Crustal evolution history of Korean Peninsula in East Asia: The significance of Nd, Ce isotopic and REE data from the Korean Precambrian gneisses

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The Precambrian basement of the Korean Peninsula, located at the east margin of Asian continent, consists of the Nangrim Massif, the Gyeonggi Massif and the Sobaegsan (Yeongnam) Massif. Two kinds of orthogneisses (biotite gneiss and granitic gneiss) from the central part of the Sobaegsan Massif show the particular difference in geochemical features suggesting the discrimination in formation history. The biotite gneisses give an Sm-Nd whole rock isochron age of 819 ± 114 Ma (2σ) with ϵ_{Nd} (0.82 Ga) = -15, and the granitic gneisses give an age of 1484 ± 810 Ma (2σ) with ϵ_{Nd} (1.48 Ga) = +7. The ϵ_{Nd} and ϵ_{Ce} values for the granitic gneisses show characteristics of highly depleted mantle material and those of the biotite gneisses show their sources having light-REE enriched continental-like feature. Chondrite-normalized REE patterns are also different. Biotite gneisses have less fractionated patterns with (La/Yb)_N ratio of 10~16 and negative Eu anomalies, while granitic gneisses have fractionated patterns with (La/Yb)_N ratio of 30~180 with no/or positive Eu anomalies. The Ce-Nd isotopic results obtained here indicate that the Sobaegsan biotite gneisses were derived from continental-like sources having light-REE enriched feature, while the Sobaegsan granitic gneisses were derived from MORB-like sources having light-REE-depleted feature. These isotopic and REE data are interpreted as recording LREE fractionation events associated with major episodes of crust formation in East Asia. And the comparison of the initial ϵ_{Nd} value of the Sobaegsan biotite gneiss at 0.82 Ga with those of the Chinese and Japanese Precambrian rocks implies that the sources for the Sobaegsan biotite gneisses and these Chinese and Japanese rocks had common light-REE enriched pattern, e.g., $^{147}\text{Sm}/^{144}\text{Nd}$ ratio ranging from 0.09–0.13. Furthermore, it suggests that these sources having light-REE enriched patterns were derived from depleted mantle at the late Archean.

INTRODUCTION

The Korean Peninsula located at the eastern margin of Asian continent (Fig. 1) consists of three Precambrian basement domains that show the difference in their source, formation history, petrography and metamorphism, that is, the Nangrim Massif, the Gyeonggi Massif and the Sobaegsan Massif (Na, 1987; Song and Lee, 1989). The link-

age of Korean Peninsula to Sino-Korean (North China) and South China Craton is still controversial (Lee, 1987; Cluzel *et al.*, 1991; Lan *et al.*, 1995; Ree *et al.*, 1996; Kwon *et al.*, 1997; Qiu *et al.*, 2000).

The basement of Korean peninsula has been traditionally regarded as a part of the Sino-Korean Craton (Lee, 1987). However, the recent discovery of rare Archean basement rocks in the

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Fig. 1. General sketch-map of east Asia. The main cratonic blocks are stippled (after Cluzel *et al.*, 1991). NM: Nangrim Massif, GM: Gyeonggi Massif, SM: Sobaegsan Massif.

South China block suggests also the possibility of correlation between South Korea and south China (Lan *et al.*, 1995; Qiu *et al.*, 2000). Lan *et al.* (1995) suggested the possibility of the presence of Archean crust in the Korean Peninsula. In addition, based on the range of T_{DM} model age, they also suggested that the southern part of Korean Peninsula (South Korea) might be correlated with the South China Craton. Further the results of recent studies also have raised a possibility that the middle part of the Korean Peninsula might be a part of the South China Craton (Ree *et al.*, 1996; Kwon *et al.*, 1997; Qiu *et al.*, 2000). On the contrary, Cluzel *et al.* (1991) suggested that the southern part of the Korean Peninsula had been a part of the Sino-Korean Craton before the early Triassic. Based on petrography and Rb-Sr isochron age data, Adachi and Suzuki (1993) suggested that the Precambrian gneissic clasts in the Kamiasso conglomerate, Japan, could be derived from the eastern Korean Peninsula (Sobaegsan Massif). Adachi (1973) and Shibata and Adachi (1974) suggested that the gneissic clasts in the Kamiasso conglomerate found in central Japan were derived from a part of the Precambrian continent in East Asia. In addition, Adachi and Suzuki (1993), judg-

ing from the nearly identical Rb-Sr age and petrographical similarity between gneisses from the two areas, suggested as provenance of the Kamiasso gneissic clasts the Samcheok area in the eastern part of the Youngnam Massif (Sobaegsan Massif), south Korea. Contrary to this, based on initial Nd and Ce isotopic data of the orthogneisses from the Kamiasso conglomerate, central Japan, Shimizu *et al.* (1996) argued that the Samcheok gneisses of the Sobaegsan Massif, South Korea and the Kamiasso orthogneiss clasts were derived from different sources. Lee *et al.* (1992) suggested also the possibility that some Precambrian orthogneisses from Korea had evolved from protoliths that had similar geochemical properties to the Precambrian orthogneisses in Japan and northern China. Such different opinions for the formation history between Korean Peninsula and Japan Precambrian basement mean that the Precambrian basement of Korean Peninsula plays a key role to clarify the crustal evolution history in East Asia.

Two kinds of orthogneisses from the middle part of South Korea show some distinct features in Nd, Ce isotope systematics and REE geochemistry. The purpose of this paper is to provide another geochemical evidence to clarify the relationship between China continent and Korean Peninsula, in East Asia crustal formation history. In this paper, based on the Nd-Ce isotopic systematics and REE geochemistry, we discuss the significance that the geochemical difference between two kinds of the Sobaegsan Precambrian orthogneisses give in East-Asia crustal evolution history.

GEOLOGY OF SOBAEGSAN MASSIF AND SAMPLE DESCRIPTION

The Sobaegsan Massif is one of the Precambrian basements in South Korea together with Gyeonggi Massif (Fig. 2(a)). Both massifs are similar in their constituent rocks and structure. The Sobaegsan Massif is mainly composed of Precambrian orthogneiss and metasediments intruded by Mesozoic granites. The metamorphic

Fig. 2. (a) Index map of Precambrian tectonic units in Korea adapted from Um and Chun (1984). (b) Geological map of central Sobaegsan Massif in Korea. (c) Sample location map of the study area.

rocks correspond mostly to the low pressure facies series, with the amphibolite facies in the series being predominant. They were also suffered from polymetamorphism and retrograde metamorphism from upper amphibolite facies to greenschist facies (Na, 1987).

The granite gneiss studied in this paper occurs at the middle part of the Sobaegsan Massif and locates at $35^{\circ}15' \text{ N}$ – $35^{\circ}56' \text{ N}$ and $127^{\circ}55' \text{ E}$ – $128^{\circ}05' \text{ E}$ (Fig. 2(b)). This gneiss is divided into the granitic gneiss and the biotite gneiss on the basis of mineral assemblage and texture. The

biotite gneiss occurs with the width of a few to tens meters. In some places, the biotite gneiss shows characteristics of xenolith or resite. In general, it is difficult to distinguish the relationship between the biotite gneiss and the granitic gneiss on a regional scale.

In order to compare major element composition, REE abundances and Nd, Ce isotopic systematics, we selected nine samples of the biotite gneiss and six samples of the granitic gneiss (Fig. 2(c)). In occurrence, the granitic gneiss is leucocratic, and shows a well-developed foliation,

and migmatitic structures such as vein and schollen type. It is composed of quartz, plagioclase, K-feldspar and biotite. Secondary muscovite and chlorite are also observed. Compared to the granitic gneiss, the biotite gneiss is dark colored and is typically banded. It comprises biotite, quartz, plagioclase and K-feldspar, with minor hornblende, clinopyroxene and orthopyroxene.

ANALYTICAL PROCEDURES

Whole rock samples were crushed into grains of several millimeters with a jaw crusher and about 20–50 g of the grains collected were pulverized in an agate mill. Major element compositions were

determined with a SHIMAZU VF-320A X-ray fluorescence spectrometer. In order to analyze REE abundance and Nd and Ce isotope compositions, about 0.5–1 g of the powdered sample was completely decomposed by HF and HClO₄ using a teflon beaker. For isotope dilution method, REE were separated from the major elements by an AG 50W-X8 resin column in HCl media. The pure Nd and Ce fractions for isotope analysis were separately isolated from the decomposed solution using an AG 50W-X8 resin column with α -hydroxy-isobutyric acid.

REE abundances were determined by isotope dilution using a JEOL JMS-05RB mass spectrometer at University of Tokyo, Japan and a VG-PQ ICP-MS at Korea Basic Science Institute

Table 1(a). Major element compositions (%) and rare earth element, Sr, Rb and Ba abundances (ppm) for biotite gneiss from the Sobaegsan Massif, Korea

	K-11	K-13	4-58a	4-59	3303	96-5-2	96-9-1	96-9-2	96-10-2
SiO ₂	63.8	63.3	61.0	53.5	66.2	59.6	64.6	59.6	65.2
TiO ₂	0.73	0.93	1.16	2.79	0.59	1.36	0.53	1.36	1.05
Al ₂ O ₃	14.5	15.8	16.2	18.1	16.7	14.9	18.8	14.9	14.3
Fe ₂ O ₃ ^{total}	8.28	8.14	9.35	10.7	5.19	10.4	2.85	10.4	7.34
MnO	0.09	0.08	0.09	0.14	0.04	0.14	0.03	0.14	0.07
MgO	2.54	2.26	2.54	3.65	1.42	2.90	0.93	2.90	2.18
CaO	3.74	3.50	3.74	6.24	3.38	4.69	4.75	4.69	3.75
Na ₂ O	3.06	2.78	3.06	3.20	3.13	2.57	5.15	2.57	2.60
K ₂ O	2.75	3.04	2.75	1.65	3.16	1.96	1.34	1.96	2.45
P ₂ O ₅	0.08	0.12	0.08	0.12	0.20	0.17	0.07	0.17	0.29
Total	99.57	99.95	99.97	100.09	100.01	98.69	99.05	98.69	99.23
La	18.2	87.1	9.72	67.4	34.9	67.6	54.1	44.1	39.9
Ce	36.8	174.9	180.1	125.1	73.1	126.1	102.5	87.8	79.9
Nd	15.4	70.8	71.4	50.1	31.1	52.7	42.0	40.5	40.0
Sm	3.30	12.1	11.2	7.66	5.76	8.47	7.23	8.31	8.35
Eu	0.90	2.32	2.10	1.45	1.41	1.79	1.92	1.57	1.75
Gd	3.14	9.74	8.11	5.34	4.93	7.78	6.54	8.76	8.29
Tb	—	—	—	—	—	1.04	0.86	1.42	1.01
Dy	2.56	7.87	5.01	3.48	4.14	6.42	4.93	9.41	6.70
Ho	—	—	—	—	—	1.24	0.81	1.89	1.27
Er	1.27	4.30	2.84	1.86	1.99	3.71	2.06	5.99	3.56
Tm	—	—	—	—	—	0.53	0.22	0.91	0.48
Yb	1.15	3.76	2.40	1.66	1.46	3.61	1.33	5.73	3.35
Lu	0.17	0.56	0.35	0.25	0.21	0.56	0.16	0.84	0.52
(La/Yb) _N ¹⁾	10.4	15.2	26.6	26.7	15.7	12.3	26.8	5.07	7.85
Eu* ²⁾	0.85	0.64	0.65	0.61	0.80	0.67	0.84	0.56	0.64

¹⁾The REE abundance in the Leedey chondrite (Masuda *et al.*, 1973; Masuda, 1975) are employed as the normalizing values.

²⁾Eu* is defined as the ratio of observed Eu abundance to that which would fall on Sm-Nd join in chondrite-normalized REE patterns.

K-11, K-13, 4-58a, 4-59 and 3303 were analyzed by IDMS, and 96-5-2, 96-9-1, 96-9-2 and 96-10-2 were analyzed by ICP-MS.

(KBSI), Korea. The isotopic composition of Ce was measured with a VG54-38 double focusing mass spectrometer at University of Tokyo. The measured isotopic ratio of Ce was normalized against $^{136}\text{Ce}/^{142}\text{Ce} = 0.01688$. The $^{138}\text{Ce}/^{142}\text{Ce}$ ratio of Johnson Matthey CeO_2 (JMC304) was 0.0225799 ± 0.0000018 ($2\sigma_m$) on 42 measurements. Nd isotopic ratios were measured at two laboratories, one on a VG 354 mass spectrometer at the University of Tokyo and the other on a VG 54-30 mass spectrometer at the Korea Basic Science Institute (KBSI). The experimental procedures for each mass spectrometer were those described by Lee *et al.* (1992), and Cheong and

Chang (1997), respectively. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratios for the La Jolla Nd standard are 0.511826 ± 0.000003 ($2\sigma_m$) on 10 measurements at VG 354, and 0.511849 ± 0.000004 ($2\sigma_m$) on 16 measurements at VG 54-30 mass spectrometer.

RESULTS

Major element and REE geochemistry

Major element compositions and REE abundance for the Sobaegsan samples are presented in Table 1. The results are plotted on the An-Ab-Or diagram (Fig. 3, O'Connor, 1965). The chemical compositions of the biotite gneiss and the granitic

Table 1(b). Major element compositions (%) and rare earth element, Sr, Rb and Ba abundances (ppm) for granitic gneiss from the Sobaegsan Massif, Korea

	96-10-1	96-13-1	4-82	4-106	4-143	K-10
SiO_2	65.8	69.2	65.1	58.7	70.7	70.5
TiO_2	0.48	0.42	0.88	1.18	0.33	0.34
Al_2O_3	17.7	16.0	16.3	21.6	16.3	16.2
$\text{Fe}_2\text{O}_3^{\text{total}}$	3.05	2.39	3.80	3.81	2.11	2.26
MnO	0.03	0.03	0.03	0.03	0.03	0.03
MgO	0.86	0.64	1.33	1.55	0.50	0.56
CaO	4.14	2.86	3.76	5.97	2.95	2.92
Na_2O	4.42	3.79	4.24	4.87	3.71	4.00
K_2O	2.34	3.51	1.83	1.97	3.30	3.10
P_2O_5	0.14	0.12	0.19	0.31	0.10	0.09
Total	98.96	98.96	97.46	99.94	100.02	100.0
La	51.8	36.1	54.9	18.3	67.7	46.3
Ce	91.3	64.7	100.3	35.1	119.6	83.7
Pr	9.53	7.18	—	—	—	—
Nd	31.5	24.9	31.0	15.0	40.0	26.5
Sm	4.16	3.95	4.09	2.40	5.40	3.64
Eu	1.23	1.09	1.09	1.76	3.18	1.03
Gd	2.85	3.25	2.44	1.77	1.41	2.20
Tb	0.26	0.36	—	—	—	—
Dy	1.48	1.98	1.34	1.03	1.18	1.23
Ho	0.20	0.30	—	—	—	—
Er	0.69	0.94	0.74	0.48	0.40	0.55
Tm	—	0.69	—	—	—	—
Yb	0.60	0.05	0.64	0.39	0.25	0.40
Lu	—	—	0.095	0.056	0.037	0.053
$(\text{La}/\text{Yb})_N^{1)}$	56.9	44.0	56.4	31.0	179	76.2
$\text{Eu}^{*2)}$	1.04	0.92	0.98	2.04	2.80	1.04

¹⁾The REE abundances in the Leedey chondrite (Masuda *et al.*, 1973; Masuda, 1975) are employed as the normalizing values.

²⁾ Eu^* is defined as the ratio of observed Eu abundance to that which would fall on Sm-Nd join in chondrite-normalized REE patterns.

4-82, 4-106, 4-143 and K-10 were analyzed by IDMS, and 96-10-1 and 96-13-1 were analyzed by ICP-MS.

Fig. 3. Plot of normative feldspars showing classification of acidic rocks after O'Connor (1965).

gneiss correspond to granodiorite and tonalite, respectively. Compared to the biotite gneiss, the granitic gneiss shows higher SiO_2 , Na_2O content and lower total Fe_2O_3 , MgO . Chondrite-normalized REE patterns (Masuda *et al.*, 1973) are shown in Figs. 4(a) (b) and (c). Although all of the Sobaegsan samples show light-REE enriched patterns, there are differences between the biotite gneiss and the granitic gneiss. The granitic gneiss has more fractionated patterns with $(\text{La}/\text{Yb})_N$ ratios between 30 and 180, and distinctly positive Eu or no anomalies (Figs. 4(a) and (b)), whereas the biotite gneiss has less fractionated patterns with $(\text{La}/\text{Yb})_N$ ratios between 10 and 16, and negative Eu anomalies (Fig. 4(c)). The REE pattern of which is composed two rectilinear lines with no Eu anomaly is also observed for the granitic gneiss (Fig. 4(a)).

Isotopic data for Sm-Nd and La-Ce

Sm-Nd isotopic compositions are given in Table 2. $^{143}\text{Nd}/^{144}\text{Nd}$ values of the biotite gneiss are 0.511274 to 0.511621, while those of granitic gneiss are 0.511803 to 0.512053. The depleted mantle model ages (T_{DM}) of the two gneisses are also distinctly different from each other. T_{DM} ages of the biotite gneiss are 2.33 Ga to 3.97 Ga and show more or less scatter; the Nd model ages of

Fig. 4. Chondrite-normalized REE pattern of granitic gneisses ((a) and (b)) and biotite gneisses (c) from Sobaegsan Massif, south Korea (solid symbol: IDMS, open symbol: ICP-MS). The REE abundances in the Leedeey chondrite (Masuda *et al.*, 1973; Masuda, 1975) are employed as the normalizing values.

Table 2. Sm-Nd and La-Ce isotopic data for orthogneisses from the Sobaegsan Massif, Korea

	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}^*$	$\varepsilon_{\text{Nd}}(0)$	T_{DM} (Ga)	$^{138}\text{La}/^{142}\text{Ce}$	$^{138}\text{Ce}/^{142}\text{Ce}^*$	$\varepsilon_{\text{Ce}}(0)$	$\varepsilon_{\text{Ce}}(T)$
Biotite gneisses								
K-11 ¹⁾	0.1299	0.511537 ± 9	-21.5 ± 0.2	2.92	0.00405	0.0225782 ± 16	+2.7 ± 0.7	+1.3 ± 0.7
K-13 ¹⁾	0.1035	0.511363 ± 9	-24.9 ± 0.2	2.46	0.00405	0.0225783 ± 20	+2.7 ± 0.9	+1.3 ± 0.9
4-58 ¹⁾	0.0948	0.511304 ± 8	-26.0 ± 0.2	2.36	0.00441	0.0225730 ± 14	+0.3 ± 0.7	-1.5 ± 0.7
4-59 ¹⁾	0.0915	0.511274 ± 8	-26.6 ± 0.2	2.33	0.00440	0.0225821 ± 12	+4.4 ± 0.5	+2.5 ± 0.5
3303 ¹⁾	0.1119	0.511411 ± 8	-23.9 ± 0.2	2.59	0.00390	0.0225773 ± 14	+4.9 ± 0.6	+1.1 ± 0.6
96-5-2 ²⁾	0.1028	0.511415 ± 8	-23.9 ± 0.2	2.37				
96-9-1 ²⁾	0.1086	0.511497 ± 6	-22.3 ± 0.1	2.39				
96-9-2 ²⁾	0.1253	0.511456 ± 6	-23.0 ± 0.1	2.90				
96-10-2 ²⁾	0.1555	0.511621 ± 8	-19.1 ± 0.2	3.97				
Granitic gneisses								
K-10 ¹⁾	0.0829	0.511872 ± 7	-14.9 ± 0.1	1.49	0.00452	0.0225748 ± 14	+1.2 ± 0.6	-1.6 ± 0.6
4-82 ¹⁾	0.0796	0.511803 ± 8	-16.3 ± 0.2	1.53	0.00447	0.0225733 ± 14	+0.5 ± 0.8	-2.2 ± 0.8
4-106 ¹⁾	0.0963	0.511995 ± 10	-12.5 ± 0.2	1.50	0.00426	0.0225800 ± 13	+3.5 ± 0.6	+1.2 ± 0.6
4-143 ¹⁾	0.0817	0.511896 ± 9	-14.5 ± 0.2	1.45	0.00463	0.0225784 ± 30	+2.7 ± 1.3	-0.2 ± 1.3
96-10-1 ²⁾	0.0763	0.511859 ± 8	-15.2 ± 0.2	1.43				
96-13-1 ²⁾	0.0972	0.512053 ± 8	-11.4 ± 0.2	1.43				

Errors are $2\sigma_m$ and correspond to the last significant figures. Ce and Nd isotopic ratios listed here corrected values relative to $^{138}\text{Ce}/^{142}\text{Ce} = 0.0225762$ for JMC304 standard (Makishima et al., 1987) and $^{143}\text{Nd}/^{144}\text{Nd} = 0.511858$ for La Jolla Nd standard (Lugmair et al., 1983).

¹⁾The Nd isotope data were already reported from Lee et al. (1992).

²⁾New data of this study.

$T_{\text{DM}} = 1/\lambda \times \ln\{1 + [(^{143}\text{Nd}/^{144}\text{Nd})_{\text{sample}} - 0.51315]/[(^{147}\text{Sm}/^{144}\text{Nd})_{\text{sample}} - 0.2137]\}$, $\lambda_{\text{Sm}} = 6.54 \times 10^{-12}$.

$\varepsilon(T) = [R_m(T)/R_{\text{CHUR}}(T) - 1] \times 10^4$, where $R_m(T)$ and $R_{\text{CHUR}}(T)$ refer to the isotopic ratios of $^{143}\text{Nd}/^{144}\text{Nd}$ or $^{138}\text{Ce}/^{142}\text{Ce}$ for a sample (m) and CHUR.

$(^{138}\text{Ce}/^{142}\text{Ce})_{\text{CHUR}}(0) = 0.0225722$ and $(^{138}\text{La}/^{142}\text{Ce})_{\text{CHUR}}(0) = 0.003089$ (Shimizu et al., 1984, 1988).

$(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}}(0) = 0.512638$ and $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{CHUR}}(0) = 0.1966$ (Wasserburg et al., 1981).

up to 3.97 Ga (sample 96-10-2) provide evidence of older reworked crustal material in Korean Peninsula. But T_{DM} ages of the granitic gneiss, 1.43 Ga to 1.53 Ga, show a much narrow range. Such a difference in Nd model age from two gneisses strongly suggests the possibility that they had originated from different source, respectively.

Lee et al. (1992) reported ca. 1.70 Ga and 1.05 Ga of Sm-Nd error-chron ages for four granitic gneisses and three biotite gneisses, respectively. In this paper, we recalculated them with addition of new Nd isotopic data to previous samples (Table 2: 96-5-2, 96-9-1, 96-9-2, 96-10-2 for biotite gneiss; 96-5-1, 96-10-1, 96-13-1). Isotopic data were fitted to isochrons following the regression method of York (1969). As a result, we obtained ages of 819 ± 114 Ma (2σ) with $\varepsilon_{\text{Nd}} = -15.3$ for the biotite gneiss, and 1484 ± 810 Ma (2σ) with $\varepsilon_{\text{Nd}} = +7$ for the granitic gneiss (Fig. 5). Even though the Sm-Nd isochron age of 1.48 Ga from

the granitic gneiss has the large error range of ± 0.8 Ga, it corresponds well with T_{DM} ages in Table 2.

La-Ce isotopic data are also given in Table 2. $\varepsilon_{\text{Ce}}(0)$ values for the biotite gneiss show ranges from +0.3 to +4.9, while those of the granitic gneiss show ranges of -2.7 to +3.5. $\varepsilon_{\text{Ce}}(T)$ were also calculated based on Sm-Nd isochron ages. $\varepsilon_{\text{Ce}}(0.82 \text{ Ga})$ values of the biotite gneiss are range of -1.5 to +2.5, while $\varepsilon_{\text{Ce}}(1.48 \text{ Ga})$ values of the granitic gneiss are range of -2.2 to +1.2.

DISCUSSIONS

Major and REE geochemistry

Even though the major element composition of biotite gneiss and granitic gneiss falls in the same compositional fields of granodiorite and tonalite, they divide into two distinct groups on the An-Ab-Or diagram (Fig. 3). Especially, the granitic gneiss shows a characteristic of Na-rich

Fig. 5. $^{143}\text{Nd}/^{144}\text{Nd}$ - $^{147}\text{Sm}/^{144}\text{Nd}$ plot for the biotite gneisses and granitic gneisses (note: the triangles in biotite gneisses are not included into isochron following the regression method of York (1969)).

granite. The difference between the granitic gneiss and the biotite gneiss can also be observed from chondrite-normalized REE pattern diagram (Fig. 4). As shown in Figs. 4(a) and (b), the granitic gneiss shows REE patterns with positive and/or no Eu anomalies, LREE-enriched and HREE-depleted. Such REE patterns of the granitic gneiss are similar to those of typical Archean tonalite and trondhjemitic, and Na-granodiorite derived from a primitive source (Taylor and McLennan, 1995). In contrast, the biotite gneiss is characterized by nearly uniform REE patterns with LREE-enriched and negative Eu anomalies, which are similar to those of post-Archean shale (Taylor and McLennan, 1985). In geology section of this paper, we said that it is difficult to distinguish the relationship between the granitic gneiss and the biotite gneiss in the area studied. In Fig. 4(c), we compared the REE pattern of granitic gneiss (dashed line), which is average value, to those of biotite gneiss. They are different from Eu anomaly, HREE abundance and gradient. Since REEs are highly insoluble and immobile, it is well known that the pattern of REEs often remain unchanged during metamorphism in most cases. It is diffi-

cult to think that that such a difference had been made from magmatism or metamorphism simply. Therefore, the sharp difference in the REE pattern between the granitic gneiss and the biotite gneiss can be also understood to reveal that these gneisses should have originated from different source materials.

Model ages and initial isotopic ratios and sources

The Sm-Nd system is ideal for investigating an evolution history of chemical reservoirs within the earth such as a net enrichment of Nd in the crust and a complementary depletion in the mantle because it reflects the history of the generation and destruction of continental crust (DePaolo, 1988; Jacobsen, 1988; Bowring and Housh, 1995). In general, the Nd model age such as T_{DM} suggests an upper limit for the formation age of the respective crustal segments although it generally cannot be assigned to geologic processes (Arndt and Goldstein, 1987). As stated in the result section, depleted mantle model ages (Table 2) between 1.43 and 1.53 Ga from Sobaegsan granitic gneiss shows good correspondence with the 1.48 ± 0.81 Ga Sm-Nd isochron age. And the de-

pleted mantle model ages of biotite gneiss are included into the ranges of 2.33 Ga to 3.97 Ga (Table 2), and much older than 0.82 Ga of the Sm-Nd systematic age (Fig. 5). The wide range of model ages from biotite gneiss may be due to the complex history of its formation process. The 0.82 Ga of Sm-Nd systematic age for biotite gneiss suggests that Nd isotopic system was significantly reset during the high-grade metamorphism. The relatively large chronological uncertainties concerned are also considered as attributing to partial re-equilibration during the high-grade metamorphism. Furthermore, the 1.48 ± 0.81 Ga Sm-Nd isochron age of the granitic gneiss possibly represents the crustal formation age of a magmatic suite that was extracted from a highly depleted mantle source.

Radiogenic isotope systematics involving REE have made major contributions to understanding of crustal evolution processes (DePaolo, 1988; Lipin and McKay, 1989). It is well known that $\epsilon_{Nd}(T)$ value depends on the product of time and the magnitude of Sm/Nd chemical fractionation parameters against CHUR. The recalculated ages and initial ϵ_{Nd} values for the Sobaegsan samples are plotted in Fig. 6. The points for $\epsilon_{Nd}(T)$ values of Chinese Precambrian rocks (solid circles: Jahn and Zhang, 1984; Xuan *et al.*, 1986; Jahn *et al.*, 1987, 1988; Jahn and Ernst, 1990; Li *et al.*, 1990; Wang *et al.*, 1990; Sun *et al.*, 1992, 1993; Hu *et al.*, 1991; Rämö *et al.*, 1995; Bai and Dai, 1996) with that (open circle) for Kamiasso gneiss clasts from Japan (Shimizu *et al.*, 1996) are also shown in Fig. 6. In the ϵ_{Nd} evolution diagram, a ϵ_{Nd} line is traced back in time from ϵ_{Nd} (0.82 Ga) point for the Sobaegsan biotite gneisses (S1), employing the observed $^{147}\text{Sm}/^{144}\text{Nd}$ values of 0.09–0.15 for these samples (line A) up to the $\epsilon_{Nd} = ca. +6$ with 2.6 Ga. Figure 6 also shows that the Nd evolution line for the Sobaegsan biotite gneiss, Chinese and Kamiasso gneisses intersect the Nd evolution lines for depleted-mantle (DM), around 2.6 Ga at the late Archean or early Proterozoic. This suggests that the source of biotite gneiss had been derived from depleted mantle at the late Archean and early Proterozoic. Our data suggests strongly

Fig. 6. ϵ_{Nd} vs. age diagram showing Nd isotopic composition of biotite gneiss (S1) and granitic gneiss (S2), orthogneiss and amphibolites of north-China Craton, Japan. Depleted-mantle line are drawn with $\epsilon_{Nd}(0) = +9$ to 11 and $\epsilon_{Nd}(4.56 \text{ Ga}) = 0$. The $\epsilon_{Nd}(0)$ values are typical of MORB (Hawkesworth and van Calsteren, 1984; Liew and McCulloch, 1985). CHUR = chondritic uniform reservoir. Solid circles (CHs) are data of Chinese samples rocks (Jahn and Zhang, 1984; Xuan *et al.*, 1986; Jahn *et al.*, 1987, 1988; Jahn and Ernst, 1990; Li *et al.*, 1990; Wang *et al.*, 1990; Sun *et al.*, 1992, 1993; Hu *et al.*, 1991; Rämö *et al.*, 1995; Bai and Dai, 1996). The point of Japanese sample (open circle) is from Shimizu *et al.* (1996).

that the source of the basement for the Sobaegsan Massif presumably had a close relationship with that of Kamiasso, central Japan in its formation history.

Even though the Sm-Nd age of granitic gneiss is more or less uncertain, the high positive ϵ_{Nd} value indicates that the source for granitic gneiss (S2) was derived from highly depleted mantle material with little or no contamination from old crustal material (e.g., biotite gneisses S1 in the same area). The high initial ϵ_{Nd} value (+7 at 1.48 Ga) of granitic gneiss appears to fall on the DM line, whereas granitoid rocks reported until now (Allègre and Ben Othman, 1980; Hamilton *et al.*, 1980; Taylor and McLennan, 1985) fall below

CHUR line. Xuan *et al.* (1986) suggested that the geochemistry of the early Archean mantle in east Asia may have been similar to that of the modern upper mantle with severe depletion in respect to magmaphile elements. Our results, along with those obtained by Jahn and Ernst (1990), also support their argument. Sivell and McCulloch (1991) reported that Hart Range meta-igneous complex of central Australia was derived from a highly depleted mantle source with initial Nd isotope ratios of +6.9 to +8.2 at 1.8 Ga. The obtained high initial ϵ_{Nd} value for the Sobaegsan granitic gneisses ($\epsilon_{\text{Nd}} = +7$ at 1.48 Ga) is essentially comparable to that of the Hart Range meta-igneous complex and reflects the presence of mantle source having a similar chemical characteristic beneath Korean Peninsula. Pearce (1996) suggested that granites from ocean ridges or volcanic arcs usually have characteristics that indicate depleted mantle sources. Such a fact indicates that the global tectonic environment that formed source magma of granitic gneiss in Korean Peninsula at 1.48 Ga ago might be like ocean ridge or volcanic arc.

Ce-Nd systematics and its implications

Because both La and Ce belong to the rare earth element group, as is the case for the Sm-Nd system, the combined application of both systems is a promising tool for isotope geochemistry. Tanaka and Masuda (1982) applied the ^{138}La - ^{138}Ce geochronometer to the Bushveld gabbro. Since then, the La-Ce system coupled with Sm-Nd system offers us an efficient tool to argue about LREE evolution (Tanaka *et al.*, 1987; Shimizu *et al.*, 1984, 1988, 1990a, 1990b, 1996). In order to compare the Sm-Nd and La-Ce isotope systematics for biotite and granitic gneisses, the data are shown in a $\epsilon_{\text{Ce}}-\epsilon_{\text{Nd}}$ diagram (Fig. 7). In Fig. 7, open symbols mean the present value of ϵ_{Ce} and ϵ_{Nd} , while solid symbols refer to the initial values of them. Even though the ages of Sm-Nd systematic from two gneisses show the relatively large uncertainty, in order to calculate the initial value of ϵ_{Ce} , we applied to 1.48 Ga and 0.82 Ga for granitic gneiss and biotite gneiss, respectively. As a result, the

Fig. 7. $\epsilon_{\text{Ce}}-\epsilon_{\text{Nd}}$ diagram of the present isotopic compositions ($\epsilon(0)$, open symbols) and initial isotopic compositions ($\epsilon(T)$, solid symbol) at 0.82 Ga (biotite gneisses, circle), 1.48 Ga (granitic gneisses, rectangle), respectively. A broken lines is drawn for old crustal rocks and indicates $\epsilon_{\text{Ce}} = -0.112\epsilon_{\text{Nd}}$ (Tanaka *et al.*, 1987).

$\epsilon_{\text{Ce}}-\epsilon_{\text{Nd}}$ diagram shows that the present isotopic data for biotite gneiss mainly fall on a line for typical crustal rocks, that is “crustal array”, as defined by Tanaka *et al.* (1987), and that the corresponding data for granitic gneiss generally appear rather scattered. In addition, initial ϵ_{Ce} (0.82 Ga) and initial ϵ_{Nd} (0.82 Ga) values for the biotite gneiss are in +1.1 to 2.5 and –11.3 to –11.8 respectively, except one (4-58a) falling also on the crustal array. The ϵ_{Ce} (0.82 Ga) and ϵ_{Nd} (0.82 Ga) data for biotite gneiss support continental-like light-REE enriched characteristics for their sources. The ϵ_{Ce} and ϵ_{Nd} values calculated for the reference age (1.48 Ga) of the granitic gneiss range from –2.2 to +1.2 and from +7.0 to +8.4, respectively, suggesting chiefly light-REE depleted nature mainly for the source of the granitic gneisses. The points for the present and initial values of Ce isotopes from granitic gneisses show severe scattered dis-

persion, which suggest also their origin different from Tanaka's old crustal array (1987). This $\epsilon_{\text{Ce}}-\epsilon_{\text{Nd}}$ diagram shows the clear difference in origin and formation history between biotite gneisses and granitic gneisses of Sobaegsan Massif, Korea. Further study may be necessary to achieve deeper interpretation of the relationship between ϵ_{Ce} and ϵ_{Nd} for reference ages of the granitic gneiss.

CONCLUSION

In conclusion, although the Sm-Nd ages obtained for the granitoid gneiss shows large uncertainties, Nd, Ce isotopic data clearly suggest the different sources between two types of the Sobaegsan gneisses. The Ce-Nd isotopic results obtained here indicate that the Sobaegsan biotite gneiss originated from continental-like sources having light-REE enriched features, while the Sobaegsan granitic gneiss was from MORB-like sources having light-REE-depleted characters. In addition, comparison of the initial ϵ_{Nd} value of the Sobaegsan biotite gneiss at 0.82 Ga with those of the Chinese and Japanese Precambrian rocks implies that source for the Sobaegsan biotite gneiss has commonly light-REE enriched pattern, e.g., $^{147}\text{Sm}/^{144}\text{Nd}$ ratio ranging from 0.09–0.13. Furthermore, it is suggested that these sources having light-REE enriched patterns could be traced back to depleted mantle at the late Archean. Especially, the highly positive initial Nd value for granitic gneiss corresponds to the extension of the mantle in the Sino-Korean Craton. Such two phenomena suggest strongly that the source for the basement of Sobaegsan Massif, Korea, had close relationship with the Sino-Korean Craton rather than South China Craton.

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