30.3	31.0	31.5	35.5
Ce	53.8	52.3	41.3	50.1	47.1	40.2	62.8	43.4	45.3	46.0	48.7	54.5	54.5	55.8	64.0
Pr	6.4	6.3	5.1	6.1	5.8	4.8	7.5	5.3	5.3	5.4	5.9	6.6	6.6	6.8	7.5
Nd	25.0	24.8	20.2	23.3	22.6	18.8	28.7	21.0	20.3	21.1	23.1	25.5	25.1	25.8	28.6
Sm	5.3	5.3	4.4	4.9	4.9	4.1	6.0	4.6	4.3	4.6	5.0	5.4	5.4	5.5	6.0
Eu	2.0	2.0	1.9	1.9	1.9	1.5	2.1	1.8	1.7	1.9	1.9	2.1	2.1	2.1	2.1
Gd	6.0	6.1	4.9	5.7	5.6	4.7	6.9	5.2	4.8	5.3	5.7	6.2	6.1	6.2	6.7
Tb	0.9	0.9	0.8	0.9	0.9	0.7	1.1	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.0
Dy	5.6	5.7	4.6	5.2	5.3	4.4	6.3	4.8	4.6	4.9	5.4	5.6	5.6	5.7	6.1
Ho	1.1	1.1	0.9	1.0	1.0	0.8	1.2	0.9	0.9	1.0	1.0	1.1	1.1	1.1	1.2
Er	3.3	3.4	2.7	3.1	3.1	2.6	3.8	2.8	2.8	2.8	3.1	3.2	3.3	3.3	3.6
Tm	0.4	0.4	0.3	0.4	0.4	0.3	0.5	0.3	0.4	0.3	0.4	0.4	0.4	0.4	0.4
Yb	3.1	3.1	2.6	3.0	2.9	2.3	3.5	2.6	2.8	2.6	2.8	3.0	3.1	3.1	3.3
Lu	0.5	0.4	0.4	0.4	0.4	0.3	0.5	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.5
Zr/Nb	3.46	3.42	3.43	3.66	3.56	3.03	3.70	3.64	3.59	4.64	3.99	3.44	3.63	3.68	3.58
Ba/Nb	11.70	11.85	13.41	11.11	13.41	14.40	11.35	11.47	11.22	13.65	12.12	11.57	11.03	11.36	11.09
La/Nb	0.50	0.48	0.39	0.47	0.44	0.52	0.66	0.43	0.41	0.55	0.52	0.45	0.48	0.50	0.52

L.O.I. = loss on ignition

Mg# = 100Mg/(Mg + Fe^{2+}), assuming Fe_2O_3/(FeO + Fe_2O_3) = 0.15

Table 2. Sr, Nd, and Pb isotopic compositions of representative SKPB

Sample	$^{87}Sr/^{86}Sr$	$2\sigma_m$	$^{143}Nd/^{144}Nd$	$2\sigma_m$	$\varepsilon Nd_{(t=o)}$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$\Delta7/4Pb$	$\Delta8/4Pb$
AD-05-1	0.703897	±22	0.512846	±4	4.06	18.105	15.562	38.408	10.9	89.2
AD-05-2	0.703951	±22	0.512860	±4	4.32	18.437	15.620	38.699	13.0	78.1
AD-05-7	0.703783	±24	0.512856	±4	4.25	17.881	15.482	38.096	5.3	85.0
AD-06-2	0.704095	±18	0.512855	±6	4.24	18.029	15.532	38.312	8.6	88.7
AD-06-3	0.703871	±14	0.512855	±4	4.24	18.005	15.516	38.250	7.3	85.5

nificantly different from those of analyzed samples, the influence of the blanks to isotope ratios of the samples is negligible within the analytical error ranges. The results are given in Table 2.

4. RESULTS

The samples studied are plotted into the field of basaltic to basaltic trachy-andesite (Fig. 3) in the nomenclature diagram of Le Bas et al. (1986), but we use the more general classification term of alkaline basalt. All samples have relatively higher SiO_2 (49.3–52.1 wt%) and lower MgO (2.1–5.5 wt%, Mg-number [(100 × Mg/(Mg + Fe^{2+})] = 41.8 to 59.9) contents compared to the other Cenozoic alkali lavas in Korea. They have K_2O concentrations from 1.7 to 1.5 wt% and thus correspond to the high-K series of alkali basalt (Table 1).

Trace element compositions of the SKPB are compared on primitive mantle normalized trace element variation plots (Sun and McDonough, 1989, Fig. 4) with those of basaltic rocks from Ganseong and Jogokni area, and the Baengnyeong, Ulleung, Dok and Jeju Islands (Park and Park, 1996; Park et al., 1996; Song et al., 1999; Lee et al., 2002; Koh and Yun, 2005; Park et al., 2005; Choi et al., 2006). For comparison of the magma generation process in mantle sources we selected the data having similar SiO_2 compositional ranges that of the SKPB. The average OIB composition (Sun and McDonough, 1989) also is plotted together.

Trace element plots of the SKPB show OIB-like convex-upward patterns with positive anomalies of Ba, Nb and Pb. They also show slight depletions in LREEs and a large variation in U content. They have lower REE contents (ΣREE = 108~167 ppm) and display somewhat flatter [(Ce/Yb)n = 4.49~5.46] and less fractionated HREE [(Dy/Yb)n = 1.11~1.29] patterns compared to the average OIB com-
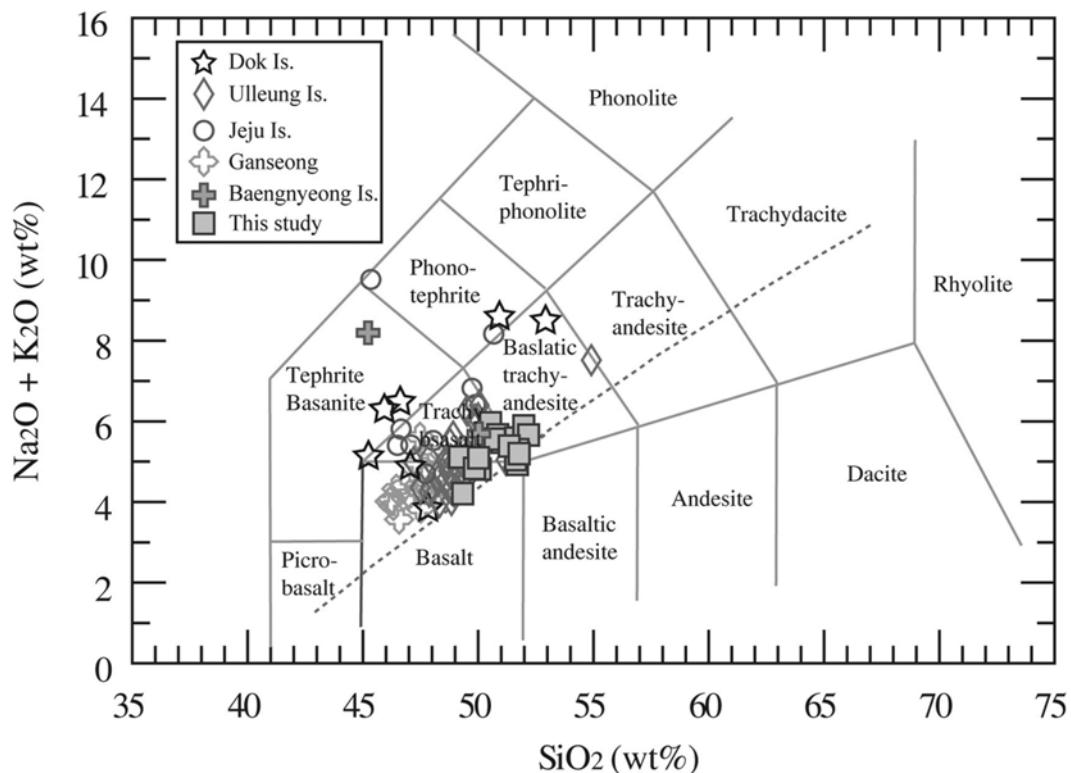
Fig. 3. Total alkali (wt%) versus SiO_2 (wt%) plot for the SKPB. Lines and fields are based on Le Bas et al. (1986). Data Sources: Park et al. (1996); Song et al. (1999); Lee et al. (2002); Koh and Yun (2005); Choi et al. (2006).
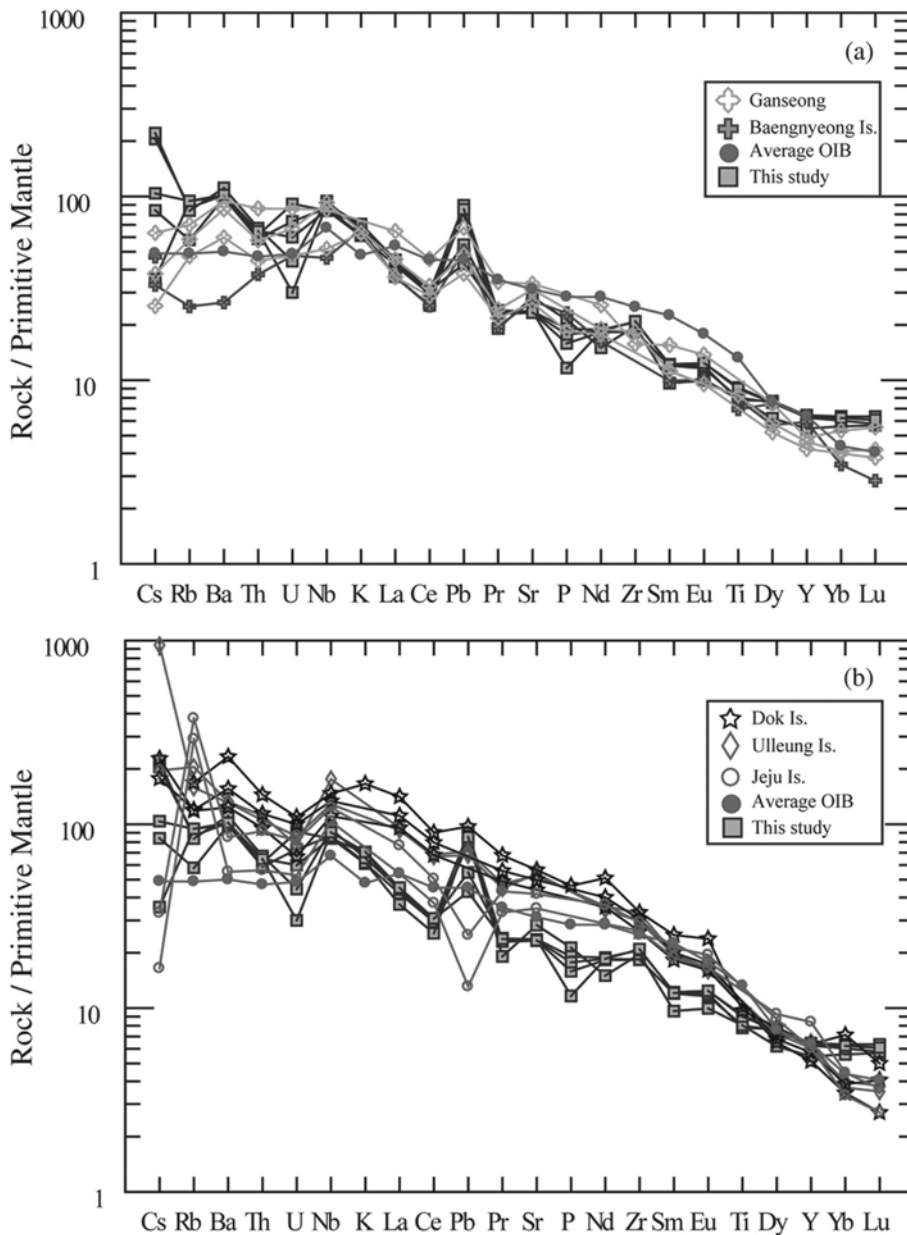
Fig. 4. Primitive mantle normalized multi-element plots of the SKPB. We compared incompatible element abundances of the primitive samples with those of representative Korea Cenozoic basalts having similar SiO_2 contents. Data sources are the same as in Figure 3. The primitive mantle and average oceanic island basalt (OIB) compositions are from Sun and McDonough (1989).

position (ΣREE = 199 ppm, (Ce/Yb)n = 10.3, (Dy/Yb)n = 1.73, Sun and McDonough, 1989). Overall trace element patterns and concentrations of the SKPB are similar to those of volcanic rocks from Ganseong (ΣREE = 124–166 ppm, Ce/Yb)n = 4.26~8.15, (Dy/Yb)n = 1.31~1.44). Compared with basalts from the Ulleung, Dok and Jeju Islands that have (Ce/Yb)n and (Dy/Yb)n ratios from 6.58–18.89 to1.26–2.66, respectively, the studied samples have lower LREE enrichment and less fractionated HREE patterns. This may be caused by (i) a larger degree of partial melting; (ii) a derivation from relatively shallower mantle with a lesser control of residual garnet; or (iii) the generation from a less enriched source. Plots of Nb/Yb versus SiO_2 (wt%) and La/Sm versus Sm/Yb ratios are displayed in Figure 5 to examine these petrogenetic constraints on depth

and source enrichment.

The degree of partial melting involved in the production of mantle-derived igneous rocks can be estimated from the SiO_2 content of a melt and the respective Nb/Y values. Nb/Y can be used as a trace element index because Nb and Y encompass a range of element incompatibilities in the source mantle materials, and have been found to be least affected by metasomatic processes (e.g., Rogers et al., 1992; Beard et al., 1998). La/Sm and Sm/Yb ratios can be used to evaluate the degree of source enrichment and depth of melting (e.g., Kay et al., 2010). Although the exact boundaries are variable depending on whole rock compositions, Sm/Yb values generally increase as pressure increases with retention of heavy REEs in residual amphibole, and particularly in garnet at Sm/Yb>~4 (e.g., Hildreth and
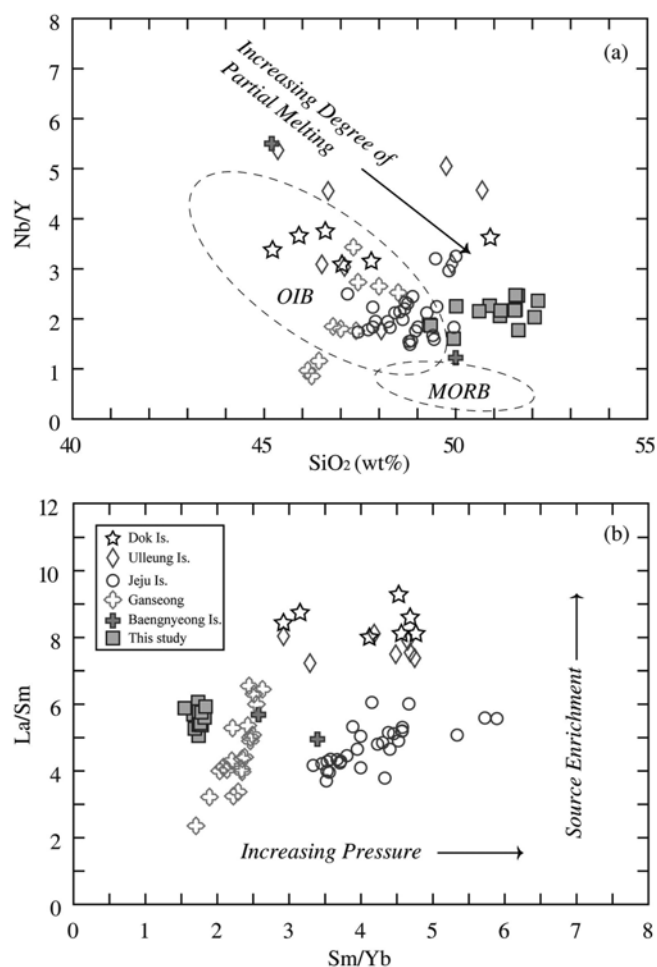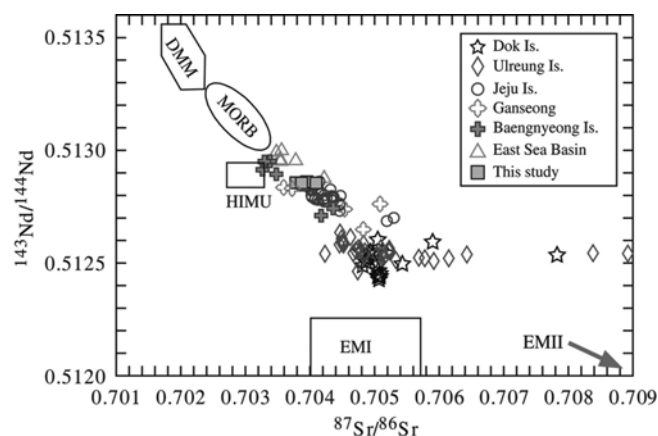
Fig. 5. Plots of Nb/Yb versus SiO₂ (wt%) (a) and La/Sm versus Sm/Yb (b) illustrating degree of partial melting, source enrichment and depth constrains for the Cenozoic Korea basalts. Increasingly higher Sm/Yb ratios generally reflect retention of heavy REEs in higher pressure residual phases. Data sources are the same as in Figure 3.


Fig. 6. Sr and Nd isotopic compositions of the SKPB. Data for Ganseong area, Baengnyeong Island, Ulleung Island, Dok Island and Jeju Island are plotted together. Data sources for the late Cenozoic Korean basaltic rocks are from Lee et al. (2002), Park et al. (2005), and Choi et al. (2006). Basalts from the East Sea basin are also shown for comparison (Tatsumoto and Nakamura, 1991; Cousens and Allan, 1992). Mantle components are from Zindler and Hart (1986). Indian MORB field is from Mahoney et al. (1989). DMM = depleted mantle, EMI and EMII = enriched mantle, HIMU = matle with high U/Pb ratio, MORB = mid ocean ridge basalts.

Moorbath, 1988; Kay et al., 2010). Figure 5 demonstrates that the SKPB is a product of larger degree melting than OIB and any other Cenozoic Korean alkaline lavas, and derived from a relatively shallower mantle with a lesser control of residual garnet. The lower Ti content in the SKPB also supports that the initial magma was derived from a shallower depth (Fig. 4). It seems that the degree of depletion of the source involved in the generation of the SKPB is similar to those of Ganseong, Baengnyeong and Jeju volcanic rocks (Fig. 5).

The analyzed basaltic samples from the SKPB have relatively low $^{87}Sr/^{86}Sr$, moderately high $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ isotopic compositions (Table 2). The isotopic compositions of the studied samples are in the range of 0.70378–0.70409 for $^{87}Sr/^{86}Sr$, 0.512846–0.512860 for $^{143}Nd/^{144}Nd$ (corresponding to $\varepsilon_{(t = 0)}$, ~4.1–4.3) and 17.88–18.44 for $^{206}Pb/^{204}Pb$, 15.48–15.62 for $^{207}Pb/^{204}Pb$, 37.86–38.46 for $^{208}Pb/^{204}Pb$.

In Figures 6 and 7, the compositions of the SKPB are compared with those of the Cenozoic intraplate basalts from the Korean Peninsula (Park et al., 2005; Choi et al., 2006) and East Sea Basin (Tatsumoto and Nakamura, 1991; Cousens and Allan, 1992). The mantle end members of DMM, HIMU, EMI and EMII (Zindler and Hart, 1986) are shown together. The Sr and Nd isotope data of the SKPB show more depleted composition compared to those of the Ulleung, Dok and Jeju island basalts, but partly overlap with the field of the Ganseong, Baengnyeong Island and East Sea Basin basalts. The $^{143}Nd/^{144}Nd$ isotope ratios are fairly similar in contrast to relatively variable Sr and Pb isotope values. In the $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ correlation plot (Fig. 7b), a good linear array defined by the data points is displaced considerably above the Northern Hemisphere Reference Line (NHRL) of Hart (1984) and is parallel to the NHRL. In the $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot, a fairly linear array is also observed and is subparallel to the NHRL. The Pb isotopic compositions clearly show the DUPAL signature (e.g., Hart, 1984; Tatsumoto and Nakamura, 1991).

5. DISCUSSION

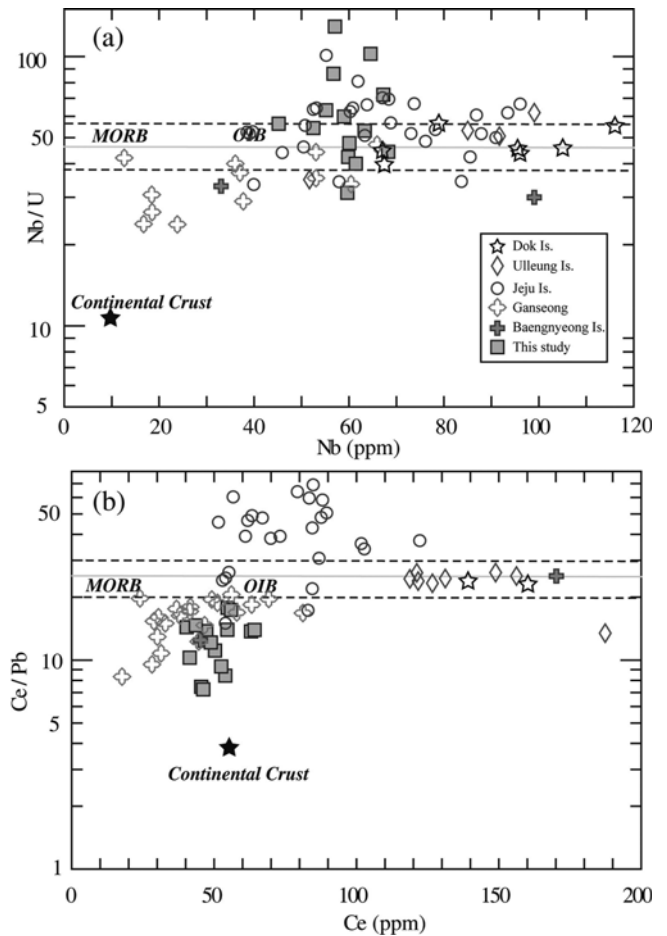### 5.1. Comparison with Ocean Island Basalts

Incompatible element patterns of the samples are broadly consistent with a dominant OIB type source component. All of the analyzed samples have high abundances of Nb, with low Zr/Nb (3.03–4.64) typical of OIB and contrary to the higher values reported for MORB (6–10). Ba/Nb and
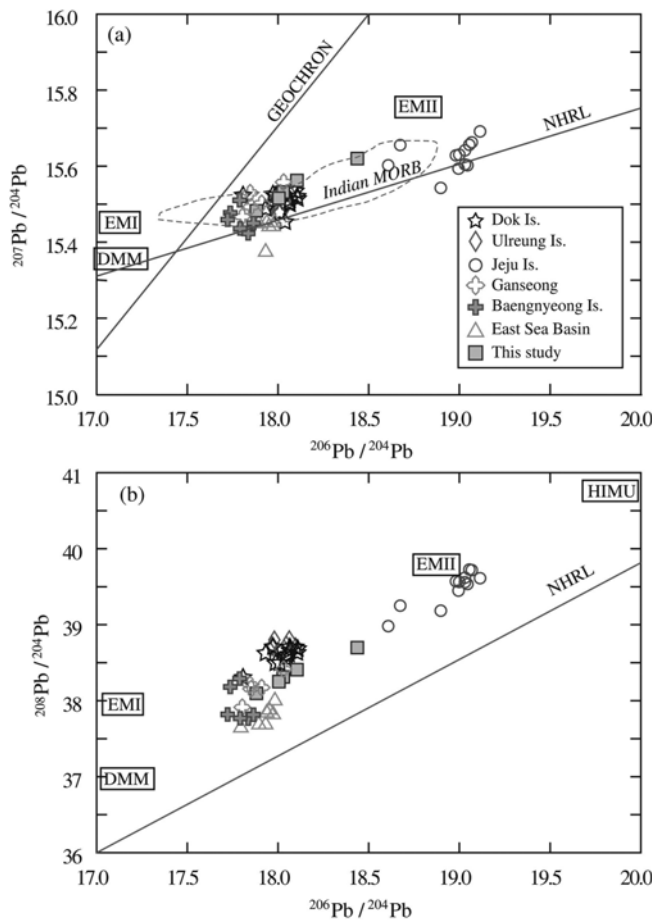
Fig. 7. Plots of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ (a) and $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ (b). Data sources are the same as in Figure 5. NHRL (Northern Hemisphere Reference Line) and Geochron are from Hart (1984).

Fig. 8. Plots of Nb/U versus Nb (a) and Ce/Pb versus Ce (b) for the Korea Cenozoic alkali basalts. The average ratios of Nb/U and Ce/Pb in OIB and MORB are from Hofmann et al. (1986). Data sources are the same as in Figure 3.

La/Nb ratios in the studied samples range from 11.03 to 14.40 and 0.39 to 0.66, respectively, overlapping with Korean Cenozoic alkali basalts (Ba/Nb = 5–15, La/Nb = 0.49–0.92) and the average OIB (Ba/Nb = 7.29, La/Nb = 0.77) composition, and are significantly different from that of MORB (Ba/Nb = 2.7, La/Nb = 1.07, Sun and McDonough, 1989).

Unlike conventional indicator such as Ba/Nb, La/Nb or Zr/Nb, all of which are known to be easily fractionated by some igneous processes, the Ce/Pb and Nb/U ratios of oceanic basalts (OIB and MORB) show virtually constant values (Ce/Pb = 25 ± 5 and Nb/U = 47 ± 7, Hofmann et al., 1986), and are higher than the values for average continental crust or arc volcanic rocks (Taylor and McLennan, 1985). These elements are not fractionated from each other during partial melting or fractional crystallization and their ratios reflect those of source regions (Hofmann, 1988). Figure 8 shows the variation of Ce/Pb and Nb/U ratios of the samples. In a variation plot of Ce/Pb versus Ce (Fig. 8b), compositions of the samples show a comparable variation range to that of basalts from Ganseong. The Ce/Pb (8.47–17.88) and Nb/U (32.08–92.01) ratios show large

variations and are inconsistent with constant values for these ratios reported in oceanic basalts. U and Pb concentrations are generally believed to be easily affected from post magmatic low-temperature alteration (Hofmann et al., 1986). Moreover, the high abundances of Nb, a large variation, but considerably higher Nb/U ratios and their homogeneous isotopic compositions suggest that the effect of crustal contamination was not significant on controlling the magma composition. Therefore, we consider here that the slightly different compositional ranges of Ce/Pb and Nb/U ratios of the samples compared to those of oceanic basalts are attributed to take up or loss of U and Pb from some samples by a post magmatic alteration process.

## 5.2. Mantle Sources and Isotopic Mixing

Previous studies have reported that isotopic characteristics of most basalts from eastern China, East Sea (Japan Sea) region and SW Japan indicate the involvement of 'Indian Ocean' MORB-type isotopic component, named as

DUPAL anomaly by Hart (1984), in magma genesis ($\Delta 8/4Pb$ values greater than 60, high $^{208}Pb/^{204}Pb$ relative to $^{206}Pb/^{204}Pb$), implying pervasive enrichment of EMI-like mantle component and long term evolution of high Th/U magmatic source beneath Eastern margin of Asia (Tatsumoto and Nakamura, 1991; Tatsumoto et al., 1992; Liu, et al., 1994; Castillo, 1996; Lui et al., 2001; Hoang and Uto, 2006). The origin of the DUPAL anomaly has been a subject of continuing debate. The DUPAL isotope anomaly was thought to be a Southern Hemisphere phenomenon that can be traced nearly continuously between the equator and 60°ýS (Hart, 1984; 1988). However, studies on MORB from the other region (e.g., Volker et al., 1993; Haase et al., 2000) have highlighted that the DUPAL feature is not restricted to the Sourthern Hemisphere. Particularly, in Eastern Asia, the DUPAL signature has been widely identified in broadly MORB-type basaltic rocks as well as in OIB-type basalts (e.g., Basu et al., 1991; Tatsumoto and Nakamura, 1991; Flower et al., 1998).

The major interpretations for the DUPAL anomaly include contamination of the asthenosphere by (1) local mantle enrichment processes via subduction or wall rock reaction (e.g., Tatsumoto and Nakamura, 1991), (2) delaminated subcontinental lithosphere during breakup of Gondwana (e.g., Allègre and Trucote, 1985; Rehkamper and Hofmann, 1997; Flower et al., 1998), and (3) pristine deep mantle (e.g., Hart, 1988; Castillo, 1996). Tatsumoto and Nakamura (1991) proposed that the East Sea region DUPAL
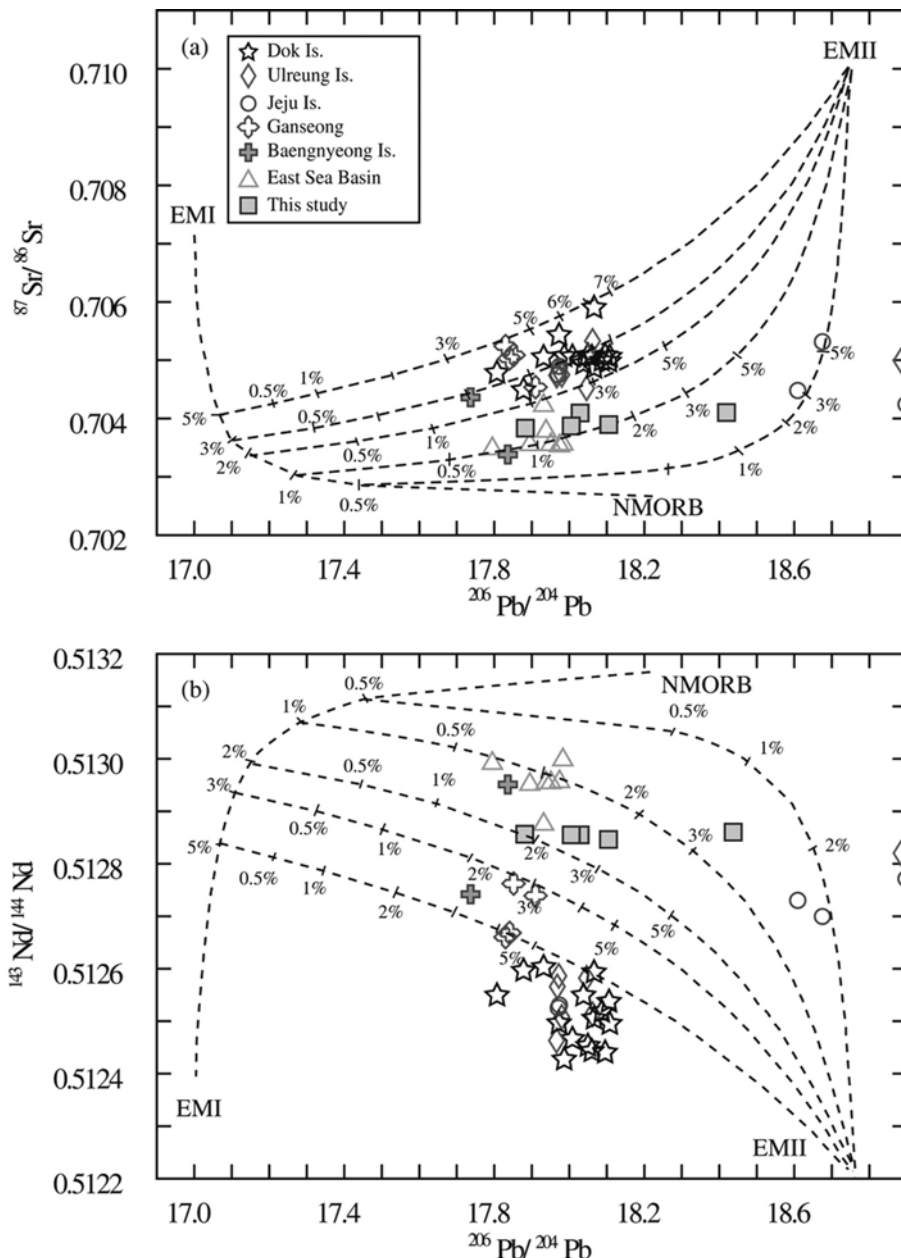
Fig. 9. Plots of $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$ (a) and $^{143}Nd/^{144}Nd$ versus $^{206}Pb/^{204}Pb$ (b) for the studied basalts together with data from Ganseong area, Baengnyeong Island, Ulleung Island, Dok Island, Jeju Island and basalts from the East Sea basin (data sources as in Fig. 5). The EMI-like end member is from the average Sino-Korean craton mantle composition interpolated from northern Chinese basalts and xenoliths (Zhang et al., 1995). An average value of sediment compositions from ODP Sites 579 and 581 was taken as the EMII-like end member (Cousens et al., 1994). The N-MORB is from Regelous et al. (1999). Values of $^{87}Sr/^{86}Sr$, Sr (ppm), $^{206}Pb/^{204}Pb$, Pb (ppm), $^{143}Nd/^{144}Nd$, Nd (ppm) respectively, taken for mixing calculation for EMI: 0.707, 180, 17.00, 17, 0.5124, 20; EMII: 0.710, 180, 18.75, 17, 0.5122, 20; N-MORB: 0.7026, 20, 18.2, 0.05, 0.51316, 1.4.

character is inherited from an old lithospheric mantle (pirior to Proterozoic) metasomatized with subduction related fluids (old subduction system). In contrast, several workers interpreted that the DUPAL-like Eastern Asia isotopic signature was endogenous and incorporated via the delamination of the EMI-rich root zone of Sino-Korean craton in response to regional geodynamic factors, particularly the Early Tertiary India-Asia plate collision (e.g., Tu et al., 1991; Hoang et al., 1996; Flower et al., 1998; Hoang and Uto, 2006). Regardless of the origin of a DUPAL-like component in East Asia basalts, it is reasonable to assume that EMI components are widespread in asthenospheric DMM mantle of this region. Besides DMM and EMI mantle components, EMII-like mantle components are needed to account for regional variations of the upper mantle isotopic compositions in East Asia (e.g., Zou et al., 2000; Choi et al., 2006; Chen et al., 2007; Yan and Zhao, 2008). The geochemical and isotopic characteristics of the Cenozoic basalts of this region have been interpreted as the result of the mixing including at least three mantle components, DMM, EMI and EMII-like, in the magma generation (e.g., Zou et al., 2000; Choi et al., 2006; Chen et al., 2007). Several workers have interpreted these mixing processes in terms of simple two step processes: (1) variable enrichment of N-MORB-like depleted mantle by cratonic EMI mantle, and followed by (2) contamination of the asthenospheric mantle by crust-derived EMII-rich components (e.g., Hoang and Uto, 2006; Yan and Zhao, 2008).

Here, we try to explain the Sr-Nd-Pb isotopic characteristics of the studied samples by a two-stage mixing model the same as suggested by Hoang et al. (2006). Plots of ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd versus ^{206}Pb/^{204}Pb are shown in Figure 9a, b with the mixing line between DMM and EMI-like mantle sources and variable addition of EMII-like source to melts of mixing compositions. In this model, EMI was assumed to have been added to pre-existing N-MORB asthenosphere to explain a DUPAL-like component (e.g., Tu et al., 1991; Hoang et al., 1996; Flower et al., 1998; Hoang and Uto, 2006). The Sr, Nd, and Pb isotopic compositions and concentrations of the DMM, EMI and EMII components for the mixing calculations are listed in Figure 9. The EMI compositions are the average cratonic mantle composition interpolated for the Sino-Korean craton from northern Chinese basalts and xenoliths (Tatsumoto et al., 1992; Zhang et al., 1995; Hoang and Uto, 2006). Crust-derived sediment compositions from East Sea ODP sites 579 and 581 (Cousens, et al., 1994) are used as an EMII-like additional contaminant. An average for East Pacific Rise N-MORB (Regelous et al., 1999) was taken as the end member of 'uncontaminated' asthenosphere (Fig. 9a, b). According to our mixing model (Fig. 9a, b) the Late Cenozoic alkali basalts of Korea can be explained by the addition from 1 to 6% of an EMI-like material to an N-MORB source prior to the addition of (from 0.5 to 7%) an EMI-

like source. The isotopic compositions of the SKPB are somewhat depleted and match well predicted mixing field, corresponding to the melt composition derived from the addition of 1–2% of EMI-like material to depleted N-MORB and superimposed by an EMII-like source (1–2%).

6. CONCLUSIONS

Geochemical and isotopic study of the SKPB leads to the following conclusions.

1. The SKPB have relatively homogeneous geochemical and isotopic composition that is similar to OIB. Overall trace element patterns and concentrations of the SKPB are similar to those of volcanic rocks from Ganseong (ΣREE = 124–166 ppm, (Ce/Yb)n = 4.26~8.15, (Dy/Yb)n = 1.31~1.44).

2. Compared with basalts from Ulleung, Dok and Jeju Islands, the SKPB have a lower LREE enrichment and less fractionated HREE patterns, indicating that the basaltic magma from the studied area was derived from a relatively shallower mantle depth with a larger degree of partial melting.

3. The Sr and Nd isotopic compositions of the SKPB are relatively depleted compared to other Cenozoic Korean alkali basalts, but share DUPAL-like Pb isotopic signatures (elevated ^{208}Pb/^{207}Pb and somewhat elevated ^{207}Pb/^{204}Pb compared with NHRL). The geochemical and isotopic characteristics of them cannot be explained by simple binary mixing between depleted end member and enriched EMI- or EMII-like sources, but reflect the magma derived from a two-stage mixing process: (1) the addition of ~2% of an EMI-like material to a N-MORB source and followed by (2) the addition of up to 2% of an EMII-like source.

REFERENCES

Allègre, C.J. and Turcotte, D.L., 1985, Geodynamic mixing in mesosphere boundary layer and the origin of oceanic islands. Geophysical Research Letters, 12, 207–210.
Basu, A.R., Wang, J.W., Huang, W.K., Xie, G.H. and Tatsumoto, M., 1991, Major element, REE, and Pb, Nd and Sr isotopic geochemistry of Cenozoic volcanic rocks of eastern China: implications for their origin from suboceanic-type mantle reservoirs. Earth and Planetary Science Letters, 105, 149–169.
Beard, A.D., Downes, H., Hegner, E., Sablukov, S.M., Vetrin, V.R. and Balogh, K., 1998, Mineralogy and geochemistry of Devonian ultramafic minor intrusions of the southern Kola Peninsula, Russia: implication for the petrogenesis of kimberlites and melilitites. Contribution to Mineralogy and Petrology, 130, 288–303.

Castillo, P.R., 1996, Origin and geodynamic implications of the Dupal isotopic anomaly in volcanic rocks from the Philippine island arcs. Geology, 24, 271–274.

Chen, Y., Zhang, Y., Graham, D., Su, S. and Deng, J., 2007, Geochemistry of Cenozoic basalts and mantle xenoliths in Northeast China. Lithos, 96, 108–126.

Choi, S.H., Kwon, S.-T., Mukasa, S.B. and Sagong, H., 2005, Sr-Nd-Pb isotope and trace element systematic of mantle xenoliths from late Cenozoic alkaline lavas, South Korea. Chemical Geology, 221, 40–64.

Choi, S.H., Mukasa, S.B., Kwon, S.-T., and Andronikov, A.V., 2006, Sr, Nd, Pb and Hf isotopic compositions of Late Cenozoic alkali basalts in South Korea: Evidence for mixing between two dominant asthenospheric mantle domains beneath East Aia. Chemical Geology, 232, 134–151.

Cousens, B.L. and Allan, J.F., 1992, A Pb, Sr, and Nd isotopic study of basaltic rocks from the Sea of Japan, ODP Leg 127/128. Proceedings of the Ocean Drilling Program, Scientific Results, 127/128, Part 2, 805–817.

Cousens, B.L., Allan, J.F. and Gorton, M.P., 1994, Subduction-modified pelagic sediments as the enriched component in back-arc basalts from the Japan Sea: Ocean drilling program sites 797 and 794. Contributions to Mineralogy and Petrology, 117, 421–434.

Flower, M.F.J., Tamaki, K. and Nguyen, H., 1998, Mantle extrusion: A model for dispersed volcanism and DUPAL-like asthenosphere in East Asia and the Western Pacific. In: Flower, M.F.J., Chung, S.L., Lo, C.H. and Lee, T.Y. (eds.), Mantle Dynamics and Plate Interactions in East Asia. American Geophysical Union Geodynamic series, 27, 67–87.

Haase, K.M., Muhe, R. and Stoffers, P., 2000, Magmatism during extension of the lithosphere: Geochemical constraints from lavas of the Shaban Deep, northern Red Sea. Chemical Geology, 166, 255–239.

Hart, S.R., 1984, A large scale isotopic anomaly in the southern hemisphere. Nature, 309, 753–756.

Hart, S.R., 1988, Heterogeneous mantle domains: signatures, genesis and mixing chronologies. Earth and Planetary Science Letters, 90, 273–296.

Hildreth, W. and Moorbath, S., 1988, Crustal contributions to arc magmatism in the Andes of Central Chile. Contributions to Mineralogy and Petrology, 98, 455–489.

Hoang, N. and Uto, K., 2006, Upper mantle isotopic components benenath the Ryukyu arc system: Evidence for 'back-arc' entrapment of Pacific MORB mantle. Earth and Planetary Science Letters, 249, 229–240.

Hoang, N., Flower, M.F.J. and Carlson, R.W., 1996, Major, trace element, and isotopic compositions of Vietnamese basalts: interaction of hydrous EM1-rich asthenosphere with thinned Eurasian litho-sphere. Geochimica et Cosmochimica Acta, 60, 4329–4351.

Hofmann, A.W., 1988, Chemical differentiation of the Earth: the relationship between mantle, continental crust, and the oceanic crust. Earth and Planetary Science Letters, 90, 297–314.

Hofmann, A.W., Jochum, K.P., Seufert, M. and White, W.M., 1986, Nb and Pb in oceanic basalts: new constraints on mantle evolution. Earth and Planetary Science Letters, 79, 33–45.

Kay, S.M., Coira, B.L., Caffe, P.J. and Chen, C.H., 2010, Regional chemical diversity, crustal and mantle sources and evolution of central Andean Puna plateau ignimbrites. Journal of Volcanology and Geothermal Research, 198, 81–111.

Kil, Y. and Lee, S.H., 2005, Geochemical characteristics of clinopyroxenes in the upper mantle rocks under the Baegryeong Island and the Boeun. Journal of Mineralogical Society of Korea, 18, 63–74 (in Korean with English abstract).

Koh, J.S., and Yun, S.H., 2005, Petrology on the Late Miocene Basalts in Goseong-gun, Gangwon Province. Jour. Korean Earth Science Society, 26, 78–92. (in Korean with English abstract)

Kwon, S.-T., 1986, Pb-Sr-Nd isotope study of the 100 to 2700 Ma old alkali rock-carbonatite complexes in the Canadian shield: Inferences on the geochemical and structural evolution of the mantle. Ph.D. thesis, University of California Santa Barbara, Santa Barbara, 242 p.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A. and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the Total Alkali-Silica diagram. Journal of Petrology, 27, 745–750.

Lee, J.I., Hur, S.D., Huh, S., Chun, J.-H. and Han, S.J., 2000, Geochemistry and Sr-Nd isotopic composition of granites sampled from the Korea Plateau, East Sea. Journal of the Geological Society of Korea, 36, 279–294. (in Korean)

Lee, J.I., Hur, S.D., Lee, M.J., Yoo, C.M., Park, B.K., Kim, Y., Kwon, M.S. and Nagao, K., 2002, Petrology and geochemistry of Dokdo volcanic rocks, East Sea. Ocean and Polar Research, 24, 465–482. (in Korean with English abstract)

Liu, C.-Q., Masuda, A. and Xie, G.-H., 1994, Major- and trace-element compositions of Cenozoic basalts in eastern China: petrogenesis and mantle source. Chemical Geology, 114, 19–42.

Liu, J.Q., Han, J.T. and Fyfe, W.S., 2001, Cenozoic episodic volcanism and continental rifting in northeast China and possible link to Japan Sea development as revealed from K-Ar geochronology. Tectonophysics, 339, 385–401.

Liu, M., Cui, X. and Liu, F., 2004, Cenozoic rifting and volcanism in eastern China: a mantle dynamic link to the Indo-Asian collision? Tectonophysics, 393, 29–42.

Mahoney, J.J., Natland, J.H., White, W.M., Poreda, R., Bloomer, S.H., Fisher, R.L. and Baxter, A.N., 1989, Isotopic and geochemical provinces of the western Indian Ocean spreading. Journal of Geophysical Research Letters, 94, 4033–4052.

Park, J.-B. and Park, K.-H., 1996, Petrology and petrogenesis of the Cenozoic alkali volcanic rocks in the middle part of Korean Peninsula (I): petrography, mineral chemistry and whole rock major element chemistry. Journal of the Geological Society of Korea, 32, 223–249. (in Korean with English abstract)

Park, J.-B., Park, K.-H. and Cheong, C.-S., 1996, Sr-Nd-Pb isotopic compositions of lavas from Cheju Islad, Korea. Journal of Petrological Society of Korea, 5, 89–107. (in Korean with English abstract)

Park, K.-H., Park, J.-B., Cheong, C.-S. and Oh, C.W., 2005, Sr, Nd and Pb isotopic systematics of the Cenozoic basalts of the Korean Peninsula and their implications for the Permo-Triassic continental collision boundary. Gondwana Research, 8, 529–538.

Regelous, M., Niu, Y., Wendt J.I., Batiza, R., Greig, A. and Collerson, K.D., 1999, Variations in the geochemistry of magmatism on the East Pacific Rise at 10º300N since 800 ka. Earth and Planetary Science Letters, 168, 45–63.

Rehkamper, M. and Hofmann, A.W., 1997, Recycled oceanic crust and sediment in Indian Ocean MORB. Earth and Planetary Science Letters, 147, 93–106.

Rogers, N.W., Hawkesworth, C.J. and Palacz, Z.A., 1992, Phlogopite in the generation of olivine-melilitites from Namaqualand, South Africa and implications for element fractionation processes in the upper mantle. Lithos, 28, 347–365.

Shin, H.J., Kil, Y.-W., Jin, M.S. and Lee, S.H., 2006, Petrological study on upper mantle xenoliths from Asan and Pyeongtaek area.

Journal of the Geological Society of Korea, 42, 95–113. (in Korean with English abstract)

Song, Y.S., Park, K.H. and Park, M.Y., 1999, Major, rare earth and trace element geochemistry of volcanic rocks from Ulleung Island. Journal of Petrological Society of Korea, 8, 57–70. (in Korean)

Sun, S.-S. and McDonough, W.F., 1989, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D. and Norry, M.J. (eds.), Magmatism in the Ocean Basins. Geological Society, Special Publications, 42, 313–345.

Tamaki, K., Suyehiro, K., Allan, J., Ingle, J.C., Jr. and Pisciotto, K.A., 1992, Tectonic synthesis and implications of Japan Sea ODP drilling. Proceedings of the Ocean Drilling Program, Scientific Results, 127/128, Part 2, 1333–1348.

Tapponnier, P., Peltzer, G. and Armijo, R., 1986, On the mechanics of the collision between India and Asia. In: Coward, M.P. and Ries, A.C. (eds.), Collision Tectonics. Geological Society, Special Publications, 19, 113–157.

Tatsumoto, M. and Nakamura, Y., 1991, DUPAL anomaly in the Sea of Japan: Pb, Nd, and Sr isotopic variations at the eastern Eurasian continental margin. Geochimca et Cosmochimica Acta., 55, 3697–3708.

Tatsumoto, M., Basu, A.R., Wankang, H., Junwen, W. and Guanghong, W., 1992, Sr, Nd, and Pb isotopes of ultramafic xenoliths in volcanic rocks and Eastern China: enriched components EMI and EMII in subcontinental lithosphere. Earth and Planetary Science Letters, 113, 107–128.

Taylor, S.R. and McLennan, S.M., 1985, The Continental Crust: Its Composition and Evolution. Blackwell, Oxford, 312 p.

Todt, W., Cliff, R.A, Hanser, A. and Hofmann, A.W., 1996, Evaluation of a ^{202}Pb-^{205}Pb double spike for high precision lead isotope analyses. In: Basu, A. and Hart, S. (eds.), Earth processes: reading the isotopic code. Geophysical Monograph 95, American Geophysical Union, 95, 429–437.

Tu, K., Flower, M.F.J., Carlson, R.W., Zhang, Z. and Xie, G.H., 1991, Sr, Nd, and Pb isotope compositions of Hainan basalts (south China): Implications for a subcontinental lithosphere Dupal source. Geology, 19, 567–569.

Tu, K., Flower, M.F.J., Carlson, R.W., Xie, G.H., Chen, C.Y. and Zhang, M., 1992, Magmatism in the South China Basin: 1. Isotopic and trace element evidence for an endogenous Dupal Mantle component. Chemical Geology, 97, 47–63.

Uto, K., Hoang, N. and Matsui, K., 2004, Cenozoic lithospheric extension induced magmatism in Southwest Japan. Tectonophysics, 393, 281–299.

Volker, F., McCulloch, M.T. and Altherr, R., 1993, Submarine basalts from the Red Sea: New Pb, Sr, and Nd isotopic data. Geophysical Research Letters, 20, 927–930.

Yan, J. and Zhao, J.X., 2008, Cenozoic alkali basalts from Jingpohu, NE china: the role of lithosphere-asthenosphere interaction. Journal of Asian Earth Science, 33, 106–121.

Zhang, M., Menzies, M.A., Suddaby, P. and Thirlwall, M.F., 1991, EM1 signature from within the post-Archaean subcontinental litho-spheric mantle: Isotopic evidence from the potassic volcanic rocks in NE China. Geochemical Journal, 25, 387–398.

Zhang, M., Suddaby, P., Thompson, R.N., Thirlwall, M.F. and Menzies, M.A., 1995, Potassic volcanic rocks in NE China: geochemical constraints on mantle source and magma genesis. Journal of Petrology, 36, 1275–1303.

Zhang, Z., Feng, C., Li, Z., Li, S., Xin, Y., Li, Z. and Wang, X., 2002, Petrochemical study of the Jingpohu Holocene alkali basaltic rocks, northeastern China. Geochemical Journal, 36, 133–153.

Zindler, A. and Hart, S.R., 1986, Chemical geodynamics. Annual Reviews of Earth and Planetary Sciences, 14, 493–571.

Zou, H., Zindler, A., Xu, X. and Qi, Q., 2000, Major, trace element, and Nd, Sr and Pb isotope studies of Cenozoic basalts in SE China: mantle Sources, regional variations, and tectonic significance. Chemical Geology, 171, 33–47.