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Geochemistry and Petrogenesis of Pliocene Alkaline Volcanic Rocks of Dok Island, Korea

Soo Meen Wee*

Department of Earth Science Education, Korea National University of Education,
250 Taeseongtabyeon-Ro, Gangnae, Heungdeok-Gu, Cheongju, Chungbuk 361-892, Korea

Abstract: Dok island comprises Pliocene volcanic products such as a series of volcanoclastic rocks and lavas ranging in composition from alkali basalts, and trachyandesites to trachytes. Compositional variation of the basaltic rocks can be attributed to fractional crystallization of olivine, clinopyroxene, plagioclase, and magnetite. Chemical variations among the trachyandesites are caused by fractionation of clinopyroxene, plagioclase, and magnetite with minor amphibole, while trachytes are controlled mainly by feldspar fractionation. Incompatible element abundance ratios and chondrite normalized LREE/HREE ratios (e.g., (La/Yb)c: 24.8 to 32.8 for basalts, 15.6 to 31.2 for trachyandesites) suggest that the origins of the basalts and trachyandesites involve both different degrees of partial melting and subsequent fractional crystallization processes. Trace element ratios of the basalts from Dok island are characterized by high Ba/Nb, La/Nb, Ba/Th and Th/U and isotopic ratios (Tasumoto and Nakamura, 1991) that are similar to the EM 1 type of oceanic island basalts such as Gough and Tristan da Cunha basalts.

Keywords: Dok-do, alkaline, REE, volcanic rocks

Introduction

The alkaline volcanic rocks were distributed along the northeast margin of the Eurasian plate and around the rim of the East Sea. West of the Japanese arc, Pliocene to Quaternary volcanic rocks are found in several places such as Cheju, Ulleung, and Dok islands, Choogaryong rift valley and Paekdusan in Korea and within the Heilongjiang and Inner Mongolia Provinces in NE China. Dok island (Takeshima, Japanese name), located about 220 km east of the Korean Peninsula in the East Sea, is composed of Pliocene volcanic rocks of dominantly alkaline character. It comprises two small islets named Dongdo (east island) and Seodo (west island), respectively. Geochemical study of the area was made in order to understand how Cenozoic volcanic activities in the Korean Peninsula relate to the tectonic evolution of the northeast margin of the Eurasian Plate, and to constrain the petrogenesis and source characteristics of the volcanic rocks.

Many geological and geochemical studies have been made on the other late Cenozoic volcanic rocks in Korea such as Choogaryong rift, Cheju island, and Ulleung island (Lee, 1966; Lee, 1982; Won and Lee, 1984; Kim, 1985; Yun, 1986; Park and Kwon, 1993), while few studies have been done on Dok island (Fig. 1). In spite of excellent exposures of outcrops, the geology of the Dok island was not fully described until recently. Shon and Park (1994) reported the geology and evolution of Dok island based on geologic mapping and lithofacies analysis. They suggested that the island formed between Early to Late Pliocene and comprises alkali basalt, trachyandesite, and trachyte. Geochemical data of the alkali volcanic rocks from Dok island exist (Kim et al., 1987; Tatsumoto and Nakamura, 1991), but are insufficient to evaluate petrochemical evolution and magma source of the lavas. Kim et al. (1987) studied the major and trace element geochemistry of the volcanic rocks from Dok

*Corresponding author: weesm@knue.ac.kr
Tel: +82-43-230-3741
Fax: +82-43-232-7176

island based on several rock samples. Tatsumoto and Nakamura (1991) measured isotopic ratios in 6 of Kim's samples and reported a Dupal-like signature. Their reconnaissance data is insufficient for a detailed analysis with respect to the chemical evolution and source enrichment processes involved in the petrogenesis of the primary magma. With the exception of the reconnaissance study by Kim et al. (1987), there has been no detailed, quantitative study of the petrogenetic relationships between the rock types. Furthermore, their chemical data are sparse and geographically limited, thus more data must be obtained in order to make reasonable interpretations of the petrogenesis of the alkali volcanic rocks and to characterize their source.

The purpose of this paper is to present major and trace element data on the Pliocene alkaline volcanic rocks from Dok island to constrain the petrogenesis and source characteristics. Since little is known about the geochemistry of the volcanic rocks from Dok island, which is located between the Japanese islands and northeast margin of the Eurasian continent, the data will help cover the spatial gap of geochemical data of the Cenozoic volcanic rocks between the Japanese islands and inland China.

General Geology and Petrography

Dok island is located in the south-central part of the East Sea which is a typical back-arc basin and commonly regarded to have been formed by the rifting and/or opening of the East Sea floor (Uyeda and Kanamori, 1979). This island is built upon on the flank of Oki Bank; its base is 1500m below sea level (Tatsumoto and Nakamura, 1991). The geology of Dok island is well described by Sohn and Park (1994).

Dok island comprises a suite of alkaline rocks ranging in composition from mildly nepheline-normative alkaline basalt to trachybasalt, trachyandesite and trachyte. Detailed mapping and K-Ar age dating of the rock samples reveal that Dok island formed during the Early to Late Pliocene (Sohn and Park, 1994; Park et al., 1995). The subaerial rock exposures on the island can be roughly divided into a lower unit and an upper unit. Pyroclastic rocks were produced during the first stage (4.6-3.7 Ma) and main lava flows in the second stage (2.89-1.89 Ma, Park et al., 1995). The lower unit volcanic rocks are composed of a thick sequence of massive basaltic breccias. The upper unit contains more differentiated compositions and is composed of trachyandesitic lavas and trachytes. Between these two units, a thinly bedded lapilli tuff conformably overlies the basaltic breccias in some places (Park et al., 1995).

Basalts occur as coarse-grained breccias several tens of meters thick. They range in texture from coarsely porphyritic to moderately porphyritic and are usually vesicular. Basalt phenocrysts consist predominantly of clinopyroxene with minor plagioclase and variable amounts of Fe-Ti oxide. Clinopyroxene and plagioclase are often zoned. Olivine is rare, but occurs as phenocrysts in some samples and is altered to iddingsite. The groundmass is hypocrystalline and consists of plagioclase laths, clinopyroxene, Ti-magnetite and interstitial glass. Trachyandesite consists of phenocrysts of alkali feldspar, plagioclase, zoned clinopyroxene, and biotite in a pilotaxitic groundmass of plagioclase, clinopyroxene and opaque mineral. Plagioclase phenocrysts range from andesine to labradorite, often show normal or oscillatory zoning, and are surrounded by thin rims of more alkali-rich feldspar. Trachyte comprises intrusive bodies of trachyte and trachyte dikes which postdate the intrusives (Park et al., 1995). Trachytes show abundant coarse grained alkali feldspar phenocrysts and rare plagioclase, clinopyroxene and biotite phenocrysts. Plagioclase grains are surrounded by thin rims of more alkali-rich feldspar. The groundmass consists predominantly of feldspar laths and minor clinopyroxene, magnetite and has a trachytic, intergranular texture. Trachyte dikes up to several meters thick are observed in several places. They have a trachytic texture of alkali feldspar laths, with alkali feldspar phenocrysts.

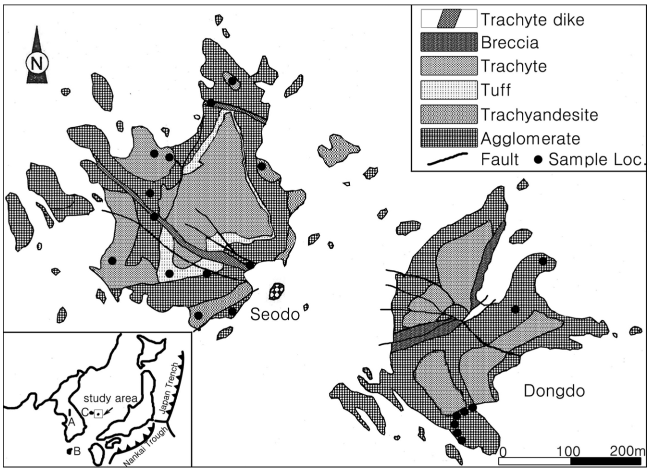

Fig. 1. Geologic map of the Dok island showing sampling sites. Inset: location of Dok island, and locations of the late Cenozoic volcanic rocks in Korea (A: Choogaryong rift, B: Cheju island, C: Ulleung island).

Sampling and Analytical Method

In spite of excellent exposures of outcrops, sampling locations are limited due to the topography of the Dok island which has very steep slopes and cliffs around the island. Since one of the purposes of this study is to report the geochemical data of the rocks in the Dok island, sampling for this study was carried out for all major volcanic units around the island.

Approximately 150 samples were collected from 21 sampling sites (Fig. 1) and 40 samples were analyzed at the Korea Basic Science Center and at the University of California, Santa Cruz. Major elements and Nb and Y were analyzed by X-ray fluorescence spectrometry. Two glass beads (major) and two pressed pellets (trace) were made and analyzed for each sample and the average was used for the data. Rare earth element and other trace elements were measured using high resolution Inductively Coupled Plasma mass-spectrometry (ICP-MS). The analytical precision of these data can be evaluated from replicate analyses of standard rocks and internal standards. The accuracy of the data is estimated to be better than 5% relative for the major elements except for Mn (~10%), and better than 5% for the trace elements except for Sc and Th (6.1 and 7.5%, respectively). Analytical errors for the REE are estimated less than 4%.

Geochemistry

Major elements

Major element compositions, together with the trace and REE abundances, are listed in Tables 1 and 2. Analyzed samples have SiO_2 ranging from 47 to 67 wt.%, and Na_2O+K_2O from 5.6 to 13.2 wt.%, and have alkalic compositions. According to the classification of La Bas et al. (1986), the rocks include basalts, trachybasalts, trachyandesites and trachytes. Selected major element variations, relative to SiO_2 as an index of differentiation, are shown in Fig. 2, and it is evident that generally well-constrained compositional trends are defined by the rocks. With increasing SiO_2 contents, MgO, TiO_2, FeO, CaO, P_2O_5 and CaO/Na_2O ratios decrease, while Na_2O, K_2O and Al_2O_3/CaO ratios increase.

The basalts are not primary melts according to the criteria of Frey et al. (1978). The most primitive basalts have Mg-numbers less than 0.56 (assuming Fe^{3+}/Fe^{2+}=0.15), Ni and Cr <50 p.p.m. (Table 1 and 2), and trend toward lower CaO and MgO with increasing SiO_2 (Fig. 2), indicating differentiated magmas. With increasing SiO_2 content, Al_2O_3 initially increases, then drastically drops at around 52-55 wt.% of SiO_2, and then increases again. This might be caused either by a different degrees of partial melting

Table 1. Whole rock major element compositions of the rocks from Dok Island (unit in wt. %)

Sample	type	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
E1-4	ba	48.79	2.93	18.58	8.50	0.15	2.70	9.03	4.17	1.47	0.90	2.60	99.82
E1-5	ba	51.11	2.32	19.51	7.04	0.15	1.57	7.79	3.12	3.96	0.83	2.54	99.94
E2-0	ba	47.27	2.87	18.45	10.16	0.17	3.79	8.44	2.61	3.27	0.82	2.05	99.85
E2-4	ba	49.61	3.01	17.64	8.46	0.14	2.83	9.04	2.56	3.49	0.86	2.05	99.69
E2-5	ba	47.47	2.87	16.99	10.34	0.38	3.01	8.80	2.55	3.43	0.79	3.16	99.79
E2-6	ba	48.13	2.50	16.22	9.56	0.12	5.91	9.68	2.86	2.86	0.71	1.33	99.88
E9-15	ba	48.75	2.97	17.58	9.18	0.20	3.10	8.64	2.66	3.78	0.79	1.99	99.64
E9-8	ba	51.95	2.69	18.94	7.21	0.10	2.19	7.57	4.88	1.70	0.92	2.08	100.23
EUC3	ba	50.91	2.83	18.22	8.33	0.13	2.35	6.90	3.14	4.60	1.08	0.72	99.22
EUC-9	ba	50.78	2.28	19.14	6.47	0.12	1.41	7.63	2.88	4.17	0.80	2.62	98.27
W24F	ba	50.50	2.64	18.68	7.04	0.18	2.14	7.67	2.94	3.86	1.13	3.12	99.90
W24F-5	ba	48.70	2.65	17.42	8.93	0.32	2.21	7.72	2.97	3.86	1.10	3.65	99.53
E5	ta	56.52	1.76	17.89	5.81	0.12	1.84	4.55	4.20	4.96	0.58	1.28	99.51
E8	ta	57.60	1.68	18.27	5.80	0.12	1.14	3.30	4.20	6.09	0.72	1.03	99.95
EUC5	ta	56.33	1.63	18.24	5.94	0.12	1.26	3.50	3.45	6.20	0.56	2.03	99.24
W25-3	ta	55.83	1.38	17.48	6.33	0.15	1.75	4.46	4.70	4.48	0.38	2.73	99.67
W29	ta	59.60	1.59	18.80	3.49	0.06	1.01	3.18	4.40	6.29	0.52	0.70	99.64
W30	ta	58.94	1.22	17.98	4.47	0.16	1.33	3.07	4.68	6.25	0.37	1.02	99.49
WUC10-2	ta	56.49	1.48	17.86	4.88	0.08	1.21	2.96	4.45	6.23	0.49	1.82	97.96
WUC10-5	ta	57.78	1.47	18.33	4.94	0.09	1.09	2.81	4.37	6.30	0.49	1.04	98.72
WUC29	ta	55.63	1.50	17.72	5.83	0.16	1.32	3.36	4.62	6.08	0.54	1.43	98.18
WUC30	ta	57.91	1.26	17.79	4.87	0.19	1.30	2.85	4.93	6.43	0.41	1.25	99.19
WUC31-3	ta	57.46	1.71	18.37	6.89	0.09	1.27	3.26	4.49	6.03	0.64	0.41	100.61
WUCO3	ta	54.22	1.43	17.25	7.71	0.18	2.17	4.83	4.58	4.77	0.40	1.03	98.58
W1-2	tr	58.55	0.27	18.47	5.25	0.20	0.15	1.63	6.55	5.84	0.04	2.35	99.30
W21	tr	59.12	0.45	18.21	5.51	0.19	0.38	1.90	4.92	5.84	0.13	2.85	99.50
W23-1-4	tr	59.47	0.25	18.75	4.74	0.14	0.16	1.48	6.35	5.89	0.06	1.94	99.23
W23-2-3	tr	58.98	0.49	18.79	4.87	0.20	0.47	2.02	5.71	6.01	0.14	2.03	99.71
W24D	tr	60.92	0.46	18.77	4.40	0.10	0.32	1.53	5.19	6.11	0.13	1.38	99.31
EUC1-3	tr	64.46	0.61	16.07	2.58	0.15	0.47	1.12	5.49	6.02	0.11	1.34	98.42
W25-3-6	tr	59.99	0.47	17.80	5.63	0.18	0.33	2.05	6.01	5.97	0.14	1.04	99.61
W27D	tr	57.94	0.21	18.28	5.36	0.19	0.12	1.69	6.86	5.97	0.05	2.15	98.82
WUC1	tr	58.87	0.25	18.56	5.39	0.16	0.30	1.21	6.27	6.02	0.06	1.78	98.86
WUC21	tr	59.34	0.64	18.65	3.60	0.07	0.42	1.77	4.18	6.54	0.19	2.27	97.65
WUC21F	tr	58.18	0.22	18.39	5.45	0.22	0.25	1.72	7.17	5.99	0.03	1.32	98.91
WUC22	tr	60.20	0.62	18.90	4.34	0.10	0.56	1.57	5.09	6.70	0.16	1.24	99.48
WUC23U	tr	59.56	0.42	18.34	5.08	0.17	0.39	1.84	6.64	6.20	0.09	0.92	99.62
WUC24	tr	58.68	0.44	17.85	5.29	0.13	0.30	1.65	4.39	6.04	0.14	2.89	97.79
WUC27	tr	58.24	0.22	18.40	5.44	0.19	0.15	1.74	6.99	6.05	0.04	1.84	99.31
WUC7	tr	58.84	0.43	18.33	5.22	0.19	0.42	1.83	5.94	6.29	0.12	1.52	99.13

*FeO represent total iron, ba: Basalts, ta: Trachyandesites, tr: Trachytes

(different melt lineage) or by extensive fractionation of plagioclase and feldspar from the same batch.

Trace and Rare Earth elements

The Dok volcanic rocks have high concentrations of incompatible elements and show a wide range in trace element compositions compared to the major element variations. The variation of selected trace elements relative to Zr is shown in Fig. 3. Zr is highly incompatible in the principal phenocryst phases and is insensitive to minor alteration, thus it is a good index of differentiation. Y, Nb, Rb and Hf also behave as incompatible elements and correlate positively with Zr through the series from basalts to trachytes and Th shows substantial scatter. In contrast, Sr and Ba show scattered decrease from basalts to trachytes to near

Table 2. Trace element compositions of the rocks from Dok Island (unit in ppm)

Sample	Ba	Rb	Sr	Y	Zr	Nb	Th	Pb	Cu	Ni	Cr	Hf	Sc	Ta	Co
E1-4	1440	84.4	1395	28.4	385.7	124.5	13.55	7.45	123.41	42.04	6.31	7.49	5.49	11.41	30.92
E1-5	1331	73.9	1350	23.5	388.0	103.0	11.74	8.38	21.64	16.56	2.46	8.04	4.51	10.29	17.94
E2-1	1069	91.5	1126	29.5	339.8	109.9	13.54	16.14	102.94	41.61	17.90	7.57	11.15	14.31	40.36
E2-4	1211	99.7	1308	31.5	423.2	112.4	12.60	8.14	34.02	20.29	14.24	8.46	9.37	10.43	28.35
E2-5	1153	97.9	1279	28.9	407.2	111.6	12.64	20.87	44.46	41.94	20.41	8.45	9.50	10.66	36.95
E2-6	1489	62.2	959.6	29.4	417.4	116.8	12.73	9.11	11.63	17.49	21.00	8.27	7.19	10.74	14.15
E9-15	939.0	86.4	1004	23.3	397.8	110.2	10.57	26.15	81.68	31.67	18.47	8.10	5.76	10.99	30.54
E9-8	961.4	41.2	933.3	24.6	476.7	139.0	9.96	12.90	17.22	22.00	3.20	9.64	3.88	12.40	21.65
EUC3	1219	113.5	1072.0	31.8	458.7	114.4	13.08	8.87	na	na	na	8.68	10.27	5.16	na
EUC-9	1263	77.2	1141.0	24.1	465.7	98.2	11.40	10.49	na	na	na	9.14	10.75	7.01	na
W24F	1253	163.0	1370	33.1	510.7	152.4	15.17	15.98	28.23	6.63	5.67	10.93	6.80	12.32	20.52
W24F-5	1318	131.8	1333	28.2	459.8	115.5	17.31	19.92	20.16	3.26	3.02	10.26	6.43	13.25	20.03
E5	1173	90.7	1227	29.4	410.3	109.6	12.00	8.83	70.49	22.94	6.93	8.25	7.74	10.02	26.85
E8	1544	130.8	1095	22.1	425.5	121.0	12.54	13.96	8.66	5.53	7.45	8.37	7.66	11.06	7.91
EUC5	1514	112.6	1030	23.2	448.7	107.5	11.49	8.96	na	na	na	8.62	7.19	6.76	na
W25-3	729.1	109.0	497.3	40.0	533.4	152.9	15.74	15.32	35.64	21.69	41.02	10.07	5.79	12.29	18.49
W29	1041	145.6	640.9	21.5	511.5	138.3	14.29	11.30	5.66	4.75	5.89	10.20	2.56	12.57	7.00
W30	801.4	169.8	612.2	26.9	648.7	163.9	16.23	14.59	6.33	4.73	7.33	11.83	1.82	13.54	5.83
WUC10-2	831.2	67.6	465.1	27.1	493.1	143.5	10.57	7.38	na	na	na	10.11	3.33	10.76	na
WUC10-5	784.3	91.7	449.4	28.8	503.6	146.6	11.30	7.66	na	na	na	9.88	3.60	10.65	na
WUC29	840.8	58.2	433.8	23.3	448.4	131.9	9.82	7.52	na	na	na	9.20	3.47	9.63	na
WUC30	591.6	84.1	330.6	31.1	532.4	152.4	10.99	8.64	na	na	na	10.79	3.01	11.51	na
WUC31-3	971.2	74.2	539.7	24.3	439.2	135.0	10.38	7.41	na	na	na	9.18	4.45	10.59	na
WUCO3	706.7	54.9	290.9	22.6	397.2	136.1	9.13	6.24	na	na	na	7.99	5.56	9.37	na
W1-2	2.3	242.5	12.2	49.9	844.4	303.4	27.75	15.66	3.93	0.31	4.51	17.91	0.56	23.61	0.61
W21	136.7	150.3	51.4	32.1	667.2	223.5	15.70	8.81	4.47	1.86	8.62	14.20	5.82	19.39	2.31
W23-1-4	7.0	224.2	26.8	47.1	794.0	255.9	29.57	16.77	0.90	0.16	1.39	16.68	0.45	23.43	0.42
W23-2-3	304.1	205.6	105.4	42.0	728.2	227.8	24.23	14.23	6.86	2.57	5.69	16.42	1.41	19.40	3.40
W24D	200.3	188.0	85.3	37.9	742.5	221.8	20.18	9.84	6.25	5.86	10.68	14.94	1.43	19.04	4.10
EUC1-3	72.6	136.7	46.2	32.3	503.2	188.6	15.32	10.37	na	na	na	10.44	2.19	12.22	na
W25-3-6	384.2	200.5	80.1	40.3	612.5	184.8	20.09	9.75	1.28	1.13	4.15	12.68	1.78	15.83	2.48
W27D	5.5	197.2	4.3	28.7	774.8	240.3	10.33	14.31	3.30	0.31	2.75	18.40	15.85	29.83	0.35
WUC1	16.5	221.3	8.3	30.2	774.8	282.2	8.71	6.45	na	na	na	14.86	1.34	17.83	na
WUC21	652.5	161.3	239.9	35.1	518.3	146.5	15.41	13.51	na	na	na	10.76	3.41	8.61	na
WUC21F	4.1	160.0	4.4	41.3	827.9	292.8	10.61	7.32	na	na	na	16.04	1.23	18.78	na
WUC22	341.1	114.0	104.8	29.8	542.2	179.1	10.17	7.02	na	na	na	11.15	2.00	12.47	na
WUC23U	134.8	136.2	62.4	39.1	740.1	227.6	16.48	9.19	na	na	na	14.80	1.94	15.51	na
WUC24	254.2	173.3	90.2	47.0	676.8	201.6	20.61	16.28	na	na	na	14.32	3.39	11.60	na
WUC27	17.2	198.9	8.8	38.7	823.1	285.7	21.28	12.32	na	na	na	16.19	1.48	18.44	na
WUC7	114.9	128.6	50.1	35.3	719.7	269.3	12.58	8.12	na	na	na	14.05	1.78	14.45	na

*na: not analyzed

zero in the evolved trachytes.

Chondrite normalized REE patterns are shown in Fig. 4. The rocks are enriched in LREE over HREE, and exhibit steep, subparallel REE trends. Chondrite normalized (La/Yb)c and (La/Sm)c ratios are 24.8-32.8, and 5.3-6.7 for basalts, 15.6-31.2, and 4.5-7.5 for trachyandesites, and 12.1-28.1, and 4.2-8.2 for trachytes, respectively. (La/Sm)c ratios are relatively constant both in absolute and relative terms in an individual rock type, while (La/Yb)c ratios show wide range in each rock type. In contrast to the major elements, the trace elements show extremely large abundance variations in the trachytes. An interesting aspect of the REE variations is that many of the trachytes have REE abundances less than the most evolved basaltic lavas. Comparison of relative abundances of highly

Table 2. Continued

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Yb	Lu
E1-4	103.7	177.0	20.88	73.05	11.49	3.48	9.41	1.19	6.35	1.08	3.00	2.56	0.33
E1-5	90.7	157.2	18.41	66.69	9.81	3.35	9.07	1.11	5.87	1.02	2.90	2.34	0.31
E2-1	92.0	151.7	18.90	68.50	10.67	3.33	9.79	1.23	6.63	1.23	3.05	2.68	0.39
E2-4	102.2	172.1	20.51	74.15	12.14	3.51	10.37	1.27	6.45	1.26	3.07	2.79	0.37
E2-5	102.0	172.8	20.68	74.33	11.63	3.55	10.26	1.26	6.33	1.23	3.17	2.45	0.37
E2-6	101.9	180.3	21.30	79.81	11.39	4.57	10.60	1.33	7.08	1.25	3.19	2.47	0.41
E9-15	87.2	142.4	16.83	58.77	9.65	2.95	8.12	1.05	5.68	1.00	2.49	2.10	0.31
E9-8	89.4	161.3	17.91	63.45	9.25	2.78	8.46	1.01	5.64	1.02	2.57	2.12	0.28
EUC3	86.9	163.7	16.81	60.69	9.80	2.80	8.34	1.03	5.40	0.91	2.28	2.00	0.32
EUC-9	97.6	169.7	17.76	63.62	10.38	3.13	8.60	0.95	5.32	0.94	2.49	2.39	0.33
W24F	121.7	205.5	23.09	79.56	11.37	3.48	10.85	1.24	6.67	1.10	3.14	2.69	0.32
W24F-5	116.6	198.8	24.06	84.16	12.28	3.93	10.18	1.26	7.09	1.24	3.16	2.84	0.35
E5	93.4	157.1	19.25	70.45	10.64	3.47	9.80	1.21	6.43	1.23	3.15	2.44	0.37
E8	90.5	149.0	17.77	63.48	10.00	4.42	7.55	1.00	5.05	0.89	2.40	1.96	0.27
EUC5	96.7	175.3	18.66	66.08	10.20	4.20	8.14	0.89	4.96	0.88	2.33	2.20	0.32
W25-3	117.2	190.8	22.63	79.26	12.86	3.06	12.10	1.48	8.22	1.49	4.08	3.53	0.51
W29	87.4	146.9	18.19	60.89	8.87	3.49	7.69	0.89	5.13	0.92	2.36	2.12	0.25
W30	101.5	160.0	18.40	60.24	8.53	2.97	7.53	0.98	5.37	1.02	2.95	2.31	0.34
WUC10-2	68.3	156.9	12.84	44.52	7.09	2.14	5.95	0.77	4.29	0.77	2.08	2.03	0.33
WUC10-5	66.3	152.9	12.40	43.04	6.82	2.10	5.83	0.78	4.48	0.82	2.28	2.20	0.36
WUC29	58.6	134.3	10.93	38.83	6.29	2.16	5.59	0.76	4.31	0.81	2.24	2.07	0.35
WUC30	53.8	134.1	10.29	34.89	5.59	1.70	4.62	0.63	3.62	0.67	1.88	1.90	0.32
WUC31-3	59.0	139.6	11.80	41.36	6.72	2.41	5.55	0.73	4.11	0.76	2.08	2.02	0.34
WUCO3	48.9	103.0	9.80	36.08	6.52	1.85	5.89	0.81	4.61	0.85	2.29	2.11	0.35
W1-2	163.0	266.8	31.81	106.17	17.19	0.89	14.65	2.09	11.41	2.05	5.95	5.43	0.77
W21	98.3	150.3	19.79	69.07	11.52	1.35	9.33	1.32	7.49	1.33	3.69	3.56	0.49
W23-1-4	176.8	293.9	33.12	108.82	15.53	1.16	14.60	1.90	10.74	2.06	5.75	5.07	0.71
W23-2-3	120.3	159.5	23.16	82.75	13.53	1.57	11.51	1.64	9.59	1.80	4.70	4.50	0.62
W24D	118.5	192.5	23.85	77.74	13.53	1.74	11.39	1.59	9.10	1.50	4.23	4.06	0.50
EUC1-3	83.0	169.9	14.20	45.08	6.40	1.20	5.34	0.69	3.99	0.73	2.00	2.99	0.30
W25-3-6	128.6	216.1	25.62	93.59	14.82	2.55	13.25	1.75	9.68	1.76	4.63	4.35	0.65
W27D	73.5	137.9	17.34	61.30	11.05	0.67	9.41	1.36	8.37	1.69	4.51	4.11	0.58
WUC1	53.9	189.0	9.69	30.83	4.75	0.36	4.20	0.57	3.26	0.62	1.77	1.88	0.30
WUC21	94.0	157.6	16.98	58.36	9.62	2.30	7.95	0.99	5.93	1.12	3.14	3.46	0.50
WUC21F	52.0	188.3	9.83	32.73	5.44	0.32	4.78	0.71	4.32	0.84	2.43	2.44	0.40
WUC22	50.5	126.2	9.28	31.30	5.06	1.10	4.34	0.62	3.65	0.70	1.99	2.04	0.34
WUC23U	71.2	172.3	13.12	43.90	7.16	0.77	6.07	0.89	5.31	1.01	2.87	2.90	0.49
WUC24	139.6	244.5	25.52	88.61	14.71	1.86	12.01	1.44	8.38	1.58	4.25	4.38	0.62
WUC27	112.8	243.0	20.25	66.33	10.59	0.64	8.64	1.25	7.37	1.39	3.91	3.80	0.61
WUC7	57.1	143.4	10.74	35.06	5.72	0.62	4.84	0.70	4.08	0.77	2.21	2.27	0.38

(Rb, Th, Ba, Nb, Ta, La, and Ce) and moderately (HREE, Zr, Hf and Y) incompatible elements in the volcanic rocks is facilitated using chondrite (Sun and McDonough, 1989) normalized abundance profiles (Fig. 5). Patterns for each rock types are similar except for notable Ba, Rb and Sr anomalies. Such anomalies apparently result from alteration, selective leaching, or enrichment of the elements. As the rocks evolved from basalts to trachytes, Ba and Sr decreased with respect to their neighboring elements while Rb increased. Ba and Sr negative anomalies in trachytes apparently result from the feldspar fractionation as shown in negative Eu anomalies in Fig. 4.

Typically, the subduction-related basalts are characterized by selective enrichment of incompatible elements of low ionic potential (Sr, K, Rb and Ba) and low

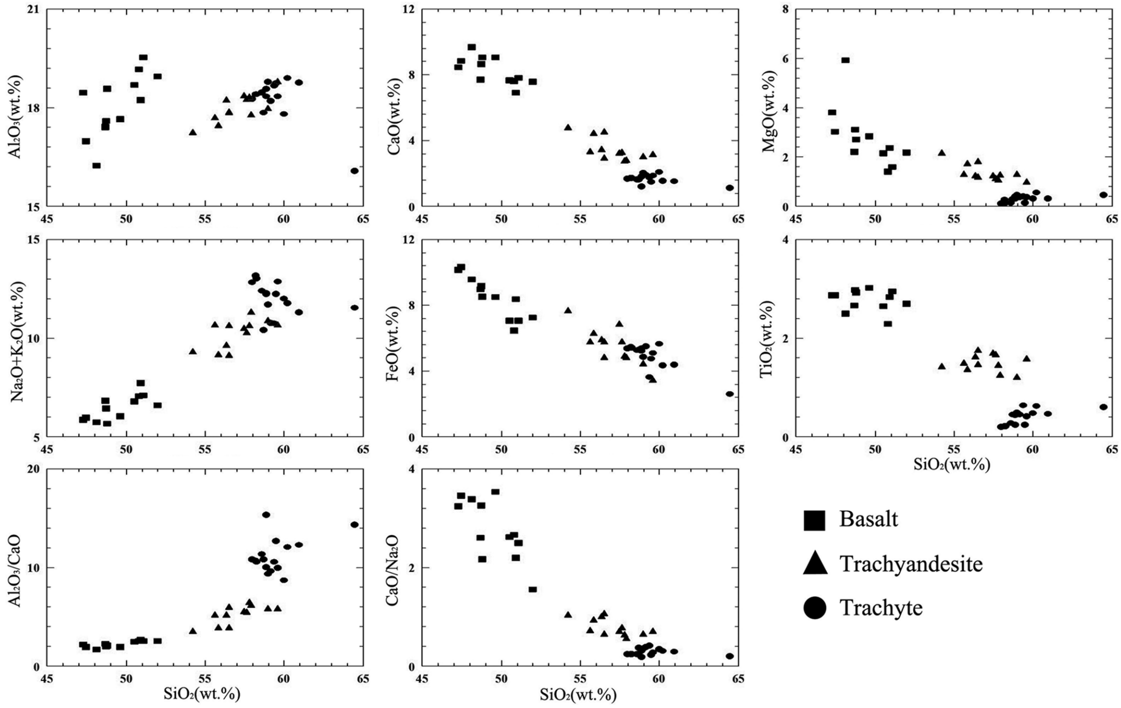

Fig. 2. SiO_2 variation diagrams for Dok volcanic rocks. Major elements as wt.% and total iron as FeO. Symbols: squares, basalts; triangles, trachyandesites; circles, trachytes.

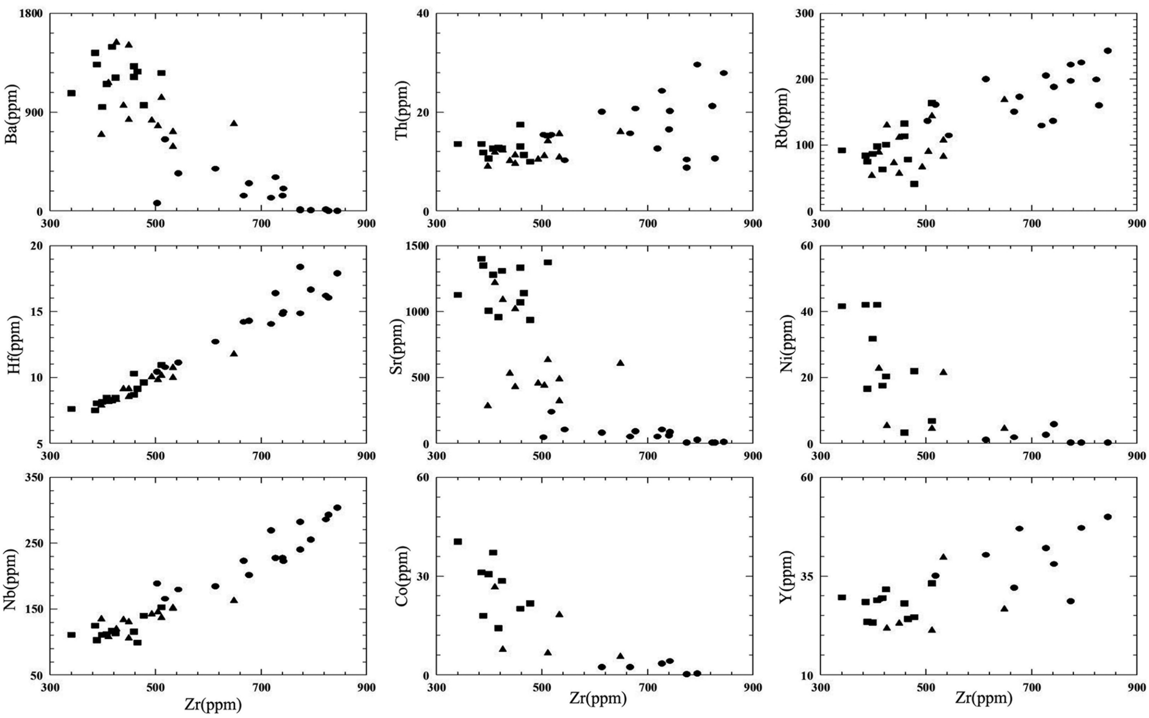

Fig. 3. Trace element variation diagrams (in ppm) for Dok volcanic rocks, Zr as an index of differentiation. Symbols are same as in Fig. 2.

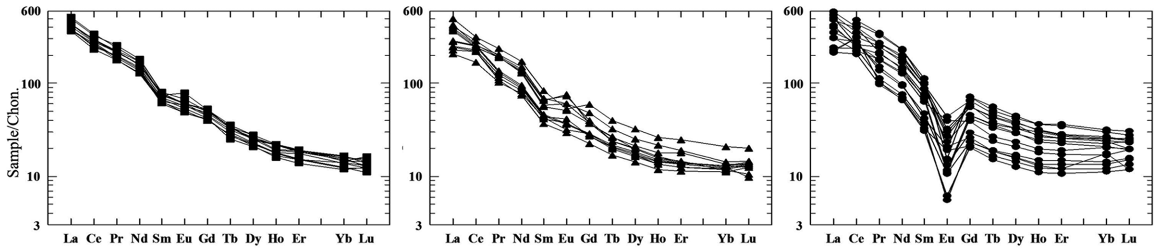

Fig. 4. Chondrite normalized REE patterns for Dok volcanic rocks. Symbols are same as in Fig. 2.

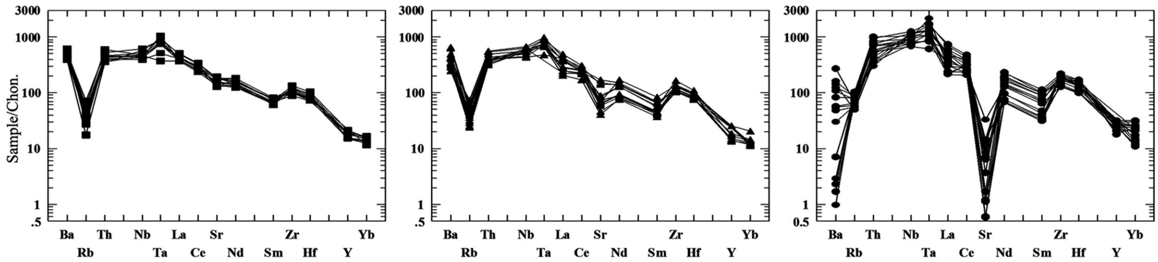

Fig. 5. Normalized incompatible element abundance patterns for representative Dok volcanic rocks. Symbols are same as in Fig. 2.

abundances of elements of high ionic potential (Na, Ce, P, Zr, Hf, Sm, etc.) relative to N-type MORB (Pearce, 1982). Trace element signatures of the basaltic rocks from this study are enriched in high ionic potential elements, and do not have a pronounced trough at Nb which is a typical characteristic of subduction related magma. Though the Dok island is located on the East Sea, which is related to the Pacific Plate subduction beneath the Japanese islands, the studied rocks do not show any subduction related geochemical characteristics.

Petrogenesis

The suites of basalts and differentiates (trachyandesites and trachytes) of the Dok volcanic rocks provide an excellent opportunity to examine the differentiation history of mantle-derived magma. Although volcanic rocks which constitute Dok island are small in volume, their geochemical characteristics vary significantly not only between each rock type but within rock types. These compositional differences are important clues for tracking the petrogenetic history of the volcanic rocks. The compositional differences in the volcanic suites reflect differences in source composition, effects of contamination, or differences in melting degrees as well as fractional crystallization processes. However, uniformity in the isotopic ratios (Tatsumoto and Nakamura, 1991) of each rock unit implies that the magmas were generated from the same source region and experienced no significant contamination after the original magma generation. Thus, the isotopic compositions of the volcanic suites preclude a heterogeneous source, or crustal contamination as primary causes of the compositional variations in the rocks.

Effects of fractional crystallization

Most of the basalts have undergone an extensive fractional crystallization process, because they have low MgO (mostly <6%), Ni, Cr contents (<50 ppm) and CaO/Al_2O_3 ratios (mostly <0.6). The porphyritic nature of the rocks and systematic major element trends indicate that crystal fractionation has significantly influenced chemical compositions. If the Dok volcanic rocks are related by crystal fractionation, the possible fractionating minerals are the phenocrysts present in the basaltic and trachytic rocks such as olivine, clinopyroxene, plagioclase, feldspar and magnetite. The SiO_2 vs. oxides variation diagrams (Fig. 2) are consistent with substantial mineral/melt fractionation.

Table 3. Mineral-melt distribution coefficients used in modeling fractional crystallization and partial melting

	Ol	Opx	Cpx	Plag	Fdsp	Amph	Biot	Mgt	Gt	Sp
Rb	0.01	-	0.001	0.01	0.01	0.2	0.8	0.01	-	-
Ba	0.01	-	0.03	0.4	3.6 - 5	0.5	10	0.01	-	-
Sr	0.01	-	0.08	1.7	5.0-10	0.41	0.7	0.01	-	-
Zr	0.01	-	0.12	0.01	0.27	0.8	1.2	0.24	-	-
Nb	0.01	-	0.09	0.01	0.01	0.9	0.9	2.16	-	-
Hf	0.03	-	0.23	0.04	0.13	0.22	1.8	0.37	-	-
Sc	0.01	-	5	0.01	0.1	1.6	0.48-8.3	3	-	-
La	0.01	0.0005	0.13	0.12	0.09	0.25	0.3	0.05	0.004	0.0006
Ce	0.01	-	0.1	0.12	0.08	0.1	0.3	0.05	-	-
Sm	0.06	-	0.44	0.1	0.03	0.76	0.016	0.76	-	-
Yb	0.01	0.0286	0.6	0.1	0.18	-	-	0.22	4.03	0.0045

(ol: olivine, Opx: orthopyroxene, Cpx: clinopyroxene, Plag: plagioclase, Fdsp: feldspar, Amph: amphibole, Biot: biotite, Gt: garnet, Sp: spinel)
Data sources: Frey et al. (1978); Pearce and Norry (1979); Villemant et al. (1981); Irving and Frey (1984); Lemarchand et al. (1987); Chen et al. (1990); Caroff et al. (1993)

Relatively constant CaO/MgO ratios with increasing SiO_2 (not shown) within basaltic rocks suggest that olivine fractionation is not a major control for the evolution of the analyzed rocks. Increasing Al_2O_3/CaO and decreasing CaO/Na_2O ratios are consistent with fractionation of clinopyroxene and/or plagioclase. The rapid decrease of FeO and TiO_2 abundances with increasing SiO_2 indicate fractionation of phase enriched in FeO and TiO_2 such as titanomagnetite, which commonly occurs in the rocks as micro-phenocrysts and are groundmass phases.

In Dok alkali volcanic suites, the differentiated rocks were interpreted to be derived from a basaltic parental magma by fractional crystallization involving olivine, clinopyroxene, plagioclase, Ti-rich magnetite, and feldspar with minor apatite (Kim et al., 1987). Regarding incompatible element abundance ratios and LREE/HREE ratios of each rock unit, however, the differentiation of the Dok volcanic rocks cannot be explained by simple fractional crystallization process. Major and trace element data indicate separate magmatic lineages for basalts and trachyandesitic compositions.

A least squares approximation technique (Bryan et al., 1969), which utilizes the analysed major element compositions of proposed parent and daughter rocks and the composition of the coexisting mineral phases is used to investigate in detail possible petrogenetic relationships among the Dok Island volcanic rocks. Trace element abundance variations are used to independently evaluate the results of the least squares models by utilizing published mineral/liquid distribution coefficients and fractional crystallization equation of Shaw (1970).

basalts: The dominance of olivine fractionation in the early stage of basalt differentiation is indicated by low MgO and depleted olivine compatible elements such as Ni and Cr. The parental composition of the samples is not a primary liquid, having been subject to olivine fractionation. In order to evaluate the compositional variations within the basalts, samples of E2-1 and EUC9 are used as end members. Based on a least squares approximation technique, the parents (E2-1) differentiated to daughter (EUC-9) by fractionation of 14.7% plagioclase, 7.1% olivine, 5.1% clinopyroxene, and 5.5% magnetite. The result of the calculation shows good agreement between calculated and observed contents of major elements. The mineral proportions estimated from major element modelling, and previously reported mineral/melt partition coefficients (Table 3) were used to calculate trace element abundances in the residual liquids. The calculated trace element abundances in the residual melts are compared to that in the proposed daughter and listed in Table 4. For the trace elements, the calculated abundances in the residual liquids agree well (mostly better than 10%) with the

Table 4. Predicted and observed trace element concentrations (ppm) of Dok volcanic rocks, calculated on the basis of the major element models

	E2-1	EUC-9			WUCO3	WUC30			WUC30	W1-2		
	parent	obs.	calc.	calc./obs.	parent	obs.	calc.	calc./obs.	parent	obs.	calc.	calc./obs.
Rb	81.50	107.20	120.30	1.12	61.90	84.10	77.80	0.93	84.10	179.50	151.40	0.84
Ba	1068.60	1263.40	1420.60	1.12	707.60	791.60	845.80	1.07	791.60	12.30	41.90	3.41
Sr	1125.60	1161.00	1160.10	1.00	290.90	330.60	307.30	0.93	330.60	12.20	11.70	0.96
Zr	349.80	465.70	501.00	1.08	397.20	532.40	481.60	0.90	532.40	844.40	808.50	0.96
Nb	101.90	128.20	129.60	1.01	136.10	152.40	152.40	1.00	152.40	303.40	297.30	0.98
Hf	7.57	9.14	10.30	1.13	7.99	10.29	9.70	0.94	10.29	17.91	17.21	0.96
Sc	11.15	10.75	9.84	0.92	5.56	4.01	4.20	1.05	4.01	0.96	1.53	1.59
La	92.00	125.60	132.90	1.06	48.90	58.80	60.90	1.04	58.80	133.50	116.60	0.87
Ce	151.70	209.70	219.20	1.05	103.00	131.10	127.60	0.97	131.10	256.80	250.70	0.98
Sm	10.17	10.98	12.18	1.11	6.52	6.59	7.54	1.14	6.59	13.82	13.10	0.95

obs.: observed value, calc.: calculated value

measured abundances in the derived sample. The generally close agreement between calculated and measured trace element abundances, coupled with the similar degrees of fractionation estimated from major element abundances suggest that fractional crystallization was the major process creating chemical variation of the basalts.

trachyandesites and trachytes: The range in composition in the andesitic rocks can be shown to result from fractional crystallization of phenocryst phases. To illustrate this, a major element least squares model relating one of the least evolved lavas (WUCO3) to one of the most evolved (WUC30) lavas were selected. The relative proportions and compositions of the fractionating phases (plagioclase, clinopyroxene, magnetite and amphibole) are consistent with the petrography of the rocks and the good agreement between calculated and observed compositions support to the proposed model. Further support is obtained from the trace element variations where good agreement is obtained between concentrations predicted on the basis of the proposed model and those observed in the derivative rock WUC30 (Table 4). The trachytes are the most evolved of the Dok alkaline volcanic rocks. Least squares modelling indicates that the major element composition of these lavas can be derived by fairly extensive (~50 percent) fractional crystallization of a parental magma with major element composition similar to that of the most evolved trachyandesites.

In summary, the chemical variation of the basaltic rocks is mainly caused by fractional crystallization of olivine, plagioclase, clinopyroxene and magnetite, and trachyandesites are fractionation of clinopyroxene, plagioclase, magnetite and amphibole, while trachytes are controlled by mainly feldspar fractionation from the evolved trachyandesitic magma. Decreasing Ba and Sr and increasing Rb of trachyandesite and trachytes (Fig. 3) also supports the argument that feldspar fractionation controls the evolution of trachyandesite to trachytic melt. The geochemical characteristics of the basalts, trachyandesites and trachytes preclude derivation by simple fractional crystallization from same parental magma compositions. Although it is difficult to assess quantitatively the exact nature of the source region(s) of these rock groups, it is clear from isotopic ratios (Tatsumoto and Nakamura, 1991) and incompatible element abundances, that parental magmas of the basalts and trachytic lavas are derived from same source region with different degrees of melting.

Role of different degrees of partial melting

The complex geochemical variations of Dok island volcanic rocks are explained by magmatic differentiation along two major lineages: 1) fractional crystallization of basalt series; 2) fractional crystallization of trachyandesites to produce the trachytes. The apparent change in parental magma composition from basalt to trachyandesites reflects a shift towards higher degrees of partial melting of mantle source. Different degrees of partial melting may be the fundamental basis for the divergent petrogenesis of Dok magmas. Assuming a homogeneous source, large ranges in highly incompatible element ratios are more effectively produced by variations in degree of partial melting, particularly at low melt fractions, than by fractional crystallization processes. We believe that the variations in the concentrations of trace elements of the Dok volcanic rocks result mainly from different degrees of partial melting of mantle source materials at different depths or from changes of melting pressures. The highly incompatible trace elements and LREE are the most enriched in silica-poor basalts rather than in the trachyandesites. The inverse correlation between the highly incompatible trace elements and SiO_2 (not shown), which can not be explained by fractional crystallization, perhaps reflects differences in melting degree for the parental magmas.

Various partial melting curves are shown in (La/Yb)c vs (La)c diagram (Fig. 6). For calculation of partial melting curves from hypothetical mantle sources of spinel peridotite (SP) and garnet peridotites (GP), batch melting models of Shaw (1970) and Hertogen and Gijbels (1976) and distribution coefficients listed in Table 4 are used. La and Yb abundances are 2× chondrite for the spinel and garnet peridotite sources (Zhang et al., 1995), and modal proportions of phases in the hypothetical mantle sources and those entering into the melts are: ol:opx:cpx:sp=60:25:10:5 and 10:20:65:5 for SP; ol:opx:cpx:gt=60:25:10:5 and 10:10:40:40 for GP. Curve SP, calculated on the basis of a hypothetical spinel peridotite source, indicates that the spinel peridotite cannot be the source of the Dok volcanics, because the La/Yb ratios are too high for the spinel peridotite source to produce Dok volcanic rocks.

The analyzed rocks might have undergone fractional crystallization, which would shift the samples to the right, so the melting curve should lie to the left of the rock groups. According to the melting curves, it suggests that a garnet peridotite source (curve GP)

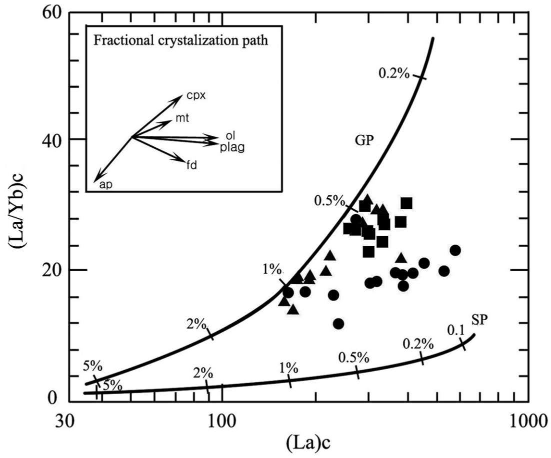

Fig. 6. (La/Yb)c vs (La)c diagram for volcanic rocks of Dok island with partial melting curves. Labels for melting curves calculated from hypothetical mantle sources: SP, spinel peridotite; GP, garnet peridotite. La and Yb abundances are both 2 times chondrite for the primitive SP and GP sources. Numbers along the curves represent melt fractions in %. Inset: Fractional crystallization trends of mineral phases. Abbreviations: ol, olivine; cpx, clinopyroxene; pl, plagioclase; fd, feldspar; mt, magnetite; ap, apatite. Symbols are same as in Fig. 2.

could provide suitable (La/Yb)c and La values. Chondrite normalized REE patterns are commonly used to infer the presence of residual garnet in the mantle source region of alkaline magma (e.g., Frey et al., 1978), the most diagnostic feature being a depletion in the HREE relative to the LREE, owing to their strong partitioning into garnet. Because the chemical compositions of these rocks do not represent a primitive melt composition and because of the uncertainty of the partition coefficients, we cannot estimate the precise percentage of melting. However, rough but reasonable estimates are obtained from the GP source with less than 1% partial melting for the basalt, and greater than 1% melting for the trachy-andesitic and trachytic source. Assuming a mantle source with 2 times chondritic REE abundances, the degree of partial melting required to produce the REE content of the studied basalts (less than 1%) is unrealistically low. However, the analyzed basalts have similar (La/Ce)c averaging at 1.4±0.082, and such a high (La/Ce)c value may be generated by partial melting from a source with a chondritic REE pattern only by a very low degree (<1%) of partial melting (Dostal et al., 1991). From these melt compositions, fractional crystallization processes controlled the chemical evolution of the each rock units.

The high contents of incompatible elements in the basalts of the Dok island imply derivation from an enriched upper mantle source, as frequently suggested for alkali basaltic rocks. They also have trace element signatures such as Zr/Nb (3.1-4.0), Rb/Sr (0.05-0.12), Ba/Nb (6.9-12.9) and La/Nb (0.6-1) ratios are similar to that of the Kerguelen and Tristan da Cunha (Weaver et al., 1986, 1987; Weaver, 1991) oceanic island basalts (OIB) that have an EM 1 signature. Compared to basalts from the Samoa and Society, which are typical EM 2 type OIB, the La/Nb and La/Ba ratios of the Dok basalts are lower and Ba/Nb and Rb/Ba ratios are higher. The island basalts also have relatively high Ba/U and Th/U ratios similar to those of Kerguelen and Tristan da Cunha. In general, the basalts from Dok island are characterized by high Ba/Nb, La/Nb, Ba/Th and Th/U ratios, which are the typical trace element features of EM 1 type OIB.

Conclusions

Major and trace element data have been used in this study to aid in understanding the petrogenesis of alkaline volcanic rocks in Dok island. The chemical variation of volcanic rocks in Dok island were caused by different degrees of partial melting followed by two major lineages of fractional crystallization; 1) basalts and 2) trachyandesites to trachytes. The followings are summary of our conclusion regarding the magmatic evolution of the Dok volcanic rocks.

Primitive basaltic magma presumably formed by very small degrees (less than 1%) of partial melting of garnet peridotite mantle source. This melt served as a primitive melt composition of the basaltic rocks. The primitive rocks among the analyzed samples are not primary liquids, as they have been subject to dominant olivine fractionation. The fractionation of olivine was followed by olivine, clinopyroxene, plagioclase and magnetite fractionation to generate the chemical variety of the basaltic rocks. More extensive melting of the source occurred after the eruption of the basaltic magma. These melts were the primitive magmas that evolved into trachyandesites and trachytes. It is possible that substantial plagioclase and feldspar fractionation increased the density of residual liquid thereby inhibiting eruption (Sparks et al., 1984), and accounting for the silica gap and time gap (basalts: 4.6 to 3.7 0.34 Ma, trachyandesites: 2.89 to 2.7 0.43 Ma, Park et al., 1995) between basalts and trachyandesites of Dok volcanic rocks. Protracted fractionation of olivine, clinopyroxene and magnetite may have eventually reduced the densities in the more evolved liquids. The evolution of the trachyandesites was controlled by fractionation of plagioclase, clinopyroxene, magnetite, with a minor amount of amphibole. Trachytes were evolved from the trachyandesites by fractionation of feldspar and plagioclase with minor amounts of biotite.

Basalts from Dok island have trace element ratios (i.e., Ba/Nb, La/Nb, Ba/Th and Th/U) similar to typical EM1 type oceanic island basalts such as Gough and Tristan da Cunha basalts. This supports the EM1 component signature in Dok volcanics as previously suggested by Tatsumoto and Nakamura (1991) by isotopic ratios.

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