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A Possibility of Dual Volcanic Chains in the Southern Part of Korea: Evidences from Geochemistry

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ABSTRACT: The development of dual volcanic chains, parallel to the trend of the subduction trench, is observed in the southern part of Korea. Elsewhere on the Earth volcanic arcs dominantly consist of two such chains. In the southern part of Korea, two volcanic chains within a single volcanic arc was developed. Kyongsang basin, where the first volcanic chain located, and Youngdong-Kwangju depression zone where the second volcanic zone located, showed sub-parallel volcanic rock distributed areas. Concentrations of incompatible elements in the southern part of Korea samples show clear across-arc variations, with lavas from the first volcanic chain being most depleted in these elements, all incompatible element concentrations increase towards the second volcanic chain. The above across-arc variation may be caused by the difference in solid phases coexisting with the fluid phases during the dehydration processes. The concentrations of incompatible elements, Zr/Y ratios, and Rb/K ratios indicate that the second volcanic chain (Youngdong-Kwangju depression zone) was generated by low degrees of partial melting at the deeper depth compared to the conditions of the first volcanic chain (Kyongsang basin) and residual garnet probably attributed to the their partial melting.

INTRODUCTION

Although volcanoes of subduction zones do not always occur within volcanic arcs, it is true that they are concentrated in certain areas. They are, in general, parallel to the trend of subduction trenches. Dual volcanic chains, defined as two volcanic chains which are parallel to a trench with a definite distance within one subduction system, have been first emphasized by Marsh (1979). Dual volcanic chains are found in Aleutians, Kamchatka, Kurile, NE Japan, Indonesia, and Scotia arc. Avdeiko *et al.* (1991) proved the characteristic distributions of dual volcanic chains, volcanic islands and submarine volcanoes, in the Kurile arc. The presence of dual volcanic chains are also recognized in other areas such as Philippine, Sangihe, New Zealand, and Chilean Andes (Tatsumi *et al.*, 1994, 1995; Tatsumi, Eggins, 1995). The distance of two separated volcanic zones becomes shorter to south in the Izu arc, which relate to steepening subduction angle toward south. Therefore, single volcanic chain appear arcs with a more highly-angled subduction. Mariana arc is an average of single volcanic chain.

When volcanic rocks in the Kyongsang basin and south coast of Korean Peninsula are viewed in terms of a series of volcanic chains in a subduction system, regular distances can be recognized between volcanic rocks in the Youngdong-Kwangju depression zone and those in the Kyongsang basin, suggesting a possibility that two volcanic areas were formed by dual volcanic chain in a single subduction system. Thus, this study are planned to examine the possibility of dual volcanic chains between volcanic rocks in the Youngdong-Kwangju depression zone and Kyongsang Basin. The geochemical characteristics of volcanic rocks in these areas were compared. Volcanic rocks in the Kyongsang basin are regarded as a first volcanic zone and those in the Youngdong-Kwangju depression zone as a second zone for the convenience of discussion (Fig. 1). Data for volcanic rocks in the Youngdong-Kwangju depression zone, Kageodo (Kageo island), Kwangju and Koheung area were cited from Kim *et al.* (1997) and Wee, So (1992), respectively.

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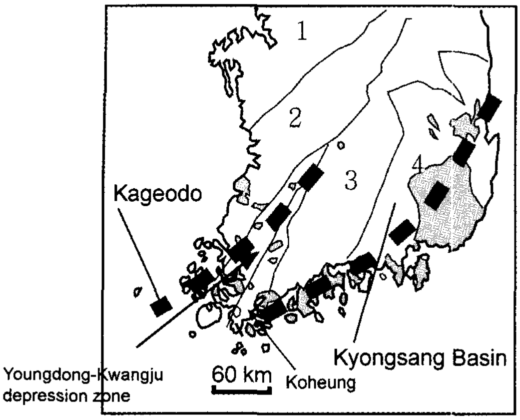

Fig. 1. Geological units of South Korea (Reedman, Um, 1975). 1; Gyeonggi massif, 2; Ogcheon fold belt, 3; Sobaegsan massif, 4; Kyongsang basin. The two thick broken lines represent the first chain (Kyongsang basin) and the second chain (Youngdong-Kwangju depression zone) of volcanic zone. Gray area; volcanics distributed area.

THE CHARACTERISTICS OF DUAL VOLCANIC CHAIN

One of the characteristics for dual volcanic chain is that larger volume of volcanoes are concentrated in the trench-side first volcanic zone (Sugimura *et al.*, 1963; Marsh, 1979; Aramaki, Ui, 1982; de Silva, Francis, 1991). On the other hand, less volcanoes are distributed in the second volcanic zone. Both zones are considered to be formed by one subduction system (e.g., Mariana arc; Stern *et al.*, 1993).

Marsh (1979) suggested mechanism for occurrences of the dual volcanic chains based on the fluid instability and numerical experiments. If an partially molten layer forms near the surface of the subducting slab, some of the upper part of melt would be unstable. As a result, volcanic zones would be formed near trench areas, whereas a second volcanic zone are formed by the deeper melt near back-arc areas. Although this model are related to the solidus temperature (1000) of hydrous peridotite, the temperature distribution of the subduction environment would be variable depending on the volcanic arcs (e.g., Peacock, 1990). Dehydration reactions of amphibole and chlorite which is pressure-dependent reactions occur at 3.5 GPa (35 kbar; e.g., Millhollen *et al.*, 1974; Goto, Tatsumi, 1990) and phlogopite at 6 GPa (Sudo, Tatsumi, 1990). This could explain the apparent

Table 1. Representative major elements and CIPW norms of the Kageodo volcanics.

Sample	kk3	kk5	kk4	kk32	kk8	kk34	kk31	kk7	kk6	kk1
SiO_2	57.61	57.72	58.66	60.67	64.45	67.41	69.52	73.33	74.95	75.40
TiO_2	1.06	0.96	0.97	0.88	0.72	0.55	0.52	0.37	0.32	0.31
Al_2O_3	16.31	16.95	16.34	16.03	15.47	15.02	14.67	13.15	13.72	12.04
Fe_2O_3*	7.99	6.92	6.73	5.74	4.68	3.34	2.44	2.00	0.49	1.43
MnO	0.11	0.11	0.11	0.10	0.07	0.06	0.04	0.02	0.01	0.01
MgO	2.87	2.69	2.69	2.32	1.86	1.00	0.48	0.34	0.13	0.29
CaO	4.93	5.65	5.65	3.70	2.57	2.35	1.12	0.71	0.23	0.95
Na_2O	3.60	3.45	3.45	3.86	3.65	3.62	3.00	1.95	1.93	2.64
K_2O	2.82	2.47	2.47	3.80	4.72	4.72	6.14	6.27	7.46	4.89
P_2O_5	0.36	0.59	0.59	0.34	0.25	0.14	0.10	0.07	0.03	0.05
LOI	1.66	1.82	1.82	1.87	1.09	1.65	1.69	1.51	0.72	1.52
Total	99.32	99.59	99.46	99.30	99.53	99.85	99.72	99.72	99.98	99.53
Q	8.67	5.35	12.11	10.92	15.52	20.97	25.18	35.92	34.78	39.21
C		1.12			0.21		1.28	2.04	2.11	0.78
Or	17.20	30.14	15.05	23.19	28.48	28.52	37.13	37.83	44.47	29.55
Ab	31.38	28.22	30.04	33.66	31.47	31.25	25.92	16.81	16.44	22.80
An	20.60	14.36	22.42	15.62	11.52	10.98	5.08	3.18	0.97	4.52
Di	2.06		2.41	1.05						
Hy	15.58	16.65	13.38	11.91	9.91	0.06	3.69	2.95	0.46	2.15
Mt	1.62	1.40	1.36	1.16	0.94	6.17	0.48	0.39	0.09	0.28
Il	2.08	1.87	1.90	1.72	1.40	1.07	1.01	0.72	0.61	0.60
Ap	0.81	0.90	1.33	0.77	0.56	0.31	0.22	0.16	0.07	0.11

Total iron is reported as FeO*

onset of pressure-related partial melting beneath those two volcanic chains (10818 and 17312 km; Tatsumi, 1989; Tatsumi, Eggins, 1995). Large fraction of melts can be generated by enormous fluid flow formed from amphibole/phlogopite breakdown and thus, more and larger volcanoes forms trenchward volcanic chain.

GEOCHEMICAL CHARACTERISTICS IN THE KYONGSANG BASIN AND YOUNGDONG-KWANGJU DEPRESSION ZONE

Representative major, trace and REE elements of the Kageodo volcanics of Youngdong-Kwangju depression zone and the volcanics of Kwangju and of Koheung area are shown in Tables 1, 2, 3 and 4. Volcanic rocks in the Kyongsang basin and Youngdong-Kwangju depression zone are mainly calc-alkaline (Fig. 2h). In order to compare their geochemical characteristics between the Kyongsang basin and Youngdong-Kwangju depression zone, incompatible elements of the Kyongsang basin and the Kageodo volcanics were plotted in Fig. 3. They generally show more enrichment in elements with larger ionic radius when comparing those with an identical charge, which is one of the characteristics of subduction-related magmas (Tatsumi *et al.*, 1986, 1995; Tatsumi, Eggins, 1995). The Kageodo volcanics show more enrichment in the elements than those in the Kyongsang basin. Volcanism in a subduction zone show somewhat different natures compared rocks to backarc-side "intra-plate" volcanism in Northland, New Zealand (Weaver, Smith, 1989; Briggs, McDonough, 1990) and from Patagonia (Stern *et al.*, 1990). The ratios of Nb/Zr clearly reflect their differences as shown

Table 2. Representative trace and REE analyses of the Kageodo volcanics.

Sample	kk3	kk4	kk32	kk8	kk34	kk31	kk7	kk6	kk1
Co	87	69	81	58	144	68	175	123	209
Sc	20	12	7	7	4	4	3	3	4
Cr	38	14	17	17	9	5	6	5	8
Ni	19	7	12	9	7	4	6	4	7
Cu	6	6	15	10	5	4	4	3	5
Pb	16	12	13	22	20	27	20	43	18
Zn	94	87	88	61	31	33	19	37	39
Rb	117	95	127	162	111	176	175	193	154
Cs	3	4	6	5	4	3	3	3	2
Ba	857	625	923	888	829	1431	1123	914	1033
Sr	649	719	359	385	219	177	307	140	273
Ga	28	22	22	21	17	25	20	19	21
Ta	0.8	0.4	0.8	0.8	1.6	1.3	1.7	1.2	1.8
Nb	11.6	7.9	12.8	11.1	17.7	18.6	18.4	15.5	28.6
Hf	3.2	1.6	5.2	3.6	6.1	6.2	5.6	6.6	6.3
Zr	77	41	112	79	120	122	104	125	133
Y	25.7	23.7	22.6	26.2	22.8	27.7	21.3	25.4	26.2
Th	11.1	11.7	20.6	21.4	28.6	31.4	36.0	36.1	30.8
U	2.1	2.1	3.8	4.1	5.1	5.8	5.1	5.6	4.6
La	42.86	42.40	52.22	55.10	62.37	63.49	58.24	65.82	64.10
Ce	88.57	84.31	102.08	108.42	120.32	125.22	103.28	126.01	122.53
Pr	10.42	9.82	11.42	12.05	12.86	13.63	11.84	13.47	13.15
Nd	39.27	37.76	42.27	42.23	43.82	48.94	39.92	43.61	44.39
Sm	7.11	7.01	7.15	7.38	7.11	8.11	6.45	7.30	7.18
Eu	1.59	1.84	1.50	1.53	1.31	1.36	0.86	1.05	1.05
Gd	6.23	6.05	5.79	6.43	5.86	6.59	4.84	5.96	5.75
Tb	0.77	0.77	0.76	0.82	0.75	0.88	0.66	0.76	0.75
Dy	4.31	4.55	4.46	4.74	4.58	5.28	3.85	4.47	4.17
Ho	0.85	0.84	0.84	0.88	0.87	0.99	0.73	0.88	0.82
Er	2.36	2.29	2.50	2.59	2.56	2.93	2.32	2.64	2.47
Tm	0.32	0.29	0.32	0.34	0.36	0.40	0.34	0.31	0.35
Yb	2.09	2.05	2.35	2.46	2.70	2.83	2.26	2.45	2.33
Lu	0.29	0.31	0.36	0.36	0.39	0.43	0.31	0.34	0.34

Table 3. Representative major elements and CIPW normative minerals of the volcanics from the Kwangju and Koheung area.

Sample	DS-13	G-2	DS-15	DS-27	U-11	DS-32	KJ-1	B-4	O-1	H-2	O-2
SiO_2	50.94	52.10	52.49	53.45	55.00	55.15	55.16	57.00	57.80	58.60	59.10
TiO_2	1.28	1.20	1.23	1.17	0.57	1.11	1.11	0.58	0.57	0.62	0.67
Al_2O_3	15.15	15.40	15.40	14.99	19.00	12.27	12.87	17.70	17.00	17.20	17.10
FeO*	9.57	6.33	8.49	8.59	7.30	8.69	9.91	6.08	6.62	6.37	5.77
MnO	0.14	0.13	0.14	0.12	0.15	0.15	0.14	0.13	0.14	0.14	0.08
MgO	8.78	5.79	7.01	7.21	3.58	8.93	9.45	4.05	3.93	3.93	3.04
CaO	6.45	6.98	6.88	4.67	7.18	6.41	4.11	6.87	6.24	6.41	5.52
Na_2O	1.82	3.57	2.02	2.15	2.41	2.39	2.19	3.17	3.21	2.31	4.05
K_2O	2.22	1.32	1.97	1.75	1.48	2.17	1.97	1.62	2.32	2.19	2.25
P_2O_5	0.80	0.01	0.77	0.72	0.11	0.66	0.46	0.07	0.10	0.10	0.28
Total	97.15	92.83	96.40	94.82	96.78	97.93	97.37	97.27	97.93	97.87	97.86
Q	1.62	2.16	5.85	10.91	10.66	5.07	7.42	9.28	8.51	14.10	8.95
C				2.74	0.61		0.65				
Or	13.50	8.40	12.07	10.90	9.04	13.09	11.95	9.84	14.00	13.22	13.59
Ab	15.81	32.47	17.69	19.14	21.03	20.60	18.98	27.52	27.68	19.93	34.95
An	27.31	23.74	28.07	19.97	36.13	16.63	18.15	30.03	25.59	30.67	22.25
Di	0.63	10.92	2.14			9.59		3.75	4.46	1.00	3.35
Hy	34.68	18.34	28.09	30.37	19.53	29.45	37.42	16.91	16.96	18.23	13.70
Mt	2.16	1.49	1.93	1.98	1.65	1.94	2.23	1.37	1.48	1.42	1.29
Il	2.50	2.45	2.42	2.34	1.12	2.15	2.16	1.13	1.10	1.20	1.30
Ap	1.80	0.02	1.74	1.66	0.25	1.47	1.03	0.16	0.22	0.22	0.62

Total iron is reported as FeO*, Data from Wee, So (1992).

Table 3. Continued

Sample	DSA1	NY-1	KJ-2	J-22	DY-4	KJ-73	DY-5	G-34	NY-2	KJ-72	BR1
SiO_2	59.21	60.30	64.060	65.20	64.15	65.75	66.95	68.30	69.20	70.72	71.27
TiO_2	0.82	0.53	.86	0.62	0.44	0.33	0.54	0.44	0.21	0.28	0.47
Al_2O_3	15.72	16.20	14.99	16.60	16.44	13.65	17.55	15.60	16.10	15.40	13.57
FeO*	7.15	5.01	5.21	3.63	3.98	2.62	2.82	2.85	2.41	2.58	3.12
MnO	0.09	0.10	0.10	0.11	0.08	0.06	0.04	0.08	0.06	0.06	0.07
MgO	5.22	2.52	2.05	1.16	1.92	1.29	0.55	0.60	0.41	0.46	4.21
CaO	2.02	5.24	6.16	2.61	5.04	3.06	2.51	1.61	0.94	3.44	0.02
Na_2O	3.23	2.68	2.93	4.59	2.56	2.67	3.53	4.51	3.53	2.00	2.56
K_2O	3.33	2.86	2.08	2.61	4.47	4.49	4.78	4.60	4.36	4.66	3.76
P_2O_5	0.25	0.60	0.38	0.13	0.18	0.13	0.13	0.06	0.07	0.11	0.10
Total	97.04	96.04	98.82	97.26	99.26	94.05	99.40	98.65	97.29	99.71	99.05
Q	12.34	18.00	22.60	20.06	17.53	25.39	20.90	18.93	28.82	32.02	34.16
C	3.76	0.45		1.79			2.28	0.39	4.11	1.03	5.29
Or	20.28	17.60	12.44	15.87	26.62	28.23	28.44	27.57	26.50	27.64	22.42
Ab	28.10	23.57	25.04	39.87	21.79	23.99	30.01	38.63	30.66	16.95	21.81
An	8.81	23.40	21.81	12.53	20.25	12.70	11.76	7.74	4.37	16.47	0.10
Di			5.71		3.22	2.18					
Hy	22.94	13.43	8.76	7.57	8.49	5.94	4.68	5.14	4.41	4.56	14.54
Mt	1.61	1.14	1.15	0.81	0.87	0.60	0.61	0.63	0.53	0.56	0.68
Il	1.60	1.05	1.65	1.21	0.84	0.67	1.03	0.85	0.41	0.53	0.90
Ap	0.56	1.36	0.84	0.29	0.40	0.30	0.29	0.13	0.16	0.24	

in Fig. 3c. All Nb/Zr ratios for rocks from the Kyongsang basin and Kageodo areas are not plotted in the field for backarc side "intra-plate" volcanism. In addition, Nb/Zr ratios for rocks from the Kyongsang basin are relatively lower than those from Kageodo and Kwangju area and similar

Table 4. Representative trace and REE compositions (ppm) of the volcanic rocks from Kwangju and Koheung area.

Sample	BR1	DS-32	DY-4	DY-5	KJ-2	KJ-17	KJ-72	DS-13	DS-15	DS-27	DSA11	KJ-73
Co	14	64	10	71	46	87	106	40	35	29	19	15
Ni	10	62	8	16	14	39	9	65	53	50	27	16
Cu	36	39	19	35	25	20	11	27	30	76	7	6
Zn	101	87	75	77	98	119	89	110	107	94	91	69
Rb	193	81	142	232	89	129	215	51	91	88	99	154
Ba	1580	896	1540	1360	1053	812	1289	803	994	842	1286	1160
Sr	442	1220	569	610	653	474	260	1236	1073	926	588	382
Ta								1.08	1.58	1.18	1.49	1.87
Nb								18.9	22.4	19.3	12.7	15.4
Hf								4.63	5.29	5.39	5.61	2.75
Zr								277	319	361	260	131
Y	66	33	37	62	34	44	55	31	35	33	33	53
Th	10.1	8.3	9.2	11.5	3.2	6.5	15.1	4.7	5.8	6.5	15.0	17.2
La								31.8	44.1	41.4	33.1	65.6
Ce								62	79	75	68	100
Nd								30.1	37.6	34.3	26.4	37.1
Sm								9.9	12.2	10.8	9.3	8.0
Eu								2.50	3.18	2.70	1.89	1.24
Gd								9.56	10.88	10.29	8.64	4.93
Tb								1.10	1.25	1.17	1.05	0.55
Yb								2.43	2.54	2.53	3.03	1.78
Lu								0.31	0.35	0.33	0.49	0.18

Data from Wee, So (1992).

to those from Koheung volcanics.

When concentrations of incompatible elements of the volcanic rocks in the Kyongsang basin, Kageodo, Kwangju and Koheung area are compared to each other, those in the Youngdong-Kwangju depression zone are characterized by their higher concentrations than those in the Kyongsang basin, showing across-arc variations except Th, Zr and Pb (Fig. 2). Although the concentration of Pb and Zr are exceptionally low, their variation trend increases steeply in the Kageodo area. Zr and Nb are inversely proportional to SiO_2 in volcanic rocks in Kwangju and Koheung areas. However, their absolute amount of concentration are higher than those in the Kyongsang basin indicating characteristics of a second volcanic chain (Tatsumi *et al.*, 1995).

FUNDAMENTALS OF ACROSS-ARC VARIATIONS

It is already well-known that across-arc variations in K_2O concentrations of basaltic rocks are present in the Kyongsang basin and Kamchatka (Erlich, Gorshkov, 1978). The concentrations of K_2O and incompatible elements are generally more enriched as being away from the volcanic front (Dickinson, Hatherton, 1967; Dickinson, 1975; Gill, 1981). Recently, Tatsumi, Eggins (1995) reported that the across-arc variations in Kurile, NE Japan, Luzon, Sunda, Sangihe, New Zealand, and Chile showing a significant increase of K_2O and incompatible elements towards the back-arcs. Based on the experimental studies on the melting phase relation of natural basalt compositions (e.g., Tatsumi *et al.*, 1983, 1994), the direct partial melting of upper mantle peridotite compositions (e.g., Takahashi, Kushiro, 1983; Falloon *et al.*, 1988; Hirose, Kushiro, 1993), and chemical compositions of natural arc basalts, it is suggested that across-arc variations fundamentally depend on the degree of partial melting related to magma generating depth. This is confirmed in the NE Japan, Izu-Bonin, and Sangihe arcs (Morrice, Gill, 1986; Sakuyama, Nesbitt, 1986; Tatsumi *et al.*, 1983, 1991, 1992).

The concentration of Sr is either constant or slightly decreased with increasing of SiO_2 in the mafic volcanic rocks in the Kyongsang basin (Sung *et al.*, 1997; Fig. 2.6a). It suggests that the effects of plagioclase was weak for the whole rock compositions although there may be abundant plagioclase phenocrysts. In addition, low-pressure

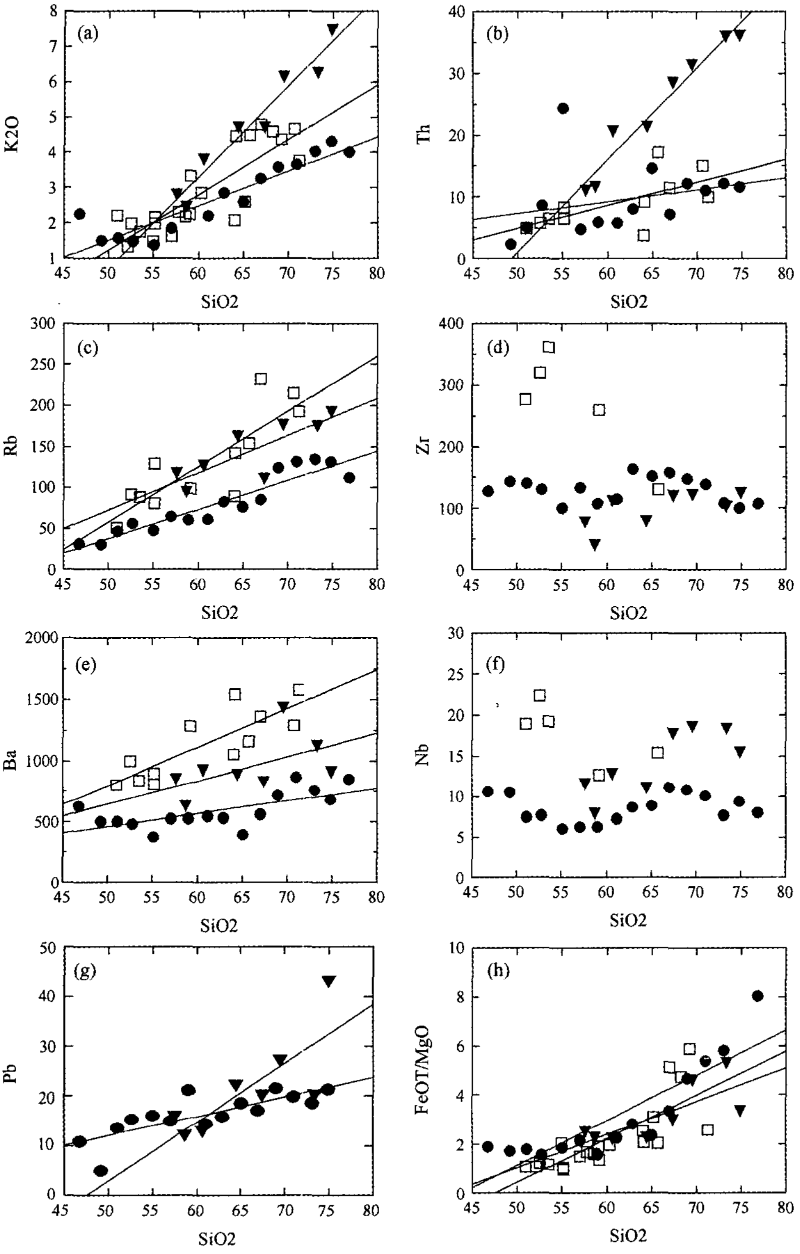

Fig. 2. Across-arc variations in concentrations of incompatible elements of the volcanics in the Kyongsang basin (●), Kageodo (▼), Kwangju (■) and Koheung area (□) volcanics. The second chain magmas are characterized by their higher concentrations of those elements than the first chain magmas.

fractionation caused by the effect of continental crust (e.g., Sung *et al.*, 1997) could generate conspicuous fractionation of peridotites (Brophy, Marsh, 1986; see their Fig. 1). Thus, the composition of primary magma can be inferred from calculations using the fractionation model of peridotites. Under the assumption that Fo and $[Fe^{2+}/(Fe^{2+}+Fe^{3+})]_{magma}$ of the residual olivine of the mantle are assumed to be Fo_{90} and 0.9, and the substitution partition coefficients of Fe-Mg to be 0.3 ($D^{Fe-Mg}_{ol/melt}=0.3$) (e.g., Tatsumi *et al.*, 1995), the primary magma compositions of the Kyongsang

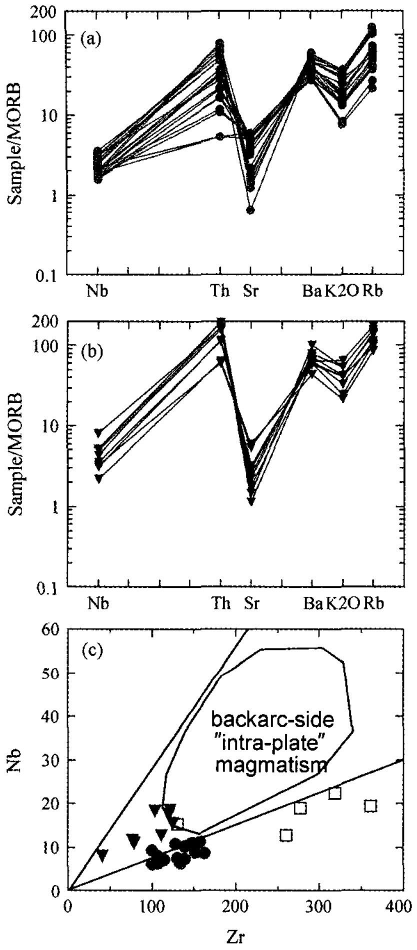

Fig. 3. Geochemical characteristics of the Kyongsang basin, Kageodo, Kwangju and Koheung volcanics. a, b) Incompatible element characteristics in sequence of increasing ionic radius from left to right. c) Nb/Zr ratios for rocks from the Kyongsang basin and Kageodo area, and "backarc side intravolcanism" range in New Zealand (Briggs, Goles, 1984; Briggs, McDonough, 1990) and Patagonia (Hickey-Vargas *et al.*, 1989).

basin are calculated from the average basalt with 52 wt.% SiO_2. For the Youngdong-Kwangju depression zone, the primary magma compositions are also calculated from the olivine fractionation from the sample (No. 5) in Min *et al.* (1988). The compositions of these inferred primary magmas are plotted in the plagioclase-olivine-quartz plane with a projection from diopside (Fig. 4). When these primary magma compositions were compared to compositional variations of partial melts of peridotites at the isobaric system (Hirose, Kushiro,

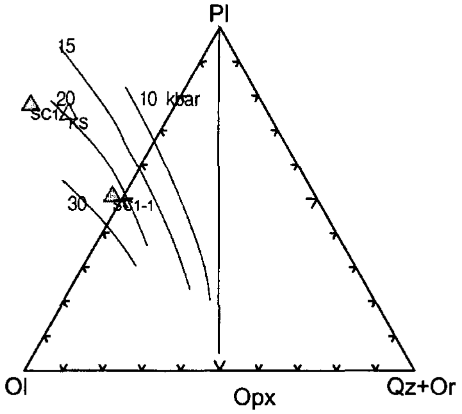

Fig. 4. Normative compositions (Walker *et al.*, 1979) of inferred primary magmas from the first (open triangle; Kyongsang basin) and the second (filled triangle; Youngdong-Kwangju depression zone) volcanic chains in the southern Korea with isobaric compositional trends for partial melts of a peridotite after Hirose, Kushiro (1993).

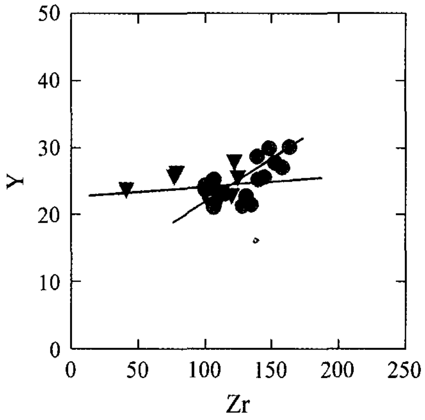

Fig. 5. Y-Zr ratios for rocks in the Kyongsang basin and Kageodo area. Rocks in second chain have systematically lower values than those from the first chain, suggesting the presence of garnet as one of the residual phases during partial melting. It follows that the second chain magmas are produced at pressures greater than 2.5 GPa and by rather smaller degrees of partial melting. Symbols are the same as Fig. 2.

1993), it is implied that magmas of second volcanic chains was generated at the deeper depth than those of first volcanic chains (e.g., Fig. 7). The role of H_2O should be considered in the primary magma to confirm the across-arc variations depending on the generated depth of magmas. Although there is no systematic measurements of H_2O content in melt inclusions in mafic phenocrysts in arc rocks, Sakuyama (1983) and Ishikawa

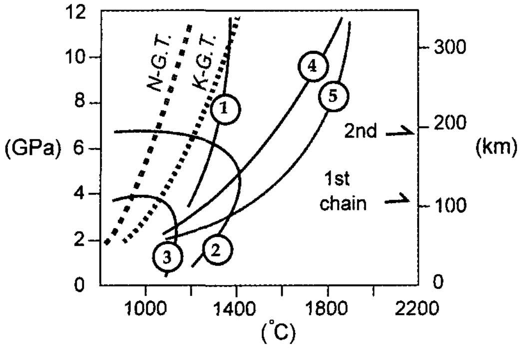

Fig. 6. Stability limits of K-amphibole (1, Foley, 1991; Sudo, Tatsumi, 1990), phlogopite (2, Sudo, Tatsumi, 1990; Yoder, Kushiro, 1969), and pargasite (3, Millhollen *et al.*, 1974; Wallace, Green, 1988) and solidus curves for an anhydrous MORB (4, Yasuda, 1990) and an anhydrous peridotite (5, Takahashi, 1986). The depth to the top of the subducting slab beneath each volcanic chain is shown. Schematic temperature distribution at the slab/wedge interface is drawn for normal arc (N-G.T.) and northern edge of Kamchatka (K-G.T.) based on the results of numerical calculations suggesting ~200°C higher temperature at the side-edge of the subducting slab at a ~300 km depth (Tatsumi *et al.*, 1994).

et al. (1980) reported the across-arc variations in phenocryst assemblages and F (fluor) contents in melt inclusion, concluding that primary magmas of second volcanic chains contained more water. If water content is considered for magmatism in the Kyongsang basin and Youngdong-Kwangju depression zone, the difference of magma generation depth between two areas would be greater than those indicated in Fig. 4.

There is further evidence for confirming the mechanism described above. The slope of Y to Zr are systematically lower in the second volcanic chains than in the first (Fig. 5), suggesting the presence of residual garnet during the partial melting process only for the second chain magmas (Smith *et al.*, 1996). It indicates that this type of magma segregation can be expected at pressures greater than 2.5 GPa accompanying a relatively smaller degree of melting.

What is the mechanism according to different depths of magma segregation in the across-arc direction? It is not been well established whether the movement of partial melt before the melt segregation from the mantle occur as pore fluid along the boundary of solid grain (McKenzie, 1984) or as diapiric ascending (Tatsumi, Eggins, 1995). Primary magma can be separated from the mantle through cracks and fractures by buoyant ascending (Anderson, Grew, 1977; Sleep, 1988; Spence, Turcotte, 1990; Takada, 1990; Lister, Kerr, 1991; Furukawa, 1993). The presence of dikes in mantle peridotites emphasizes the importance of melt-filled crack propagation under relatively shallow lithospheric mantle conditions (Shaw, 1980; Nicolas, Jackson, 1982; Nicolas, 1986). Crack creation and growth may be governed by local differential stress. When melts rose up by pore fluids or mantle diapir, and reached to the more rigid (high viscosity) overlying region upper area, ascent is curtailed and the melt may be forced to flow horizontally. This may result in significant differential stress within the rising body and make it possible for buoyant melts to be separated and to generate cracks. The viscosity of mantle materials is strongly controlled by their temperatures and significant increases of viscosity are induced at or near the asthenosphere/lithosphere boundary or near particular isotherm. The degree of partial

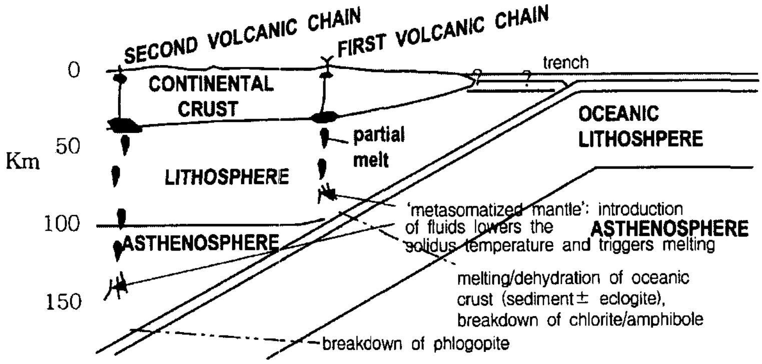

Fig. 7. Schematic cross section of dual volcanic chains in the southern part of the Korean Peninsula.

melts decreases toward backarc because the depth of the asthenosphere/lithosphere are deepened to this direction.

It is consistent with the seismic data from the NE Japan arc (Zhao, 1991) and also with numerical simulation of the thermal structure in the mantle wedge (e.g., Furukawa, 1993). Both examples indicate that iso-velocity or iso-thermal contour are inclined and thus, locate at the deeper part beneath the backarc within single arc system (Furukawa, 1993). When these arguments are simply applied to the Kyongsang basin and Youngdong-Kwangju depression zone, magmas in the Youngdong-Kwangju depression zone (the second volcanic chain) which is more close to the backarc side, may be generated at the deeper level with low degree of partial melting than those in the Kyongsang basin (the first volcanic chain). It is also compatible with discussion in the preceeding chapter, in which volcanic rocks in Youngdong-Kwangju depression zone contain more enriched incompatible elements indicating low degree of partial melting.

Thermal structures in mantle are formed basically from the movement of materials derived from the secondary convection which is caused by a slab subduction (e.g., Honda, 1985; Davies, Stevenson, 1992). According to numerical calculation of simulation experiments (Furukawa, 1993), iso-therms in the mantle wedge are inclined upwards from the back-arc toward the volcanic arc. It is consistent with the arguments that the separation depth of primary magma is deeper beneath the backarc-side of normal subduction zones.

ORIGIN OF THE DUAL VOLCANIC CHAINS IN THE SOUTHERN PART OF KOREA

It is known that the depth of seismic zone of Kamchatka are 110 km and 180 km beneath the first and the second volcanic chain, respectively. These values are similar to 108±18 km and 173±12 km reported from the most subduction zones with two volcanic chains, respectively. The constant depth to the top of downgoing slab is due to pressure-related dehydration reactions of down-dragged hydrous peridotite layer at the base of mantle wedge (Tatsumi, 1989; Tatsumi *et al.*, 1991; Tatsumi, Eggins, 1995). The initial melts for the first chain magmas are generated in the mantle wedge by influx of fluid phases released through decomposition of both amphibole and chlorite at ~3.5 Gpa and those for the second chain magmas through phlogopite decomposition at ~6 GPa (Tatsumi *et al.*, 1995).

The thermal gradients in the Kyongsang basin and Youngdong-Kwangju depression zone were probably similar to the ordinary thermal gradients in a single subduction system as shown in Fig. 6. And the melts to the dual volcanic chains may be generated when solidus temperatures were lowered by the water resulted from the dehydration reaction according to and in Fig. 6. Rarely, a third chain exists in Kamchatka, which is due to the different thermal gradient in the northern Kamchatka (Fig. 6). Since the data about subcrustal geothermal gradient or deep seismicity for subcrustal structure of Korea including the Kyongsang basin are insufficient, the possibility of a third volcanic chain for the volcanism in the Gyeonggi massif remains to be answered.

Rb/K ratios for rocks from the Kyongsang basin and Youngdong-Kwangju depression zone (Fig. 2) showing well-defined across-arc variations. Higher ratios of Rb/K in the second chain lavas than first chain lavas (Fig. 8) are reported from various regions such as the Sangihe (Tatsumi *et al.*, 1991), Kurile (Bailey *et al.*, 1989), Izu-Bonin (Tatsumi *et al.*, 1992), and Kamchatka (Tatsumi *et al.*, 1995). These elements behave as incompatible elements during the processes of both crystallization differentiation and partial melting, suggesting the above across-arc variation is caused by the difference in the source compositions. Both Rb and K have low ionic potentials (charge/ionic radius), so that they are likely to behave as soluble ions in a super-

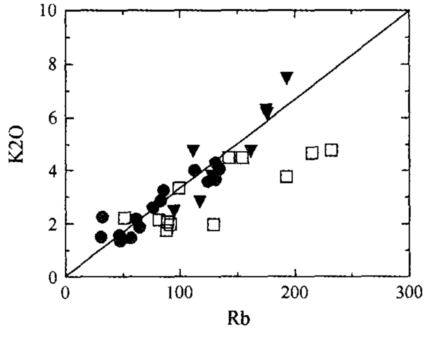

Fig. 8. Rb/K ratios for rocks from dual volcanic chains in the southern Korea. Symbols are the same as Fig. 2.

Table 5. Primary magma compositions.

	1st chain[1]	2nd chain[2]	
	KS	SC1-1	SC1
SiO_2	48.58	49.52	49.52
TiO_2	0.90	1.38	1.38
Al_2O_3	14.25	15.47	15.47
FeO*	8.22	8.64	8.64
MnO	0.12	0.04	0.04
MgO	11.45	12.01	12.01
CaO	12.26	6.01	6.01
Na_2O	2.69	3.19	5.05
K_2O	1.24	3.19	1.33
P_2O_5	0.27	0.55	0.55
Total	100.00	100.00	100.00
FeO*/MgO	0.72	0.72	0.72

Total iron is reported as FeO*.

[1] Sung (2000; average basalts of Kyongsang basin).

[2] Min *et al.* (1988; Jeonnam area, sample number 5).

critical aqueous fluid under upper mantle P-T conditions, which has been also shown by dehydration experiments by Tatsumi *et al.* (1986) and Tatsumi, Nakamura (1986). Therefore, if it is assumed that the across-arc variation in Rb/K ratios results from a difference in the added components to the melt from mantle, in the absence of pre-existing across-arc compositional variation in the mantle wedge, then the hydrous fluid phase responsible for the variable source chemistry has higher Rb/K ratios beneath the second volcanic chain than the first volcanic chain (e.g., Tatsumi *et al.*, 1995). Based on the crystal-structure-control of element partitioning between solid and melt or possible fluid phases (Matsui *et al.*, 1977), the above across-arc variation may be caused by the difference in solid phases coexisting with the fluid phases during the dehydration processes. Aqueous fluid phase containing low Rb/K are derived from amphibole/chlorite breakdown in the presence of phlogopite at 3.5 GPa beneath the first volcanic chain, whereas they are derived from decomposition of phlogopite in the presence of K-amphibole at 6.0 GPa beneath the second chain (Tatsumi *et al.*, 1991). Therefore, the depths of dehydration reactions are consistent with the depth to the base of mantle wedge as emphasized before.

CONCLUSIONS

It is observed that the distribution pattern of volcanic rocks in the Kyongsang basin is parallel to that of Youngdong-Kwangju depression zone and is related to the trend of the subduction trench. The geochemistry of these two regions distinctively show the charateristics of dual volcanic chains related with one subduction. In terms of dual volcanic chains, Kyongsang basin would be a first trenchward chain and Youngdong-Kwangju depression zone would be a second backarcward chain.

The concentrations of incompatible elements, Zr/Y ratios, and Rb/K ratios indicate that the second volcanic chain (Youngdong-Kwangju depression zone) was generated by low degrees of partial melting at the deeper depth compared to the conditions of the first volcanic chain (Kyongsang basin) and residual garnet probably attributed to the their partial melting.

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2000년 7월 11일 원고접수, 2000년 8월 16일 게재승인.

한국 남부의 쌍화산대 가능성: 지화학적 근거

성종규 · 김진섭 · 박맹언 · 양경희

요 약 : 한국 남부에서 섭입 해구의 방향과 나란히 쌍으로 발달한 화산대가 발견된다. 경상분지와 영동-광주 함몰대의 화산암류는 거의 나란한 양상을 보이며, 이들은 각각 동일한 섭입 체계에 따르는 첫 번째 화산대, 두 번째 화산대이다. 경상분지와 영동-광주 함몰대 화산암류의 불호정성 원소 함량은 호를 가로지르는 변화를 뚜렷하게 보인다. 즉, 첫 번째 화산대 (경상분지 및 남해안 도서지역) 용암들의 불호정성 원소 함량은 두 번째 화산대 (영동-광주 함몰대)에 비해 더욱 결핍되며 두 번째 화산대에서 더욱 증가하는 경향을 보인다. 이와 같이 호를 가로지르는 변화를 보이는 것은, 탈수과정 동안 유체상과 공존하는 고체상의 차이에 기인한 것으로 보인다. 두 번째 화산대의 불호정성 원소의 함량, Zr/Y 비, Rb/K 비는 첫 번째 화산대에 비해 더 깊은 깊이에서 더 적은 정도의 부분 용융, 그리고 용융 과정에서의 잔류 석류석에 기인할 것이다.