Petrogenetic relationship between mafic magma of somma lavas and voluminous felsic magma with caldera formation: A case study of Akan volcanic field, eastern Hokkaido, Japan

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Volcanic activity in the Akan volcanic field in the southwestern end of the Kurile arc began in early Pleistocene and formed stratovolcanoes. The somma lavas are tholeiite series and range from 51–60 wt% SiO₂. The eruption of voluminous calc-alkali rhyolitic magma (68–73 wt% SiO₂) with caldera formation took place at middle Pleistocene. The trace-element characteristics of the volcanic rocks from the Akan volcanic field suggest that the felsic magma implies a difficulty for its derivation from basaltic magma such as the somma lava. Modeling the trace element processes in volcanic rocks indicate that the most basic rock of the somma plots near partial melting 20% of the mantle source with the fractional crystallization subsequent to the partial melting. On the other hand, the Akan pyroclastic flow deposits may be produced by variable degree of partial melting of an andesitic crust source with local heterogeneity of the source material. The most plausible heat source for the genesis of the felsic magma may be latent heat from the mantle-derived basaltic magma such as the somma lava.

Introduction

It is well known that mantle-derived basalt magmas at the deep crust are inevitably associated with the anatexis of the crustal rocks (e.g. Hildreth, 1981; Takahashi et al., 1997). Some Japanese Quaternary volcanoes are characterized by activity of basaltic magmas of somma and voluminous rhyolitic magma with caldera formation. The volcanic activities at the subduction zone are expected the formation of felsic magmas by latent heat from the mantle-derived basalt magmas (e.g. Hildreth, 1981; Wada, 1989; Ikeda, 1991; Takahashi et al., 1997). This petrogenetic relationship is of particular importance to discuss about the magma-feeding system in subduction zone.

The Akan volcanic field is composed of precaldra stratovolcano (somma) and the Akan caldera formed after the voluminous eruption of pyroclastic flow and the deposition of pyroclastic fall (Satoh, 1965). Some data of major elements for the volcanic rocks are presented in Satoh (1965) and Wada (1989). Trace element

studies became a vital part of modern petrology and more capable to discriminate petrological processes than that on the major elements alone (Rollinson, 1993). This report is presented the geochemical information including major and trace elements of the Akan magmas and discussed the petrogenetic relationship between mafic magma of somma lavas and voluminous felsic magma.

Geological setting

The Akan volcanic field in eastern Hokkaido (Fig. 1) is located at the southwestern end of the Akan-Shiretoko volcanic chain, belonging to the Kurile volcanic zone. Paleogene- and Neogene-Tertiary basement rocks (sedimentary and volcanic rocks) exist underneath the volcanic field (Satoh, 1965). The stratovolcanoes in the volcanic field is distinct on the NW and SE walls, composed of piles of somma lavas and pyroclastic rocks of basaltic-andesitic compositions (Satoh, 1965) (Fig. 1). The volcanic formation has been presumed early Pleistocene in age (Katsui and Koide, 1976). K-Ar age on a somma lava indicates Pliocene age (2.82 Ma; NEDO,

Figure 1. Distribution of somma lavas, Aka pyroclastic flow deposits and post caldera stratovolcanoes; Meakan including Furebetsu and Fuppusi, and Oakan (modified from Geological Survey of Hokkaido, 1980), and locations of caldera rim (simplified from Satoh, 1965) and analyzed samples in the Akan volcanic field.

1992). After the formation of stratovolcanoes, eruption of voluminous pyroclastic flows and pumice falls (Akan pyroclastic flow deposits) were succeeded. The Akan caldera was formed in middle Pleistocene (Satoh, 1965; Okazaki, 1966; Satoh and Sato, 1976) (Fig. 1). The volume of the Akan pyroclastic flow deposit is estimated to be about 100 km^3 (Ishikawa et al., 1969), and mass deficiency calculation on the caldera is 165 km^3 (Ohkawa and Yokoyama, 1979). K-Ar ages on the two samples of Akan pyroclastic flow deposits have been dated as 0.59 and 2.2 Ma (NEDO, 1992). The isotopic ages of the pyroclastic flow deposits are not necessarily in agreement with the stratigraphic age (middle Pleistocene). The Akan caldera is rectangular shape (ca. 20 km in E-W diameter) and the gravity anomalies show

inverted cone (Ohkawa and Yokoyama, 1979). Four post caldera stratovolcanoes; Furebetsu, Fuppusi, Meakan (included in Meakan in Fig. 1), and Oakan, have grown in the caldera or the caldera-rim since late Pleistocene (Satoh, 1965).

Samples and analytical methods

Sample localities are shown in Figure 1. Phenocrysts of somma lavas for SL1 and SL2 are plagioclase, olivine and small amount of clinopyroxene lie in an intergranular matrix of plagioclase, clinopyroxene and iron mineral. The somma lavas for Kikin 1 and Kikin 2 are aphyric and a little plagioclase phenocrysts are embedded in an intergranular groundmass of plagioclase,

clinopyroxene and iron mineral. The commonest phenocrysts of Akan pyroclastic flow deposits are plagioclase followed in the order of abundance by orthopyroxene and clinopyroxene.

Concentrations of major elements and trace elements (Rb, Sr, Ba, Nb, Y, Zn and Zr) were determined by XRF (X-ray fluorescence Rigaku RIX 3000) at National Institute of Polar Research, Tokyo. Analytical procedures of Motoyoshi and Shiraishi (1995) were used.

Other trace elements (Hf, Ta, Th, and U) and REE (La, Ce, Sm, Eu, Tb, Yb and Lu) were analyzed by instrumental neutron activation analysis (INAA) at the Institute for Atomic Energy, Rikkyo University, Yokosuka. Samples of ~200mg were doubly packed into precleaned polyethylene bags and irradiated for 12 h in a TRIGA MARK II (100 kw) research reactor facility. The irradiated samples were left standing for about one week to cool the radioactivities of the short-lived nuclides such as La, Sm, Yb, and Lu. The cooling time was about four weeks for long-lived nuclides such as Ce, Eu and Tb. After the suitable cooling time, γ -ray spectrometry was carried out with a Ge detector. The analytical uncertainties for most samples were estimated to be about $\pm 10\%$, but Ta and Tb for some samples were ± 15 –20%.

Geochemical characteristics

The major and trace element compositions of the volcanic rocks are given in Tables 1 and 2. The volcanic rocks are grouped on the basis of SiO_2 content into basalt (45–53%), basaltic andesite (53–57%), andesite (57–63%), dacite (63–68%), and rhyolite (>68%) after the proposition by Basaltic Volcanism Study Project (1981). The somma lavas are basalt for SL1 and SL2 (51% SiO_2) and basaltic andesite to andesite for Kikin 1 and Kikin 2 (55–60% SiO_2). The range of SiO_2 contents for somma lavas are in general agreement with the data given by Wada (1989). The Akan pyroclastic flow deposits are rhyolite (68–73% SiO_2). Most of the volcanic rocks of the Akan volcanic field are subdivided into Medium-K type (Le Maitre et al., 1989) on the basis of K_2O vs. SiO_2 diagram (Fig. 2). The different trend of tholeiite rock series and calc-alkali rock series can be used to SiO_2 vs. FeO^*/MgO diagram (Miyashiro, 1974). The somma lavas and the Akan pyroclastic flow deposits belong to the tholeiite rock and to the calc-alkali rock series, respectively (Fig. 3).

Rb, Sr and Ba vs. SiO_2 diagrams for the volcanic rocks from the Akan Volcanic field is shown in Figure 4. Rb and Ba contents of the somma lavas increase

Table 1. Major element abundances (wt%) in the volcanic rocks from the Akan volcanic field

	Somma lavas			
	SL1	SL2	Kikin1	Kikin2
SiO_2	51.28	51.42	55.06	60.23
TiO_2	0.77	0.78	1.12	0.95
Al_2O_3	17.97	17.76	16.19	15.97
Fe_2O_3^*	10.25	10.31	11.97	9.70
MnO	0.17	0.17	0.22	0.16
MgO	5.85	5.83	3.43	2.18
CaO	11.02	11.02	7.57	6.23
Na_2O	2.01	2.09	3.42	3.71
K_2O	0.43	0.47	0.81	1.34
P_2O_5	0.06	0.06	0.19	0.23
Total	99.81	99.91	99.98	100.70

Fe_2O_3^* : total iron as Fe_2O_3

Table 2. Trace element abundances (ppm) in the volcanic rocks from the Akan volcanic field

	Somma lavas			
	SL1	SL2	Kikin1	Kikin2
Rb	9.79	12.02	15.43	29.62
Sr	358.15	355.93	386.18	350.61
Ba	93.55	89.06	195.73	312.46
Nb	2.50	1.82	4.69	4.69
Y	15.48	15.62	27.72	36.06
Zn	69.06	68.97	99.68	93.99
Zr	52.12	55.03	81.87	117.67
La	5.17	3.95	9.54	14.50
Ce	8.89	8.05	18.75	26.02
Sm	2.20	2.34	3.87	5.88
Eu	0.80	0.72	1.39	1.64
Tb	0.50	0.49	0.85	0.75
Yb	1.74	1.31	2.74	3.45
Lu	0.27	0.27	0.41	0.55
Hf	1.02	1.43	2.32	2.95
Ta	0.41	0.35	0.55	0.69
Th	0.57	0.75	1.18	2.11
U	0.53	0.33	0.35	0.80

Table 1. continued

Akan pyroclastic flow deposits										
	SEAWT	KAAWT	SIAWT	2AK1	3AK2	5AK3WP	5AK3BP	SIAW2	SIAW3PF	SIAW3
SiO ₂	72.43	72.93	72.38	70.70	72.92	70.89	68.62	71.91	71.73	71.54
TiO ₂	0.54	0.51	0.52	0.48	0.51	0.49	0.59	0.56	0.46	0.43
Al ₂ O ₃	13.37	13.36	13.88	15.13	13.50	13.58	14.39	14.68	13.94	13.89
Fe ₂ O ₃ *	3.08	2.73	2.71	3.21	2.53	3.60	4.55	2.88	3.03	3.07
MnO	0.11	0.13	0.13	0.09	0.12	0.08	0.10	0.14	0.10	0.09
MgO	0.64	0.71	0.73	0.85	0.67	0.95	1.20	0.74	0.80	0.86
CaO	2.38	2.43	2.55	2.96	2.46	3.09	3.60	2.60	2.75	3.06
Na ₂ O	4.15	4.46	4.54	3.88	4.56	3.75	3.54	4.41	3.92	4.07
K ₂ O	1.99	1.66	1.56	1.77	1.65	2.26	2.00	1.50	1.94	1.94
P ₂ O ₅	0.06	0.08	0.08	0.07	0.08	0.05	0.08	0.08	0.06	0.06
Total	98.75	99.00	99.08	99.14	99.00	98.74	98.67	99.50	98.73	99.01

Table 2. continued

Akan pyroclastic flow deposits										
	SEAWT	KAAWT	SIAWT	2AK1	3AK2	5AK3WP	5AK3BP	SIAW2	SIAW3PF	SIAW3
Rb	48.21	35.62	34.40	39.92	34.72	59.88	53.38	33.02	44.62	43.97
Sr	193.24	204.93	218.26	200.09	209.90	202.27	230.49	219.50	190.71	205.51
Ba	361.97	384.62	392.23	378.61	366.90	343.25	319.88	362.57	429.42	377.69
Nb	4.67	2.89	3.53	3.97	4.22	5.12	4.85	3.86	4.64	3.25
Y	43.16	40.94	42.41	31.79	40.06	33.90	33.01	43.46	30.82	28.40
Zn	65.08	72.61	76.79	45.37	62.06	45.96	54.55	74.02	49.72	46.45
Zr	150.49	142.26	143.94	163.61	143.44	164.79	151.85	151.03	160.02	147.36
La	13.14	14.28	15.35	14.13	13.36	11.50	11.51	13.93	13.99	13.71
Ce	29.32	30.62	32.05	36.55	36.38	30.44	25.97	36.89	35.81	33.01
Sm	5.71	5.40	5.60	4.17	5.47	4.33	4.56	5.51	4.17	4.01
Eu	1.31	1.46	1.48	1.08	1.51	0.93	1.16	1.68	1.04	1.00
Tb	1.03	1.17	1.22	0.54	1.07	0.68	1.02	1.00	0.73	0.57
Yb	4.34	3.93	4.27	3.55	4.57	3.67	4.04	4.45	3.26	3.09
Lu	0.72	0.69	0.72	0.54	0.62	0.53	0.56	0.61	0.54	0.50
Hf	4.24	4.18	4.53	4.53	4.13	4.60	4.55	4.41	4.41	4.03
Ta	0.43	0.21	0.32	0.23	0.18	0.20	0.24	0.15	0.23	0.23
Th	3.70	3.98	3.93	5.63	4.12	4.47	4.04	4.29	5.39	5.00
U	1.36	1.13	0.88	1.60	1.26	1.39	1.41	1.16	1.63	1.30

Figure 2. K_2O vs. SiO_2 diagram for the volcanic rocks from the Akan volcanic field. Boundaries among the rock suite fields are after Le Maitre et al. (1989).

Figure 3. SiO_2 vs. FeO^*/MgO diagram for the volcanic rocks from the Akan volcanic field. FeO^* is total iron as FeO . Solid line defines tholeiitic (TH) and calc-alkalic (CA) series, following Miyashiro (1974).

Figure 4. Rb, Sr and Ba vs. SiO_2 diagram for the volcanic rocks from the Akan volcanic field.

with increasing SiO_2 content, while variation trend of Sr change to decreasing at fractionated somma lava, indicating the role of plagioclase as fractionating phase. Sr contents of the Akan pyroclastic flow deposits show also negative correlations. Rb contents of the pyroclastic flow deposits are plotted in scattered pattern. As shown in Ba vs. SiO_2 diagram, the somma lavas and the pyroclastic flow deposits show independent variation trend.

Rb vs. Sr and Ba vs. Sr diagrams show more definite

Figure 5. (A) Rb vs. Sr and (B) Ba vs. Sr showing fractional crystallization of mineral vector diagrams for the volcanic rocks from the Akan volcanic field. The fractionation vectors are shown for clinopyroxene (Cpx), orthopyroxene (Opx), hornblende (Hbl), biotite (Bi), orthoclase (Kspar) and plagioclase (Plag) after Rollinson (1993).

Figure 6. Rare earth element abundances in the volcanic rocks from the Akan volcanic field, normalized to chondritic values after Masuda et al. (1973) and Masuda (1975).

Figure 7. La vs. Th diagram (Gill, 1981) for the volcanic rocks from the Akan volcanic field.

non-genetic relationship between them (Fig. 5). The Ba vs Sr diagram of the somma lavas indicates apparently the fractionation of pyroxene and plagioclase as the controlling factor of compositional variation. These trace elements indicate that the Akan pyroclastic flow deposits cannot be derived from the basaltic magma of the somma lava through simple fractional crystallization.

The REE pattern of the somma lavas are light REE (LREE) enriched, while the heavy REE (HREE) parts

Figure 8. Normalized (Ce/Sm) vs Ce and (Ce/Yb) vs Ce diagrams for the volcanic rocks from the Akan volcanic field. The normalizing values and primitive mantle source take from Masuda et al. (1973) and Rollinson (1993), respectively. Mineral/melt partition coefficients compiled from compilation data of Rollinson (1993). Line 1 indicates primitive mantle (olivine : orthopyroxene : clinopyroxene = 60 : 27 : 13) fusion, assuming partition coefficients $D_{Ce}/D_{Sm}/D_{Yb}$ of 0.006/0.007/0.049, 0.02/0.05/0.34, and 0.092/0.445/0.542 for olivine, orthopyroxene, and clinopyroxene, respectively. Line 2 indicates partial melts of a crust, assuming initial composition Kikin2 (CIPW norm quartz : K-feldspar : plagioclase : clinopyroxene : orthopyroxene : magnetite : ilmenite : apatite = 13.36 : 7.93 : 54.46 : 5.48 : 15.02 : 1.41 : 1.81 : 0.53), and assuming partition coefficients $D_{Ce}/D_{Sm}/D_{Yb}$ of 0.014/0.014/0.017, 0.037/0.025/0.03, 0.267/0.165/0.09, 1.833/5.233/6.367, 0.93/1.6/2.2, 3/2.2/1.8, 7.8/6.9/4.1, and 34.7/62.8/23.9 for quartz, K-feldspar, plagioclase, clinopyroxene, orthopyroxene, magnetite, ilmenite, and apatite, respectively. Numbered tickmarks indicate percent melting. The horizontal arrow shows effect of fractional crystallization.

show depleted or flat profile with no Eu anomalies (Fig. 6). The REE abundances of the somma lavas are a type of REE enrichment with the increase of SiO_2 . The fractionation of REE may be caused by their incompatibility with plagioclase, olivine, and clinopyroxene during the magma evolution. On the other hand, the

LREE variation patterns of the Akan pyroclastic flow deposits are steep and the HREE parts are flat or slightly enriched compared to middle REE such as Tb profile with negative Eu anomalies (Fig. 6). Generally, the negative Eu anomalies are mainly controlled by removal of feldspar from a magma or partial melting of a rock in which feldspar retained in the source. The REE patterns of the fractionated somma lavas overlap with those of the Akan pyroclastic flow deposits. The REE patterns indicate that the pyroclastic flow deposit is not likely to have been derived from the basaltic magma of the somma lava by fractional crystallization of plagioclase and pyroxene as well as observed in the trace element data (Figs. 4 and 5).

Petrogenetic relationship between the somma lavas and the felsic rocks

The geochemical characteristics of the volcanic rocks from the Akan volcanic field indicate a difficulty to derive the felsic magma (Akan pyroclastic flow deposit) from basaltic magma (somma lava).

Ratios of highly incompatible trace elements are indicative of source compositions because they do not change appreciably during either melting or fractionations (Gill, 1981). Consequently, the low La/Th ratios of the Akan pyroclastic flow deposits shows a significant difference of their sources from those of the somma lavas (Fig. 7). Further constraints to distinguish the magma processes during fractional crystallization from that of the partial melting can be obtained from vector diagram such as (Ce/Yb) vs. Ce and (Ce/Sm) vs. Ce concentrations (Allègre and Minster, 1978; Gill, 1981; Rollinson, 1993). Figure 8 (Ce/Sm vs. Ce and Ce/Yb vs. Ce) illustrates this difference. Data of primitive mantle source (olivine 60%, orthopyroxene 27% and clinopyroxene 13%) and partition coefficients for basaltic liquids for the calculation of batch melting were compiled from Rollinson (1993). The data of the most basic rock of the somma lavas plot near partial melting 20% of the mantle source. Variations of the data plot of the somma lavas show horizontal variation indicating effect of fractional crystallization.

On the other hand, the data plot for the Akan pyroclastic flow deposits cross the partial melting line or variation trend of the somma lavas. Line 2 in Figure 8 shows compositions of partial melts of andesitic crust, assuming initial composition Kikin 2 ($\text{SiO}_2 = 60.23\%$) with the CIPW norm mineralogy: quartz (13.36%), plagioclase (54.46%), K-feldspar (7.93%), orthopyroxene (15.02%), clinopyroxene (5.48%), magnetite (1.41%), ilmenite (1.81%) and apatite (0.53%). Data of partition

coefficients for dacitic and rhyolitic liquids used in the calculation of the partial melting are compiled from Rollinson (1993). The straight line with steep slope on such diagram identifies partial melting (batch melting). The compositional variations of the Akan pyroclastic flow deposits are concordant with the straight line. It indicates that the Akan pyroclastic flow deposits are derived from an andesitic crust source. The variety in composition of the Akan pyroclastic flow deposits may be produced by variable degree of partial melting of the crustal rock and local heterogeneity of the source material. The most plausible heat source for the genesis of the felsic magma may be latent heat from the mantle-derived basaltic magma such as the somma lava as discussed in Hildreth (1981), Wada (1989), Ikeda (1991), and Takahashi et al. (1997).

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