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Geochemistry and provenance of Lower Cretaceous Sindong and Hayang mudrocks, Gyeongsang Basin, Southeastern Korea

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ABSTRACT: Lower Cretaceous Sindong and Hayang mudrocks in the Gyeongsang Basin, Korea, have been analyzed for major and trace elements, including the rare earth elements (REEs). The Sindong mudrocks are relatively enriched in most large-ion lithophile (LIL) elements such as K_2O, Rb, Ba, Zr, Th and LREE than the Hayang mudrocks, and they are more depleted in Fe_2O_3(total), MgO, MnO, CaO, Na_2O, Sr, Cu, Zn and Mo compared with the Hayang mudrocks. The REE distribution patterns indicate that the Sindong and Hayang mudrocks are largely derived from upper continental source rocks. The differences in chemistry between the two groups mainly reflect the occurrence of intermediate to silicic volcanics in the source area during the deposition of the Hayang Group.

Key words: Sindong, Hayang, mudrock, provenance, chemistry, Gyeongsang Basin

1. INTRODUCTION

Gyeongsang Basin, the largest Cretaceous non-marine sedimentary basin in Korea, is located in the southeastern part of Korea (Fig. 1). Cretaceous rocks in the Gyeongsang Basin are divided into four groups based on presence of volcanism and plutonism: the Sindong Group, the Hayang Group, the Yucheon Group and intrusive rocks with decreasing age (Chang, 1975). The Sindong and Hayang groups are composed of sandstone, mudrock, minor amounts of conglomerate and marl deposited in a nonmarine environment. In the Hayang Group minor amounts of extrusive rocks are intercalated. After the deposition of the Hayang Group, active volcanism dominated in and around the basin and formed the Yucheon Group that consists dominantly of volcanic rocks with subordinate volcaniclastic rocks. Upper Cretaceous to Lower Tertiary granitic rocks, which are interpreted to be co-magmatic with the Yucheon volcanic rocks (Lee et al., 1987), intruded all of the previous sequence.

In a sedimentary provenance study, geochemistry of sedimentary rocks is especially useful when framework compositions of sandstones and mudrocks are modified or obscured during diagenesis or metamorphism (Maynard et al., 1982; Bhatia and Crook, 1986; McLennan et al., 1993). Chemical composition of sedimentary rocks is controlled by many factors, and among them chemical composition of source rocks, which is related to tectonic setting, is considered as the major control (McLennan et al., 1993; Fralick and Kronberg, 1997). Although several studies have been conducted about the provenance of Sindong (Choi, 1986; Koh, 1986) and Hayang (Lee and Lee, 2000) sediments, the geochemistry of the sedimentary rocks in the Gyeongsang Basin has not been applied for sedimentary provenance. Recently, the major element characteristics of the lower Hayang Group near the Daegu area has been reported by Shin et al. (2001), but additional major element data from other parts of the basin as well as trace element data are necessary to understand the geochemistry of sedimentary rocks in the Gyeongsang Basin more thoroughly.

In this study, we have investigated major and trace element chemistry of the Sindong and Hayang mudrocks and discussed its implications on the sedimentary provenance and tectonic settings of the Gyeongsang Basin. Samples have been taken from the areas covering most of the Uiseong and Miryang subbasins for a basin-scale analysis (Fig. 1). Mudrocks have been chosen for the analysis because they are more suitable for a sedimentary provenance study than sandstones due to their more homogeneous elemental distribution (Cullers, 1995).

2. METHODS

Thirty Sindong and Hayang mudrock samples were analyzed for major, trace and rare earth elements (REEs). SiO_2, Al_2O_3, Fe_2O_3(total), TiO_2, MnO, CaO, MgO, K_2O, Na_2O and P_2O_5 were analyzed by an X-ray fluorescence spectrometer (XRF) Phillips PW1480 at the Korea Basic Science Institute (KBSI). Sc, Cr, Co, Ni, Cu, Zn, Ga, Rb, Sr, Zr, Nb, Mo, Cd, Cs, Ba, Hf, Ta, Pb, Th, U and REEs were analyzed by an inductively coupled plasma mass spectrometer (ICP–MS) PQ II Plus at KBSI. Analytical precision for the trace elements as well as the REEs is generally better than 5%.

To see the distribution of major and trace elements among the mineral fractions in mudrocks, ten samples were selected and subjected to the selective chemical leaching process following the method of Tessier et al. (1979). The selective sequential chemical leaching and chemical analyses are for detection of the abundance of elements in different components fractions: exchangeable fraction, fraction bound to

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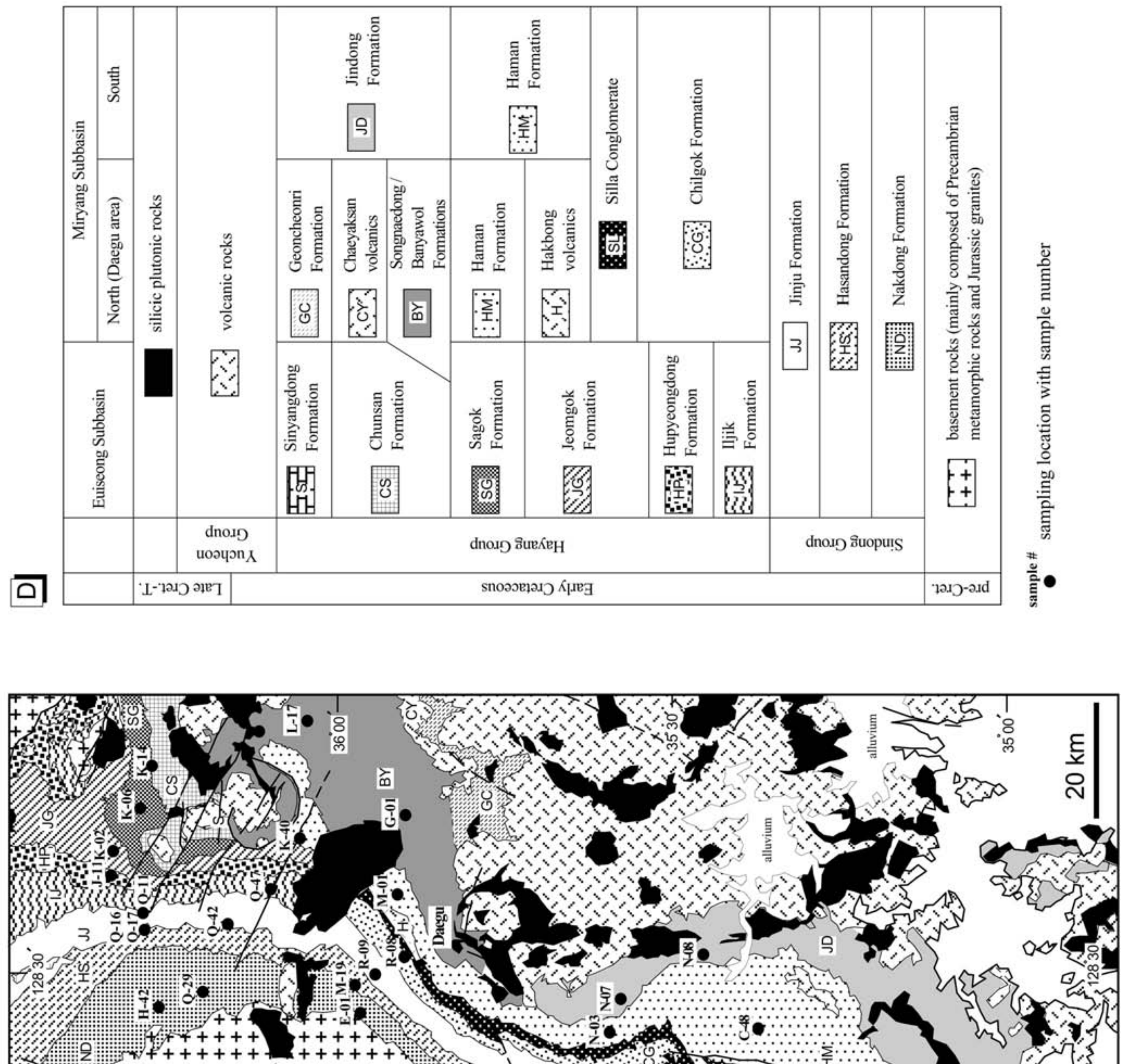

Fig. 1. (**A**) Location of the Gyeongsang Basin. (**B**) Subbasins of the Gyeongsang Basin and study area. (**C**) Geological map of the study area and sample locality. (**D**) Stratigraphy of the study area (modified after Chang, 1987, 1988).

carbonates, fraction bound to organic matter and sulfides, and residue which is mainly composed of silicate mineral fraction. The concentrations of Al_2O_3, Fe_2O_3(total), TiO_2, MnO, CaO, MgO, K_2O, Na_2O, Zn, Sr and Ba were analyzed by an inductively coupled plasma atomic emission spectrometer (ICP–AES) SEIKO I SPS-1200 at Geological Survey of Japan. ICP–AES analyses were performed on bulk samples and separated fractions. Bulk samples and residues after extracting each fraction were checked with an X–ray diffractometer to detect changes in mineralogy. Concentrations of K_2O and Na_2O were measured for bulk samples and silicate fractions only.

3. RESULTS

3.1. Major Elements

Concentrations of major elements of Sindong and Hayang mudrocks are shown in Table 1. SiO_2, Al_2O_3 and K_2O are more abundant in the Sindong mudrocks than in the Hayang mudrocks, whereas in the Hayang mudrocks Fe_2O_3, MgO, MnO, CaO and Na_2O are more abundant. Compared with North American shale composite (NASC) (Gromet et al., 1984), Sindong mudrocks are enriched in Al_2O_3, CaO and K_2O, and Hayang mudrocks are enriched in Fe_2O_3(total), CaO, MgO and Na_2O (Table 1).

Abundance of major elements is intimately related to mineralogy of the mudrocks. Figure 2 shows the abundance of some major elements compared with that of Al_2O_3. More abundant MgO content in the Hayang mudrocks than in the Sindong mudrocks seems to be related with abundant chlorite in the Hayang mudrocks. Na_2O is more abundant in the Hayang Group than Sindong Group, which is consistent with abundance of albitized plagioclases in the Hayang mudrocks (Lee and Lee, 1998). Contents of Fe_2O_3, MgO, CaO* (CaO associated with silicate fraction) and Na_2O are poorly correlated with that of Al_2O_3, suggesting that mineral phases bearing these elements, such as chlorite and plagioclase, are not dominant controls on Al_2O_3 content in the Sindong and Hayang mudrocks.

Mudrock samples of the Nakdong Formation show especially high Al_2O_3 and K_2O contents but lower Fe_2O_3, CaO* and NaO contents than the samples from the upper stratigraphic sequence (Fig. 2). In the Al_2O_3 versus K_2O plot, the Nakdong samples plot close to the illite line, suggesting that major K_2O- and Al_2O_3-bearing minerals in the samples are illite (Fig. 2). The concentrations of Al_2O_3 and K_2O in some Nakdong mudrocks are especially high, implying that illite is the dominant aluminosilicate in the samples. This interpretation is supported by the low K_2O/Al_2O_3 ratios (<0.29). This high amount of Al_2O_3 and illite in the mudrocks suggests that they may be finer-grained than the other mudrock samples. Although grain size can play an important role in controlling the composition of sediments, the lower concentrations of Fe_2O_3, CaO*, and Na_2O in the Nakdong mudrocks compared with those in the mudrocks of the upper sedimentary sequence of similar Al_2O_3 content implies that other factors such as source rocks or weathering are the major control of the compositional differences.

For a provenance study using major element chemistry, concentration of CaO has to be modified because CaO in sedimentary rocks are commonly bound to carbonate minerals that are mostly authigenic in origin. CaO contents of the Sindong and Hayang mudrocks are higher than NASC (Gromet et al., 1984; Table 1). Relationship between CaO and loss-on-ignition (LOI) shows that CaO is roughly correlated with LOI ($r=+0.85$), and the correlation is even stronger in the samples with high content of CaO and LOI (Fig. 3). It implies that the abundance of CaO content in the mudrocks probably reflects the abundance of carbonate minerals. The shift of the trend toward higher LOI indicates the presence of other volatile materials (Fig. 3). Concentrations of major elements in carbonate, Fe–Mn oxide, sulfide and silicate fractions are shown in Table 2. On average, about 84% of CaO is bound to the carbonate fraction if we only consider the analyses of better than 10% error. To prevent the effect of additional CaO on the provenance analysis, abundance of major elements of the Sindong and Hayang mudrocks have been recalculated to free of LOI and also free of CaO in carbonate fraction. Much of MnO is also bound to the non-silicate fractions (Table 2). Concentrations of MnO in carbonate, Fe–Mn oxide and silicate fractions are 40.2, 18.6 and 39.5%, respectively. However, the total amount of MnO is less than 0.1% in general, so effect on the provenance analysis is minimal. Other major elements are generally concentrated in the silicate fraction (Table 2). Result of this study suggests that content of major oxides in mudrocks can be used in a provenance analysis without much modification except the amount of CaO in the carbonate fraction.

3.2. Trace and Rare Earth Elements

Concentrations of trace and rare earth elements of the Sindong and Hayang mudrocks are shown in Table 1. Compared with NASC (Gromet et al., 1984), Sindong mudrocks have higher concentrations of Rb, Sr, Cs, Ba and light rare earth element (LREE), and have lower concentrations of Cr, Co, Ni, Zr, Hf, Ta and heavy rare earth element (HREE) (Table 1).

Large-ion lithophile elements (LIL) such as K, Rb, Ba, Zr, Th, LREE are generally enriched in the Sindong mudrocks. High concentration of Rb and Ba in the Sindong Group is tied to the abundant K_2O. Among LIL, Sr is the only element that is richer in the Hayang Group. Sr generally substitutes Ca in carbonate and silicate minerals, so abundant plagioclase (Lee and Lee, 2000) and carbonate minerals in the Hayang mudrocks may be responsible for abundant Sr

Table 1. Concentrations of major elements (in wt%) and trace element (in ppm) for the mudrocks of the Sindong and Hayang groups.

Fm.	Nakdong					Hasandong				
sample	D-50	E-01	H-42	I-03	Q-29	D-42	M-19	N-32	Q-16	Q-17
SiO_2	49.38	68.78	60.02	59.94	50.38	49.87	65.73	54.98	58.60	58.64
Al_2O_3	14.42	16.52	21.44	19.57	24.65	16.56	15.58	15.11	15.04	15.52
Fe_2O_3	5.72	2.88	2.41	4.73	4.47	6.38	5.19	7.08	5.03	5.82
TiO_2	0.56	0.69	1.01	0.92	1.27	0.66	0.86	0.69	0.67	0.71
MnO	0.05	0.00	0.00	0.01	0.02	0.05	0.01	0.04	0.09	0.06
CaO	7.62	0.16	0.37	0.93	0.65	7.21	0.69	6.94	5.86	5.93
MgO	3.56	0.72	1.71	3.12	3.32	3.88	2.57	1.46	3.19	2.13
K_2O	4.01	4.47	6.25	5.22	7.17	4.46	3.68	4.64	3.51	3.97
Na_2O	0.27	0.65	0.49	0.24	0.37	0.00	0.66	0.16	1.18	1.45
P_2O_5	0.60	0.06	0.22	0.19	0.27	0.19	0.21	0.13	0.22	0.16
LOI	13.86	4.57	5.62	4.81	6.96	10.37	4.50	8.76	6.32	5.18
sum	100.05	99.50	99.54	99.68	99.53	99.63	99.68	99.99	99.71	99.57
Sc	12.6	9.7	16.4	16.0	22.4	15.4	13.4	12.7	10.4	9.5
Cr	82.3	64.3	70.0	78.8	149.6	89.7	73.5	74.2	70.3	43.9
Co	13.9	3.1	6.9	9.3	8.2	17.7	12.8	11.5	12.3	11.0
Ni	52.5	18.9	35.7	48.3	56.3	64.3	55.7	63.4	27.0	21.8
Cu	129.4	14.5	46.2	31.0	45.5	43.8	33.5	29.8	43.6	7.6
Zn	124.2	114.6	133.1	104.4	90.2	136.9	119.1	131.6	144.1	136.1
Ga	53.0	76.9	62.3	77.2	103.7	52.8	79.5	63.6	65.4	74.8
Rb	143.3	163.2	238.1	170.4	265.0	168.9	168.2	111.6	119.5	148.7
Sr	342.2	80.2	67.9	49.7	49.3	226.2	81.4	67.0	311.2	627.0
Y	38.0	21.1	25.0	27.2	35.7	28.4	27.7	19.1	18.1	16.9
Zr	14.8	85.1	33.6	64.7	160.0	7.1	39.8	19.4	41.7	21.3
Nb	4.4	10.7	14.2	11.6	24.1	2.3	7.5	4.2	10.4	7.6
Mo	1.2	1.0	0.5	0.4	0.9	0.7	0.3	0.9	0.3	0.4
Cd	0.3	0.4	0.3	0.3	0.2	0.4	0.3	0.1	0.2	0.3
Cs	12.6	17.0	13.8	10.1	19.9	14.1	12.4	12.1	7.9	7.2
Ba	624.3	643.8	613.3	844.0	1052.2	556.0	850.8	676.4	686.2	745.8
La	63.4	50.6	53.4	49.4	22.8	56.2	40.6	40.4	33.8	36.7
Ce	129.6	105.9	112.5	100.9	54.7	107.6	82.4	79.0	69.6	73.1
Pr	15.3	11.7	12.9	11.1	7.0	12.3	9.8	9.1	7.9	8.2
Nd	59.8	41.3	45.2	39.9	24.5	44.3	36.0	32.5	28.8	30.8
Sm	11.6	7.1	7.8	6.6	5.7	8.2	7.0	5.9	5.5	5.6
Eu	2.3	1.3	1.6	1.2	1.3	1.6	1.6	1.1	1.2	1.3
Gd	12.1	6.6	6.9	6.4	5.9	7.9	6.9	5.5	5.2	4.9
Tb	1.5	0.8	0.9	0.9	0.9	1.0	0.9	0.7	0.6	0.6
Dy	7.5	4.4	5.0	5.2	6.0	5.4	5.1	3.8	3.6	3.2
Ho	1.2	0.8	0.9	0.9	1.3	1.0	1.0	0.7	0.6	0.6
Er	3.6	2.4	2.9	2.9	4.4	3.1	2.9	2.3	2.0	1.7
Tm	0.4	0.3	0.4	0.4	0.6	0.4	0.4	0.3	0.3	0.2
Yb	2.7	2.1	2.8	3.0	4.2	2.7	2.6	2.0	1.7	1.5
Lu	0.3	0.3	0.4	0.5	0.7	0.4	0.4	0.3	0.2	0.2
Hf	0.6	3.5	1.4	2.0	5.9	0.3	1.4	0.5	1.6	0.8
Ta	0.3	0.8	1.0	0.6	2.0	0.1	0.5	0.4	0.8	0.5
Pb	36.6	20.2	22.1	32.3	23.5	37.5	12.7	38.1	15.5	21.9
Th	12.7	16.0	18.4	16.5	23.9	16.9	13.6	13.0	13.9	12.9
U	2.8	3.8	4.7	3.9	5.8	2.7	2.3	2.6	3.2	2.3

Table 1. (continued).

Fm.	Jinju				Chilgok		Haman				
sample	D-34	R-09	Q-11	Q-42	B-36	R-08	C-48	K-40	M-01	N-03	N-22
SiO_2	60.75	55.75	46.92	62.32	55.62	61.29	59.18	49.75	51.79	48.92	55.18
Al_2O_3	15.25	14.51	14.88	15.27	18.13	14.54	15.35	15.16	13.88	15.12	15.97
Fe_2O_3	5.82	6.44	6.74	5.81	8.00	6.91	6.40	6.45	5.32	5.75	6.85
TiO_2	0.70	0.66	0.62	0.67	0.73	0.89	0.80	0.59	0.55	0.57	0.67
MnO	0.04	0.07	0.09	0.04	0.07	0.03	0.05	0.08	0.12	0.10	0.09
CaO	3.80	6.09	10.42	2.25	3.26	3.76	4.20	7.86	9.03	9.51	5.44
MgO	3.10	3.25	3.43	2.38	3.14	1.01	3.09	4.79	4.51	4.32	3.76
K_2O	3.17	3.89	3.54	4.00	4.49	4.38	2.47	3.16	2.64	3.69	3.45
Na_2O	1.02	0.66	0.23	1.39	1.42	1.52	2.78	2.29	1.97	1.08	1.79
P_2O_5	0.17	0.18	0.26	0.15	0.19	0.18	0.23	0.21	0.20	0.24	0.24
LOI	5.98	8.05	12.63	4.53	4.55	5.33	4.98	9.30	10.03	10.72	5.87
sum	99.80	99.55	99.76	98.81	99.60	99.84	99.53	99.64	100.04	100.02	99.31
Sc	12.4	13.2	10.9	12.8	11.8	10.0	13.2	12.4	11.0	13.5	13.2
Cr	59.1	89.8	56.0	76.5	36.9	68.7	56.5	53.0	56.7	53.2	51.9
Co	14.6	9.6	12.1	15.5	13.9	10.3	12.2	12.7	10.0	10.3	15.3
Ni	63.9	73.2	29.0	55.8	22.1	41.0	30.1	43.9	43.8	37.6	31.9
Cu	38.7	39.4	30.5	37.6	7.4	14.4	3813.6	55.7	24.9	25.1	43.7
Zn	119.0	139.5	117.6	124.0	124.7	112.7	33466.1	149.9	149.9	124.7	133.0
Ga	78.6	49.8	91.8	52.0	57.6	26.7	71.3	37.5	20.5	23.6	57.1
Rb	123.2	143.3	173.3	151.6	140.3	136.8	97.0	111.3	68.1	109.5	113.8
Sr	199.8	200.8	172.3	174.0	321.6	86.0	277.6	193.1	247.6	263.1	494.5
Y	21.3	24.4	22.5	21.4	19.6	19.6	21.8	19.9	16.9	21.1	22.1
Zr	81.2	9.1	59.5	26.9	15.8	43.8	94.5	22.1	10.9	11.6	60.1
Nb	8.5	5.3	12.1	3.0	2.3	9.0	11.9	5.2	2.9	3.1	7.0
Mo	2.4	1.8	41.3	0.5	0.9	1.1	0.8	0.5	0.9	0.8	0.9
Cd	0.4	0.2	0.5	0.4	0.0	0.1	0.3	0.5	0.9	0.1	0.4
Cs	9.7	11.2	22.1	12.0	10.3	11.8	6.8	11.9	8.3	13.0	8.9
Ba	624.6	545.4	608.8	573.4	1050.4	492.1	478.4	252.6	258.5	262.4	630.7
La	38.6	39.0	44.3	40.2	42.4	43.5	27.3	34.3	30.4	30.4	36.1
Ce	80.8	83.2	93.3	83.9	83.7	84.6	58.0	70.8	60.5	64.3	76.0
Pr	9.4	9.2	10.3	9.3	9.9	10.1	7.3	7.9	6.9	7.4	8.7
Nd	34.2	35.0	37.5	34.0	36.3	37.2	27.4	28.8	25.9	27.3	32.7
Sm	6.4	6.6	6.9	6.2	6.8	6.4	5.5	5.4	4.8	5.1	6.4
Eu	1.5	1.5	1.4	1.4	1.6	1.3	1.3	1.2	0.8	1.1	1.5
Gd	6.0	6.6	6.7	5.9	6.4	5.8	5.7	5.6	4.9	5.7	6.4
Tb	0.7	0.8	0.8	0.7	0.8	0.7	0.7	0.7	0.6	0.7	0.8
Dy	4.3	4.8	4.5	4.1	4.4	4.0	4.4	4.1	3.4	4.0	4.5
Ho	0.8	0.9	0.8	0.8	0.8	0.7	0.8	0.7	0.6	0.8	0.9
Er	2.5	2.7	2.2	2.5	2.4	2.4	2.5	2.3	1.8	2.5	2.5
Tm	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3
Yb	2.3	2.5	2.3	2.2	2.1	2.1	2.2	2.1	1.8	2.2	2.2
Lu	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.4	0.3
Hf	3.2	0.4	2.4	0.6	0.5	1.6	3.6	0.7	0.4	0.4	2.4
Ta	0.7	0.3	1.0	0.2	0.1	0.7	0.9	0.2	0.1	0.2	0.3
Pb	13.0	16.2	24.6	20.3	20.6	29.3	120.1	17.0	37.8	6.3	26.6
Th	12.1	13.7	16.6	13.5	11.6	14.5	9.8	12.5	10.1	10.4	10.5
U	2.2	3.4	2.3	2.4	2.5	3.7	2.3	3.0	4.6	3.2	2.9

Table 1. (continued).

Fm.	Jindong		Banyawol		Iljik	Hupyeondong	Jeomgok	Sagok	Chunsan
sample	N-07	N-08	G-01	L-17	Q-47	J-11	K-02	K-06	K-14
SiO_2	53.73	55.18	58.82	61.25	50.45	55.25	45.71	54.60	43.02
Al_2O_3	14.73	15.29	15.40	14.15	16.76	15.45	13.27	14.43	12.31
Fe_2O_3	6.34	6.71	5.68	5.25	11.31	6.89	5.77	7.19	5.25
TiO_2	0.58	0.63	0.66	0.54	1.20	0.73	0.50	0.68	0.43
MnO	0.06	0.04	0.06	0.08	0.07	0.08	0.16	0.12	0.27
CaO	5.65	5.45	4.05	4.64	1.77	5.37	9.44	3.13	14.15
MgO	3.86	3.07	2.24	3.01	6.20	2.44	6.68	6.11	6.11
K_2O	3.48	3.23	3.68	2.34	3.03	4.02	3.36	4.35	2.84
Na_2O	2.15	1.46	1.59	2.22	1.43	1.66	2.36	2.15	1.01
P_2O_5	0.18	0.18	0.17	0.17	0.19	0.17	0.23	0.19	0.22
LOI	7.82	8.21	6.63	6.39	7.16	7.51	11.89	6.57	14.42
sum	98.58	99.45	98.98	100.04	99.57	99.57	99.37	99.52	100.03
Sc	14.9	15.0	9.5	6.8	18.2	13.6	13.1	11.6	9.0
Cr	57.3	64.9	48.0	36.8	47.3	68.4	55.0	75.1	47.1
Co	12.5	3.8	4.9	11.1	18.9	23.5	16.0	15.5	11.8
Ni	37.2	34.7	22.3	25.0	46.6	43.8	42.9	44.9	33.6
Cu	23.5	56.7	22.4	23.6	61.7	14.2	47.2	40.3	15.6
Zn	137.0	139.9	100.7	126.3	205.2	136.5	156.6	156.2	112.1
Ga	25.8	47.2	16.2	2.9	50.3	26.6	21.3	51.0	16.2
Rb	112.0	109.8	126.5	74.3	118.9	143.2	93.4	115.1	88.8
Sr	199.9	196.7	143.1	128.8	109.5	123.0	483.8	260.0	424.0
Y	23.6	27.2	20.4	19.3	20.8	23.7	20.4	17.6	19.0
Zr	13.2	88.1	26.6	18.6	57.6	31.0	44.1	7.3	11.5
Nb	5.3	6.7	5.9	2.3	10.7	7.5	5.0	6.6	4.1
Mo	0.5	1.0	0.5	0.8	1.0	1.3	141.6	0.6	0.5
Cd	0.3	0.2	0.2		0.6	0.2	0.8	0.2	0.2
Cs	11.8	12.9	16.8	10.0	13.8	12.7	7.5	6.1	13.3
Ba	280.5	475.1	396.0	186.6	447.6	283.9	250.5	616.4	511.8
La	29.5	35.8	31.4	27.9	40.3	35.4	32.6	33.3	25.0
Ce	62.9	65.3	67.1	58.0	89.1	72.0	66.0	71.3	52.7
Pr	7.1	8.7	7.8	6.9	9.9	7.9	7.2	7.8	6.1
Nd	27.5	31.4	29.7	26.3	37.8	30.1	27.6	28.7	23.2
Sm	5.3	6.5	5.5	5.1	6.9	5.8	5.3	5.4	4.8
Eu	1.0	1.2	1.1	0.9	1.3	1.3	1.1	1.0	1.0
Gd	5.7	6.9	5.6	5.2	6.4	5.9	5.5	5.2	4.4
Tb	0.7	0.9	0.8	0.7	0.8	0.8	0.8	0.6	0.6
Dy	4.0	5.1	4.3	3.9	4.2	4.7	4.1	3.5	3.5
Ho	0.8	1.0	0.8	0.7	0.8	0.9	0.8	0.6	0.6
Er	2.4	2.7	2.6	2.3	2.5	2.6	2.2	2.1	2.1
Tm	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Yb	2.2	2.3	2.4	2.1	2.3	2.5	2.0	1.8	1.9
Lu	0.4	0.4	0.3	0.3	0.4	0.4	0.3	0.3	0.3
Hf	0.4	2.9	1.1	0.6	2.5	0.9	1.4	0.2	0.4
Ta	0.3	0.2	0.3	0.2	0.7	0.4	0.4	0.2	0.3
Pb	5.9	18.1	8.1	38.7	29.1	12.4	21.0	31.7	14.5
Th	10.6	11.7	11.8	10.7	14.3	12.2	11.8	13.0	9.1
U	3.0	3.1	2.6	2.5	3.9	3.3	7.9	2.3	3.1

Table 1. (continued).

	Sindong average	Hayang average	NASC (LOI-free) Gromet et al. (1984)	Sindong LOI-free	Hayang LOI-free
SiO_2	57.29	53.73	64.80-64.82	62.05	58.66
Al_2O_3	16.74	15.00	16.88-17.05	18.13	16.37
Fe_2O_3	5.32	6.63	5.59-5.70	5.76	7.24
TiO_2	0.76	0.67	0.78-0.80	0.83	0.73
MnO	0.04	0.09	0.06-0.25	0.04	0.10
CaO	4.21	6.04	3.51-3.68	4.56	6.60
MgO	2.70	4.02	2.83-2.86	2.93	4.39
K_2O	4.43	3.41	3.87-3.97	4.79	3.73
Na_2O	0.63	1.81	1.12-1.15	0.68	1.97
P_2O_5	0.22	0.20	0.11-0.17	0.23	0.22
LOI	7.30	7.96			
sum	99.63	99.57			
Sc	13.4	12.3	14.9	13.4	12.3
Cr	77.0	54.8	124.5	77.0	54.8
Co	11.3	12.7	25.7	11.3	12.7
Ni	47.6	36.3	58	47.6	36.3
Cu	40.8	268.1		40.8	268.1
Zn	123.9	338.2		123.9	338.2
Ga	70.1	34.5		70.1	34.5
Rb	163.4	109.9	125	163.4	109.9
Sr	189.2	247.0	142	189.2	247.0
Y	24.8	20.8		24.8	20.8
Zr	47.4	34.8	200	47.4	34.8
Nb	9.0	6.0		9.0	6.0
Mo	3.8	9.6		3.8	9.6
Cd	0.3	0.3		0.3	0.3
Cs	13.0	11.0	5.16	13.0	11.0
Ba	688.9	429.6	636	688.9	429.6
La	43.5	33.5	31.1	43.5	33.5
Ce	89.7	68.9	67.0-67.2	89.7	68.9
Pr	10.2	8.0		10.2	8.0
Nd	37.4	29.9	30.4-31.9	37.4	29.9
Sm	6.9	5.7	5.98-6.18	6.9	5.7
Eu	1.5	1.2	1.25-1.29	1.5	1.2
Gd	6.7	5.7	5.5	6.7	5.7
Tb	0.8	0.7	0.85	0.8	0.7
Dy	4.8	4.1	5.54	4.8	4.1
Ho	0.9	0.8		0.9	0.8
Er	2.7	2.4	3.28	2.7	2.4
Tm	0.4	0.3		0.4	0.3
Yb	2.5	2.1	3.11-3.14	2.5	2.1
Lu	0.4	0.3	0.456	0.4	0.3
Hf	1.8	1.3	6.30	1.8	1.3
Ta	0.7	0.3	1.12	0.7	0.3
Pb	23.9	27.3		23.9	27.3
Th	15.3	11.5	12.3	15.3	11.5
U	3.2	3.4	2.66	3.2	3.4

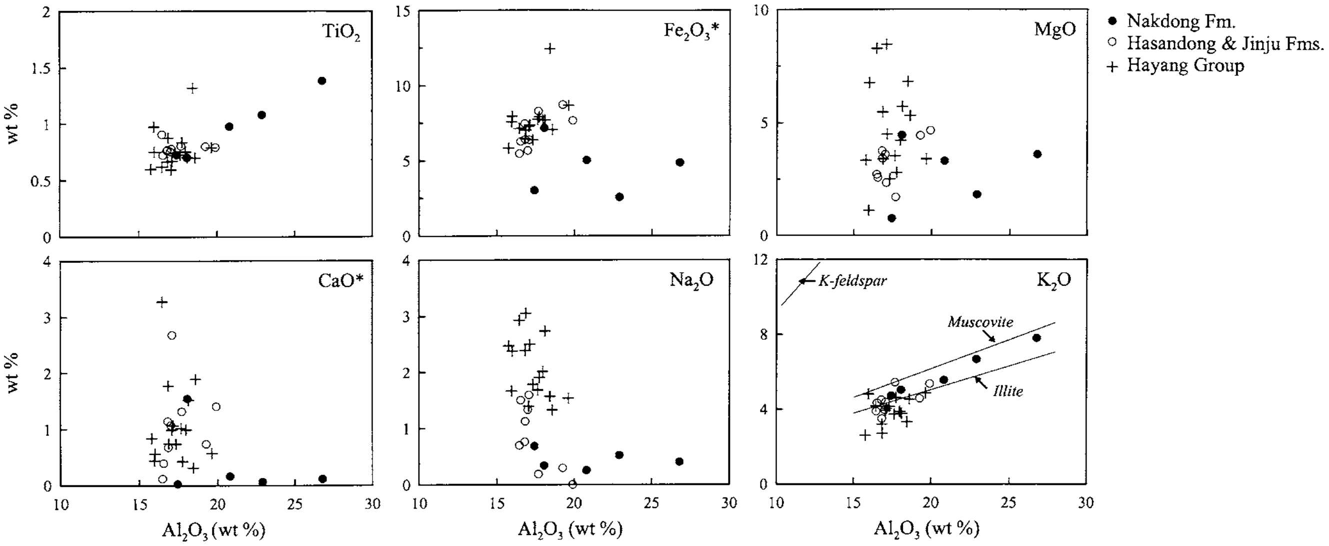

Fig. 2. Major element oxide contents plotted against Al$_2$O$_3$ content for Nakdong, Hasandsong and Jinju formations, and Hayang Group mudrocks. CaO*: CaO associated with silicate only.

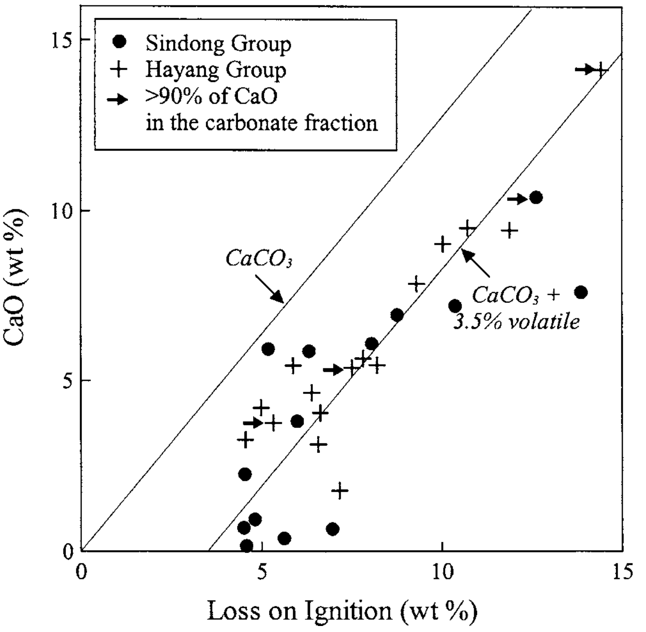

Fig. 3. CaO content of Sindong and Hayang mudrocks plotted against loss on ignition.

in the Hayang mudrocks. On the contrary, Sr vs. CaO plot of the bulk samples shows weak correlation (r=+0.55) between the two elements (Fig. 4A). However, separate plots for the Sr and CaO content in the silicate and carbonate mineral fractions shows that Sr and CaO are well correlated to each other within each fraction (Fig. 4B); their correlation coefficient is 0.96 for silicate fraction and 0.89 for carbonate fraction. Figure 4B shows that Sr substituted Ca in silicate mineral (mostly plagioclase) about seven times more than Ca in carbonate mineral (mostly calcite).

Some of the trace elements are more abundant in the Hayang mudrocks than Sindong mudrocks. Particularly anomalously high concentrations of Cu and Zn in sample C48 and Mo in sample K02 are noteworthy (Table 1). These samples were collected near the highest illite crystallinity zone defined by Lee and Lee (2001). They interpreted that illite crystallinity of the Gyeongsang Basin were influenced by thermal effect by magmatism rather than by burial. Thus, it is likely that the high concentrations of Cu, Zn and Mo in these samples are not inherited from the sediment source, but due to the mineralization process, possibly hydrothermal in origin.

REEs are not easily fractionated during sedimentation and diagenesis, thus sedimentary REE patterns reflect the average REE pattern of the sources (Taylor and McLennan, 1985; McLennan, 1989; Condie, 1991). Enrichment in LIL elements in the upper continental crust compared to the ultramafic mantle sources results in LREE enrichment, and Eu enrichment in the lower continental crust causes negative Eu anomaly in the upper crustal rocks (McLennan, 1989). Mixing of various provenance components results in remarkable uniformity of the REE patterns in fine-grained sedmentary rocks (e.g., McLennan et al., 1993; Singh and Rajamani, 2001). The REE patterns of the Sindong and Hayang mudrocks show characteristic sedimentary REE distribution patterns derived from upper continental crust rocks; high LREE, flat HREE, and negative Eu anomaly (Fig. 5). It implies that none-upper crustal rocks were not significantly exposed around Gyeongsang Basin at the time of deposition. REE concentration and LREE/HREE are slightly higher in the Sindong mudrocks [REE=208.4, $(La/Sm)_N$=3.9] than in the Hayang mudrocks [REE=200.5, $(La/Sm)_N$=3.6], indicating that REEs of the Sindong mudrocks are fractionated more than those of the Hayang mudrocks.

Table 2. Concentrations of major and some selected trace elements in exchangeable fraction (A), carbonate-bounded (B), Fe,Mn-oxide-bounded (C), organic matter and sulfide-bounded (D), silicate fraction (E) and whole rock (whole). Relative abundances of elements in each fractions are shown in %. Analysis with large errors (difference between whole concentration and sum of each fractions larger than 20%) is not shown.

sample	frac-	Al_2O_3		Fe_2O_3		TiO_2		MnO		CaO		MgO		K_2O	Na_2O	Zn		Sr		Ba	
Fm	tions	wt%	%	wt%	%	wt%	%	wt%	%	wt%	%	wt%	%	wt%	wt%	ppm	%	ppm	%	ppm	%
Q-29	whole	25.14		4.01		1.24		0.03		0.66		3.12		6.97	0.65	71.6		57.6		1244.4	
Nakdong	A	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00				0.0	0.00	0.0		0.0	
	B	0.02		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.02				0.0	0.00	0.0		14.0	
	C	0.13		0.57	16.04	0.01	0.49	0.00	14.25	0.22		0.22				16.1	19.94	6.7		5.5	
	D	0.24		0.03	0.97	0.00	0.23	0.00	3.84	0.02		0.06				5.2	6.47	1.0		3.8	
	E	12.51		2.96	82.99	1.29	99.28	0.02	81.90	0.09		2.03		5.90	0.51	59.4	73.59	23.8		711.1	
Q-17	whole	15.70		5.65		0.72		0.06		5.59		2.06		3.80	1.79	101.0		579.3		823.8	
Hasan-	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.0	0.00	0.0	0.00	0.0	0.00
dong	B	0.00	0.00	0.00	0.00	0.00	0.00	0.01	21.98	3.17	58.92	0.00	0.00			0.0	0.00	14.3	2.73	13.1	1.81
	C	0.04	0.30	0.22	3.85	0.00	0.09	0.00	5.53	0.18	3.30	0.11	5.95			10.7	11.29	4.9	0.94	5.4	0.75
	D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.73	0.00	0.00	0.00	0.00			2.6	2.76	0.0	0.00	0.0	0.00
	E	12.62	99.70	5.39	96.15	0.69	99.91	0.05	71.76	2.03	37.78	1.75	94.05	3.52	1.64	81.8	85.95	504.7	96.33	703.0	99.44
Q-11	whole	15.05		6.92		0.61		0.09		9.68		3.27		3.28	0.38	105.2		201.0		659.3	
Jinju	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.0	0.00	0.0	0.00	0.0	0.00
	B	0.00	0.00	0.00	0.00	0.00	0.00	0.04	45.07	8.74	94.54	0.04	1.40			0.0	0.00	155.3	79.00	39.8	7.17
	C	0.13	1.06	0.88	12.99	0.00	0.01	0.01	7.65	0.29	3.14	0.23	7.40			38.6	36.69	11.9	6.07	15.7	2.82
	D	0.27	2.17	0.04	0.61	0.00	0.45	0.00	0.90	0.03	0.31	0.03	1.13			6.5	6.20	1.7	0.88	11.2	2.02
	E	12.07	96.77	5.87	86.40	0.66	99.55	0.04	46.38	0.19	2.02	2.77	90.07	2.98	0.37	60.0	57.10	27.6	14.05	488.3	87.99
B-36	whole	18.43		7.65		0.72		0.07		3.13		3.04		4.26	1.70	100.1		337.4		1184.5	
Chilgok	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.0		0.0	0.00	0.0	0.00
	B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.58	0.32	12.70	0.01	0.35			0.0		0.0	0.00	7.5	0.69
	C	0.06	0.35	0.16	2.19	0.00	0.08	0.01	13.13	0.24	9.59	0.15	5.26			237.8		8.7	2.75	13.8	1.28
	D	0.16	0.98	0.00	0.04	0.04	6.40	0.00	2.01	0.09	3.75	0.03	1.12			29.0		2.6	0.83	8.1	0.75
	E	16.17	98.67	6.91	97.77	0.64	93.52	0.05	80.28	1.87	73.96	2.64	93.26	3.79	1.55	0.0		304.5	96.42	1050.4	97.28
R-08	whole	14.45		6.56		0.70		0.03		3.61		0.98		4.07	1.85	82.9		96.1		579.3	
Chilgok	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.0	0.00	0.0	0.00	0.0	0.00
	B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.09	2.97	89.35	0.00	0.00			0.0	0.00	13.4	16.89	60.4	12.30
	C	0.06	0.46	0.66	10.18	0.00	0.01	0.02	65.24	0.22	6.57	0.03	3.40			23.6	26.28	4.3	5.48	32.4	6.60
	D	0.07	0.55	0.01	0.19	0.00	0.17	0.00	3.04	0.02	0.51	0.00	0.38			4.5	5.03	1.0	1.20	20.2	4.11
	E	12.79	98.99	5.80	89.63	0.83	99.82	0.01	17.62	0.12	3.57	0.89	96.22	3.94	1.79	61.6	68.69	60.5	76.43	377.8	76.99

Table 2. (continued).

sample	frac-	Al_2O_3		Fe_2O_3		TiO_2		MnO		CaO		MgO		K_2O	Na_2O	Zn		Sr		Ba	
Fm	tions	wt%	%	wt%	%	wt%	%	wt%	%	wt%	%	wt%	%	wt%	wt%	ppm	%	ppm	%	ppm	%
N-22	whole	16.32		6.45		0.67		0.08		5.19		3.54		3.38	2.17	102.0		489.7		767.6	
Haman	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.0	0.00	0.0	0.00	0.0	0.00
	B	0.00	0.00	0.00	0.00	0.00	0.00	0.01	14.01	2.37	54.83	0.00	0.02			0.0	0.00	29.5	6.48	13.1	1.94
	C	0.18	1.23	0.30	4.70	0.00	0.63	0.01	15.85	0.27	6.22	0.28	8.24			25.5	23.57	8.7	1.90	8.5	1.26
	D	0.19	1.34	0.01	0.21	0.04	5.25	0.00	1.55	0.07	1.66	0.05	1.41			4.6	4.23	1.8	0.39	4.4	0.64
	E	13.88	97.42	6.01	95.09	0.64	94.12	0.05	68.59	1.61	37.29	3.03	90.33	2.96	1.93	78.2	72.20	416.1	91.23	652.3	96.17
N-08	whole	15.43		6.31		0.56		0.04		5.10		2.92		2.99	1.68	99.7		193.5		563.2	
Jindong	A	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.0	0.00	0.0	0.00	0.0	0.00
	B	0.00		0.00	0.00	0.00	0.00	0.02	64.61	3.85	89.11	0.01	0.30			0.0	0.00	77.1	48.99	21.8	4.79
	C	0.25		0.63	10.17	0.00	0.01	0.00	10.74	0.33	7.58	0.41	15.58			22.2	22.35	9.8	6.24	8.0	1.75
	D	0.16		0.01	0.14	0.00	0.13	0.00	1.51	0.06	1.50	0.08	3.04			6.0	6.07	2.5	1.57	4.7	1.04
	E	11.66		5.53	89.69	0.61	99.86	0.01	23.14	0.08	1.82	2.14	81.09	2.78	1.50	71.1	71.58	68.0	43.21	420.4	92.42
J-11	whole	15.58		6.85		0.64		0.08		5.10		2.44		3.86	2.14	101.0		135.9		331.7	
Hupye-	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.0	0.00	0.0	0.00	0.0	0.00
ongdong	B	0.00	0.00	0.00	0.00	0.00	0.00	0.05	65.96	4.42	93.06	0.01	0.35			0.0	0.00	65.2	56.50	30.2	12.07
	C	0.19	1.37	0.52	7.85	0.01	0.73	0.01	12.95	0.24	4.98	0.20	8.90			17.2	18.45	6.3	5.49	11.6	4.65
	D	0.13	0.96	0.01	0.13	0.00	0.18	0.00	0.68	0.01	0.31	0.02	1.13			2.4	2.54	0.9	0.80	3.0	1.22
	E	13.58	97.67	6.05	92.02	0.70	99.09	0.01	20.41	0.08	1.65	1.98	89.62	3.52	1.90	73.8	79.01	42.9	37.21	205.6	82.06
K-02	whole	12.87		5.51		0.50		0.14		8.82		6.45		3.26	2.75	121.7		459.3		291.4	
Jeomgok	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.0	0.00	0.0	0.00	0.0	0.00
	B	0.00	0.00	0.15	2.67	0.00	0.00	0.07	56.27	6.04	72.01	1.03	16.14			0.0	0.00	258.2	56.53	12.9	4.92
	C	0.02	0.17	0.38	6.91	0.00	0.03	0.04	31.52	2.05	24.46	1.39	21.77			2.0	1.72	143.9	31.51	2.4	0.93
	D	0.37	3.21	0.13	2.39	0.00	0.01	0.01	4.09	0.15	1.80	0.19	2.97			80.2	69.82	18.5	4.05	6.5	2.49
	E	11.26	96.61	4.80	88.03	0.51	99.96	0.01	8.12	0.14	1.72	3.77	59.13	3.00	2.46	32.7	28.46	36.1	7.91	240.8	91.66
K-14	whole	11.83		5.61		0.43		0.23		13.36		6.04		2.55	1.20	92.0		419.3		584.4	
Chunsan	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.0	0.00	0.0	0.00	0.0	0.00
	B	0.00	0.00	0.00	0.00	0.00	0.00	0.17	76.64	12.02	94.95	0.14	2.48			0.0	0.00	341.8	82.77	108.6	24.51
	C	0.31	3.09	0.44	8.24	0.00	0.02	0.01	5.07	0.53	4.20	0.46	8.01			9.9	10.80	21.5	5.21	71.2	16.06
	D	0.17	1.66	0.01	0.20	0.00	0.32	0.00	0.54	0.03	0.21	0.10	1.77			5.0	5.48	3.2	0.77	55.7	12.58
	E	9.58	95.25	4.85	91.57	0.46	99.66	0.04	18.75	0.08	0.65	5.00	87.73	2.24	1.05	76.8	83.72	46.4	11.25	207.6	46.85

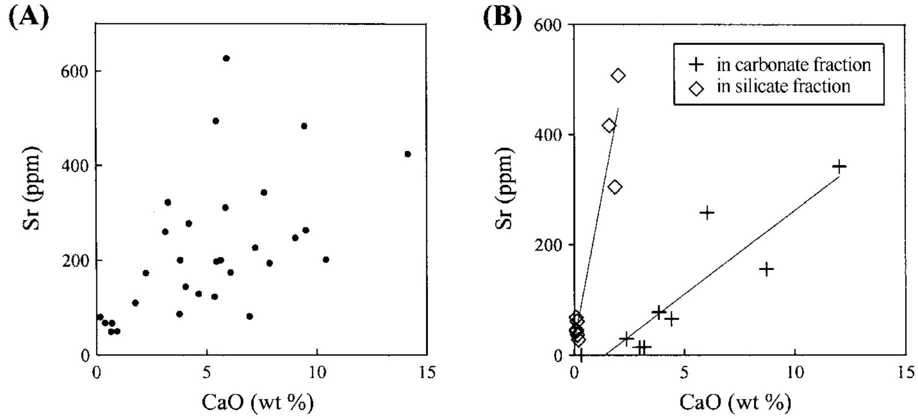

Fig. 4. (**A**) Sr versus CaO plot for Sindong and Hayang mudrocks. (**B**) Sr and CaO concentrations in carbonate minerals and in silicate minerals.

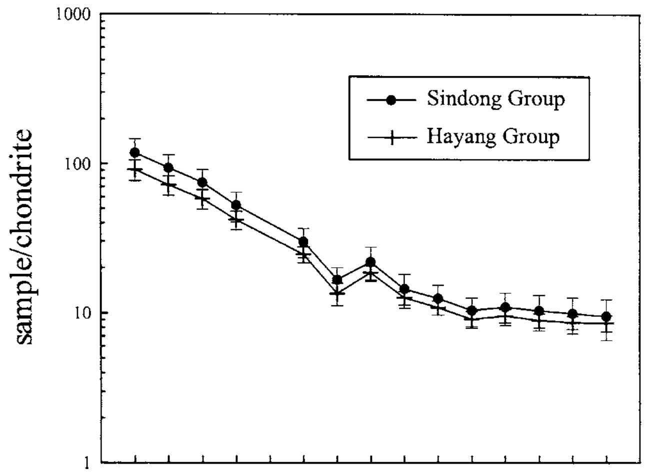

Fig. 5. Average REE distribution patterns of Sindong and Hayang mudrocks normalized to chondrite. Error bars represent the standard deviation of the samples.

4. SOURCE ROCKS AND TECTONIC SETTING

4.1. Major Elements and Provenance

Chemical index of alteration (CIA; Nesbitt and Young, 1982) is a good measure of the degree of chemical weathering. CIA is $[Al_2O_3/(Al_2O_3+CaO^*+Na_2O+K_2O)] \cdot 100$ in *molecular proportions*, where CaO* is the CaO associated with silicate fraction. In this study, CaO* has been directly analyzed for ten samples (Table 2), and CaO* of the other samples has been approximated applying the average proportion of CaO* from CaO*-measured samples. The CIA values of the Sindong mudrocks range from 58.3 to 75.6 with an average of 70.1. The CIA values of the Hayang Group range from 51.9 to 73.1, and the average is 64.4. Average CIA value of Sindong mudrocks is higher than that of Hayang mudrocks. The CIA values of the Nakdong Formation are especially high, ranging from 62.7 to 75.6 with an average of 72.8.

Sindong and Hayang mudrock samples are plotted on A–CN–K compositional space to estimate the effect of source composition, weathering and diagenesis (Fig. 6). On the A–CN–K space, the compositions of the samples are scattered in a linear array that is quite different from the predicted weathering trend which is expected to run subparallel to A–CN join (Nesbitt and Young, 1989). A straight line through the data intersects the A–CN join, which is not expected if the samples were products of chemical weathering of the source rocks under the influence of natural waters located on the CN–K join. Composition of sediments may deviate from the normal weathering trend and move toward the K apex when enrichment of K_2O by K-metasomatism occurs (e.g., Nesbitt and Young. 1989; Fedo et al., 1997). If this had been the case for the Sindong and Hayang mudrocks, CIA values before K addition should have been much higher than the present CIA values (Fig. 6A). Line passed through data intersects the feldspar join at a point indicative of the plagioclase-K-feldspar ratio in the source terrane (Fedo et al., 1995), which may correspond to the composition of tonalite. Assuming that all the sediments were derived from the same source, the compositional difference between the Sindong and Hayang mudrocks may have been controlled by different degree of weathering (Fig. 6A). However, this does not seem to be the case for the Gyeongsang Basin because such a large pre-Cretaceous tonalitic body is not found anywhere surrounding the Gyeongsang Basin.

Figure 6B shows estimation of source composition assuming first-cycle sediments for the Nakdong Formation, Hasandong and Jinju Formations, and Hayang Group in the Miryang and Uiseong subbasins. Estimated source rock composition for the Nakdong Formation is lowest in CN content, and those for the Hayang mudrocks in the Miryang Subbasin contain higher CN content. It is consistent with previous provenance studies which suggested that the Sindong Group was largely derived from granite and gneiss (Choi, 1986; Koh, 1986) and source for the Hayang Group in the Miryang Subbasin included intermediate volcanic and volcaniclastic rocks (Lee and Lee, 2000). This scenario implies that the Sindong mudrocks are more extensively weathered than the Hayang mudrocks. Estimation of degrees of weathering by CIA values is based on the assumption that

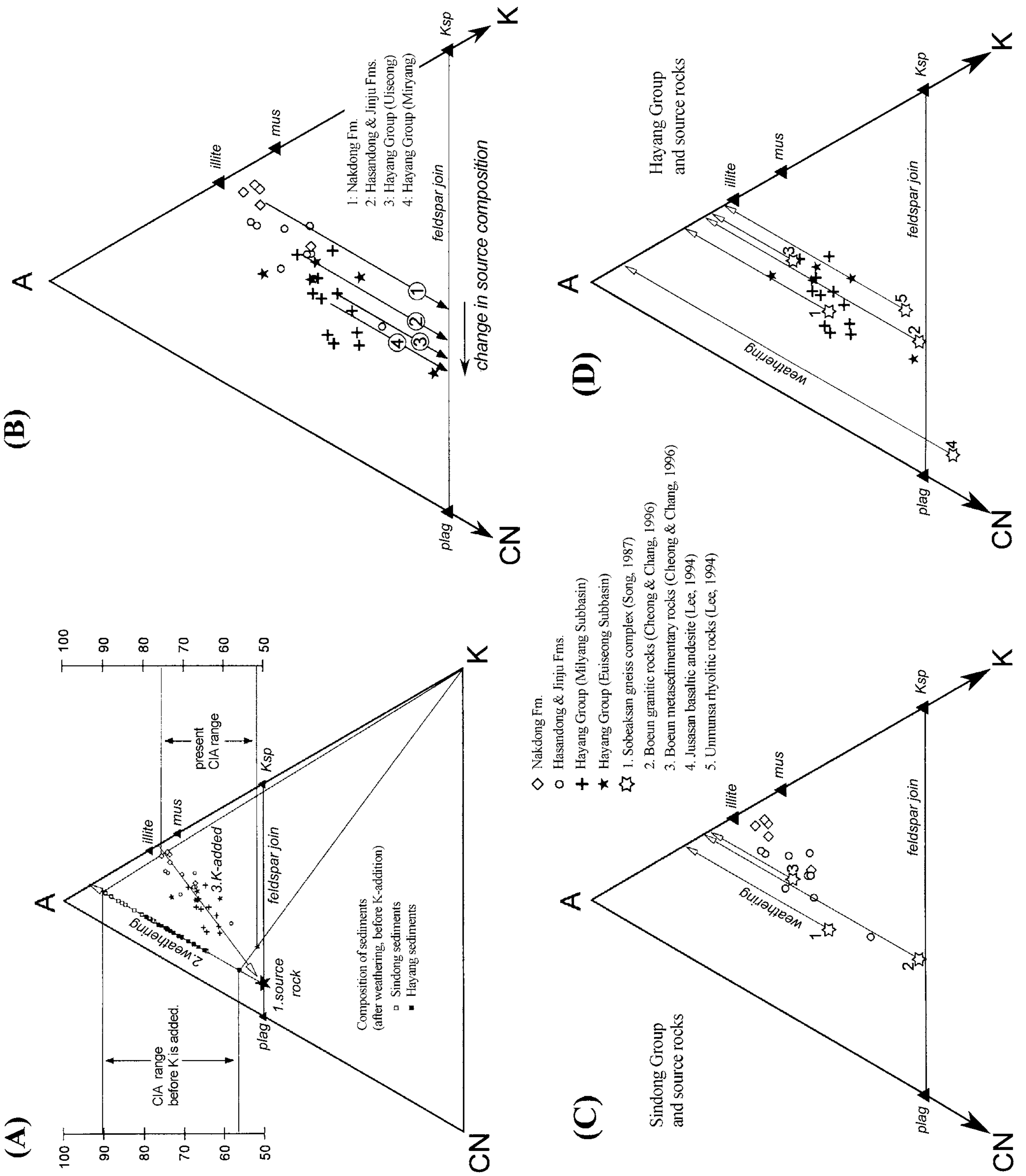

Fig. 6. Sindong and Hayang mudrocks plotted on A–CN–K diagrams. (**A**) Source rock composition and evolution of sediments assuming the same source rock for all the samples. Weathering of the presumed source rock (composition marked by star) produces sediments of wide range of CIA (squares), and K-addition to the sediment resulted in the present compositions of the mudrocks. (**B**) Estimation of source compositions assuming first-cycle sediments and different sources for each group. (**C**) Sindong mudrocks and (**D**) Hayang mudrocks plotted with predicted weathering trends of possible source rocks surrounding the Gyeongsang Basin.

the sediments are of first-cycle, i.e., composition of the source rocks plots on or near the feldspar join. However, if the source rock includes sedimentary or metasedimentary rocks, the average composition of the source rocks would plot well above the feldspar join in the A–CN–K space and thus degree of weathering of these source rocks would be less than that of plutonic rocks.

Compositions of selected igneous and metamorphic rocks around the Gyeongsang Basin are plotted on A–CN–K diagram and they are compared with compositions of Sindong and Hayang mudrocks (Fig. 6C, D). Provenance studies using sandstone petrography suggest that the source area of the Sindong Group is composed of various amounts of granite, gneiss and (meta)sedimentary rocks, and that contribution from (meta) sedimentary source decreased toward upper sequence in the Sindong Group (Choi, 1986; Koh, 1986). Compositions of Precambrian Sobaeksan gneiss complex (Song, 1987), Permian to Triassic granitic rocks and Paleozoic metasedimentary rocks in Boeun area (Cheong and Chang, 1996) have been selected to represent compositions of gneiss, granite and (meta) sedimentary source rocks, respectively. Plots of Sindong mudrock compositions are slightly shifted toward K-apex from the weathering trend of these rocks, thus it seems that some potassium were added to the system (Fig. 6C). The weathering would have been less intense than predicted in Figure 6A and B considering that the source rocks were more aluminous than igneous sources. Nakdong mudrocks plot closest to the A–K join, and this is consistent with higher content of detritus from (meta)sedimentary rocks in the Nakdong Formation (Choi, 1986; Koh, 1986). It is also possible that the Nakdong mudrocks represent more severely weathered materials than the Hasandong and Jinju mudrocks because paleoclimate during the Nakdong deposition is considered to have been more humid than during the Hasandong and Jinju deposition (Choi, 1985).

In addition to the source rocks in common with the Sindong Group, Hayang mudrocks were also derived from volcanic rocks (Lee and Lee, 2000). Compositions of Upper Cretaceous Jusasan andesitic rocks and Unmunsa rhyolitic rocks in the Gyeongsang Basin (Lee, 1994) were used to represent the compositions of andesitic and rhyolitic source rocks (Fig. 6D). The Hayang mudrocks are slightly to moderately weathered. Lower CIA ranges of the Hayang mudrocks were partly caused by short transport distance of volcanic detritus to the basin during the Hayang deposition (Lee and Lee, 2000). Hayang mudrocks from the Uiseong Subbasin generally lie on the weathering trends of granitic and rhyolitic rocks (lines 2 and 5 in Fig. 6D), but mudrocks from the Miryang Subbasin have lower K content than those from the Uiseong Subbasin (Fig. 6D). It seems to reflect sediment contribution from andesitic volcanic source rocks to the Miryang Subbasin during the deposition of the Hayang Group (Lee and Lee, 2000). Considering the weathering trends, metasedimentary rock did not play an important role as source rock for the Hayang Group (Fig. 6D).

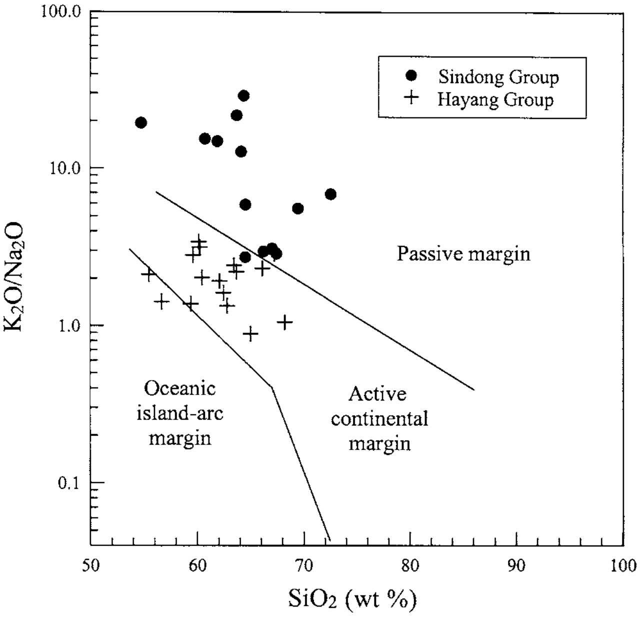

Fig. 7. The K_2O/Na_2O vs. SiO_2 discrimination diagram (Roser and Korsch, 1986) showing tectonic setting fields for Sindong and Hayang mudrocks.

Figure 7 shows a tectonic-setting-discrimination diagram using K_2O/Na_2O ratio and SiO_2 content (Roser and Korsch, 1986) applied to the Sindong and Hayang mudrocks. Sindong mudrocks are similar to sediments deposited in the passive margin, whereas Hayang mudrocks are similar to sediments deposited in the active continental margin (Fig. 7). Sediments in the passive margin field are those derived from stable continental areas and deposited in sites away from active plate boundaries, and sediments in active continental margin include material derived from continental margin magmatic arcs and uplifted area associated with strike-slip faults and deposited in pull-apart basins (Roser and Korsch, 1986). The presence of volcanogenic detritus in the Hayang mudrocks may have lowered K_2O/Na_2O ratio of Hayang mudrocks compared to Sindong mudrocks.

4.2. Trace Elements and Provenance

Concentrations of trace element and their ratios can be useful discriminators of tectonic settings because some trace elements are considered to be immobile during sedimentation (Bhatia and Crook, 1986). Trace elements that are used to discriminate tectonic settings and source composition are listed in Table 3 with values of Sindong and Hayang mudrocks. Absolute values are different from graywacke data (Bhatia and Crook, 1986) because concentrations of trace elements in mudrocks are different from sandstones due to grain size effect. Rb/Sr, Hf, Th/U, La, Nd, La/Sc and Th/Sc decrease from passive margin to active continental margin, to continental island arc, and to oceanic

Table 3. Trace element discriminators of tectonic settings and source composition.

			Bhatia and Crook (1986), graywackes				Cullers (1994)	
	Sindong Group	Hayang Group	passive margin	active continental margin	continental island arc	oceanic island arc	high-silica metamorphic sources	low-silica metamorphic sources
Discriminators decreasing toward oceanic island arc or low-silica sources								
Pb	23.9	27.3	16	24	15.1	6.9		
Th	15.3	11.5	16.7	18.8	11.1	2.27	17	8.0
Zr	47.4	34.8	298	179	229	96		
Hf	1.8	1.3	10.1	6.8	6.3	2.1	12.2	6.9
Nb	9.0	6.0	7.9	10.7	8.5	2		
La	43.5	33.5	33.5	33	24.4	8.72	57	45.5
Ce	89.7	68.9	71.9	72.7	50.5	22.53	127	87.0
Nd	37.4	29.9	29	25.4	20.8	11.36		
Rb/Sr	1.7	0.6	1.19	0.89	0.65	0.05		
La/Y	1.8	1.6	1.31	1.33	1.02	0.48		
La/Sc	3.4	2.8	6.25	4.55	1.82	0.55	20	1.8
Th/Sc	1.2	0.98	3.06	2.59	0.85	0.15	7.0	0.33
Th/U	5.0	3.7	5.6	4.8	4.6	2.1		
Ba/Sc	53	36					268	29.5
La/Cr	0.6	0.6					3.7	0.98
Th/Cr	0.2	0.2					1.1	0.11
Discriminators increasing toward oceanic island arc or low silica sources								
Ti	0.8	0.7	0.22	0.26	0.39	0.48		
Sc	13.4	12.3	6	8	14.8	19.5	4.5	31
Co	11.3	12.7	5	10	12	18		
Zn	124	338	26	52	74	89		
Cr	77.0	54.8					18.5	113
Ti/Zr	29.6	31.5	6.74	15.3	19.6	56.8		
K/Th	290	297	681	1252	1296	4055		
Zr/Hf	28.2	28.7	29.5	26.3	36.3	45.7		
Zr/Th	3.0	3.0	19.1	9.5	21.5	48		
La/Th	3.0	2.9	2.2	1.77	2.36	4.26		
Sc/Cr	0.18	0.23	0.16	0.3	0.32	0.57		

island arc, and these values are higher in the Sindong mudrocks (Table 3). In contrast, Ti/Zr, Co, Zn, Sc/Cr increase in the reverse order from passive margin to oceanic island arc, and they are higher in the Hayang mudrocks. K/Th, Ti and Sc are similar in both groups.

Concentration of La, Th, Ba, Sc, Co, Cr and their element ratios such as La/Sc, Th/Sc, Ba/Sc, La/Cr, Th/Cr are useful indicators discriminating basic and felsic source rocks (Andre et al., 1986; Cullers et al., 1988; Cullers 1994). Also listed in Table 3 are element ratios of high-silica and low-silica metamorphic source rocks. Results suggest that sources for the Sindong mudrocks are slightly more silicic than those for the Hayang mudrocks.

A La–Th–Sc ternary diagram is used to discriminate tectonic setting or composition of source rocks (Bhatia and Crook, 1986; Cullers, 1994). Granitic gneiss sources are plotted near La–Th join, but basic sources contain higher amount of Sc (Fig. 8; Cullers, 1994). Sindong and Hayang mudrocks are most similar to sediments derived from mixed sources, but some Hayang mudrocks contain significant amount of detritus from mafic sources (Fig. 8).

Σ REE increases from oceanic island arc to continental island arc, and it is highest in Andean-type margin and passive margin (Bhatia, 1985). Σ REE of the Sindong and Hayang mudrocks is higher than graywackes reported by Bhatia (1985) due to concentration of REE in clay fractions (Cullers et al., 1979; McLennan, 1989). Σ REE and K_2O/Na_2O ratio of mudrocks from known sources (Bhatia, 1985) were compared with Sindong and Hayang mudrocks (Fig. 9). Sindong mudrocks have higher K_2O/Na_2O ratios and average Σ REE than Hayang mudrocks, and are compositionally close to mudrocks derived from granite-gneiss and sedimentary sources. Hayang mudrocks plot in the field of mudrocks deposited in a basin formed by rifting of the continental crust in an

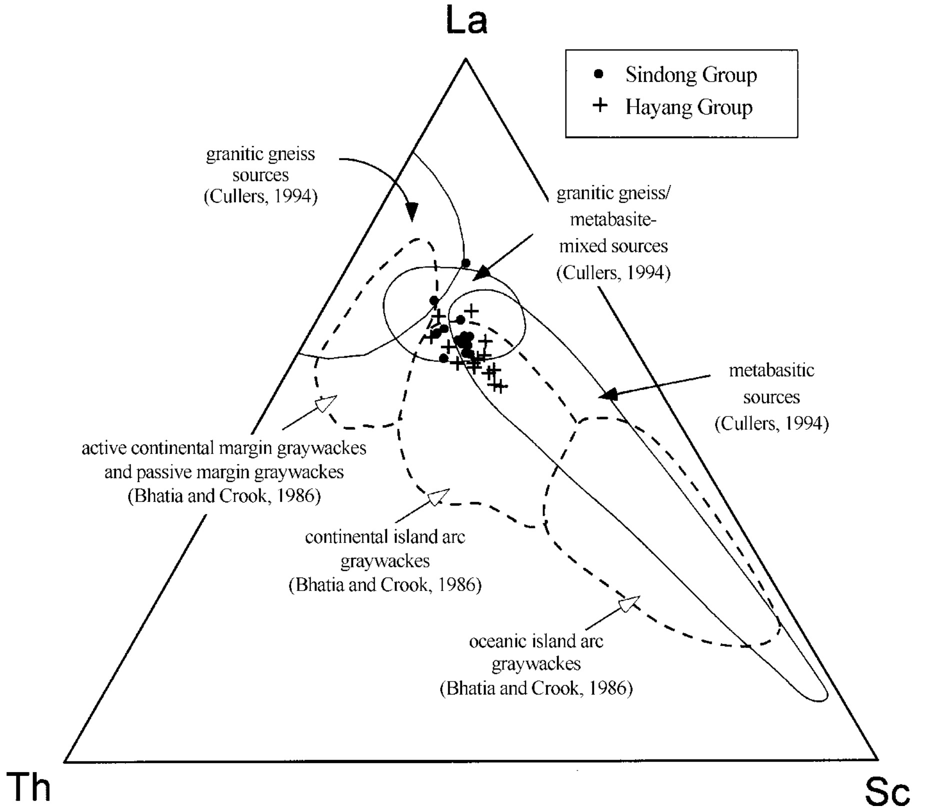

Fig. 8. La–Th–Sc discriminating diagram for Sindong and Hayang mudrocks. Compositional fields of graywacke from known tectonic settings and metamorphic sources of various composition are drawn for comparision.

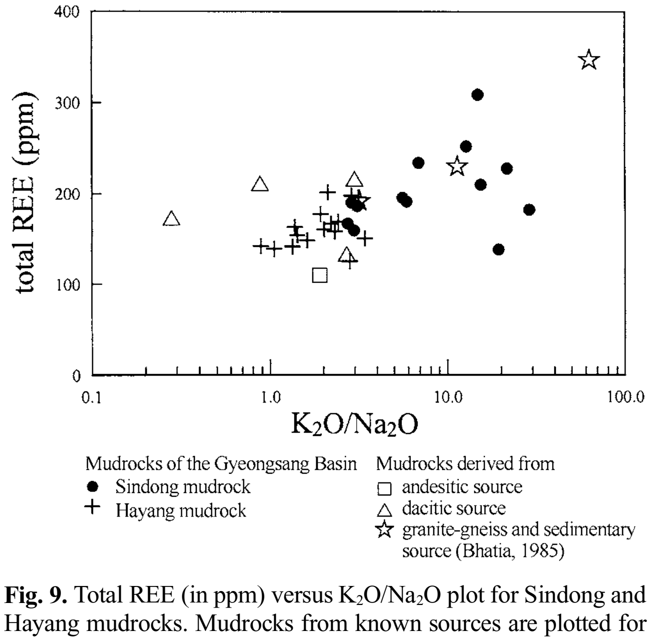

Fig. 9. Total REE (in ppm) versus K_2O/Na_2O plot for Sindong and Hayang mudrocks. Mudrocks from known sources are plotted for comparison.

arc-terrain and of mudrocks derived from dacitic volcanics with minor sedimentary rocks (Bhatia, 1985).

5. CONCLUSIONS

Despite the possible influence of weathering and diagenesis on the chemical composition of the Sindong and Hayang mudrocks, information on provenance and tectonic settings could be obtained from major, trace and rare earth element composition of mudrocks. Upper continental crust rocks were the most important sources for both the Sindong and Hayang groups considering REE patterns. Source area was composed of granite-gneiss and sedimentary rocks during the deposition of the Sindong Group, but volcanic rocks started to yield detritus to the basin from the deposition of the Hayang Group. Such a setting can be found in a basin formed on continental crust with minor volcanism. Tectonic-setting discrimination diagrams and trace and rare earth element characteristics indicate similarity of chemical compositions of Sindong and Hayang mudrocks to those of sediments deposited in passive to active continental margin. The Gyeongsang Basin was formed on eastern continental margin of Asia where volcanic activity was not important during Sindong deposition, thus overall chemical compositions of the Sindong mudrocks are similar to those of sediments deposited in passive margin setting. Volcanism in the source area during Hayang deposition changed the sediment composition closer to that of active continental margin sediments.

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