Geochemical Journal, Vol. 16, pp. 79 to 87, 1982

Sr/Ca-Ba/Ca systematics in Miyakejima, Ōnoharajima, Mikurajima and Inambajima volcanoes, the Izu Islands, Japan

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(Received October 9, 1981: Accepted March 5, 1982)

Ca, Sr and Ba contents of basalts and andesites from Miyakejima, Ōnoharajima, Mikurajima and Inambajima volcanoes, the Izu Islands, Japan, have been determined by an inductively coupled plasma optical emission spectrometer. The data reveal that Miyakejima, Ōnoharajima and Mikurajima volcanoes gave three different series of Sr/Ca - Ba/Ca systematics, while an Inambajima andesite belongs to Mikurajima systematics. The difference is considered to reflect different degrees of partial melting of a common mantle material with chondritic Sr/Ca and Ba/Ca ratios. The degree of partial melting decreases from Ōshima to Miyakejima and is constant from Miyakejima to Mikurajima along the arc, while it decreases from Miyakejima to Ōnoharajima across the arc. Therefore, there seems to be no relationship between the "degree" of partial melting and the distance from the Izu-Ogasawara Trench in this region.

INTRODUCTION

We have started to investigate arc volcanism on the basis of Sr/Ca-Ba/Ca diagram which can visualize both partial melting of mantle material and crystal fractionation in a magma chamber operated beneath a volcano (ONUMA, 1980; 1981, ONUMA and HIRANO, 1981). In the previous paper (ONUMA *et al.,* 1981), we have selected four volcanoes in Ōshima as a reference standard of the Izu Islands region and clarified that three older volcanoes (Okata, Gyōjanoiwaya and Fudeshima) gave the same Sr/Ca-Ba/Ca systematics (SB systematics for short hereafter), while younger volcano (Ōshima) showed a slightly different SB systematics starting from a common precursor. The two different series of systematics suggest that the primary magma was the same in terms of "degree" of partial melting of mantle material, but crystal fractionation process in the "magma chamber" was slightly different.

In this paper, we report SB systematics of four volcanoes: Miyakejima, Ōnoharajima, Mikurajima and Inambajima lying south of Ōshima (Fig. 1). The questions are: (1) magmatism operated beneath the volcanoes lying parallel to the Izu-Ogasawara Trench (Ōshima, Miyakejima and Mikurajima) is the same or not, and (2) magmatism operated beneath the volcanoes lying near or far off the Izu-Ogasawara Trench (Miyakejima *vs.* Ōnoharajima and Mikurajima *vs.* Inambajima) is the same or not.

GEOLOGICAL SETTING

Geology and petrography of Miyakejima and Ōnoharajima have been reported by one of the authors (ISSHIKI, 1960, 1964, 1977), and those of Mikurajima and Inambajima also by him (ISSHIKI, 1980). Brief descriptions on the volcanoes are summarized as follows:

(1) Miyakejima volcano:

Miyakejima is one of the largest islands of the Izu Islands and is situated about 200 km south-southwest of Tokyo and 34°05′N and 139°32′E (Fig. 1). The island is a basaltic volcano consisting of a pre-caldera stratovolcano, a post-caldera stratovolcano and a number of central and parasitic cones and craters. Rocks

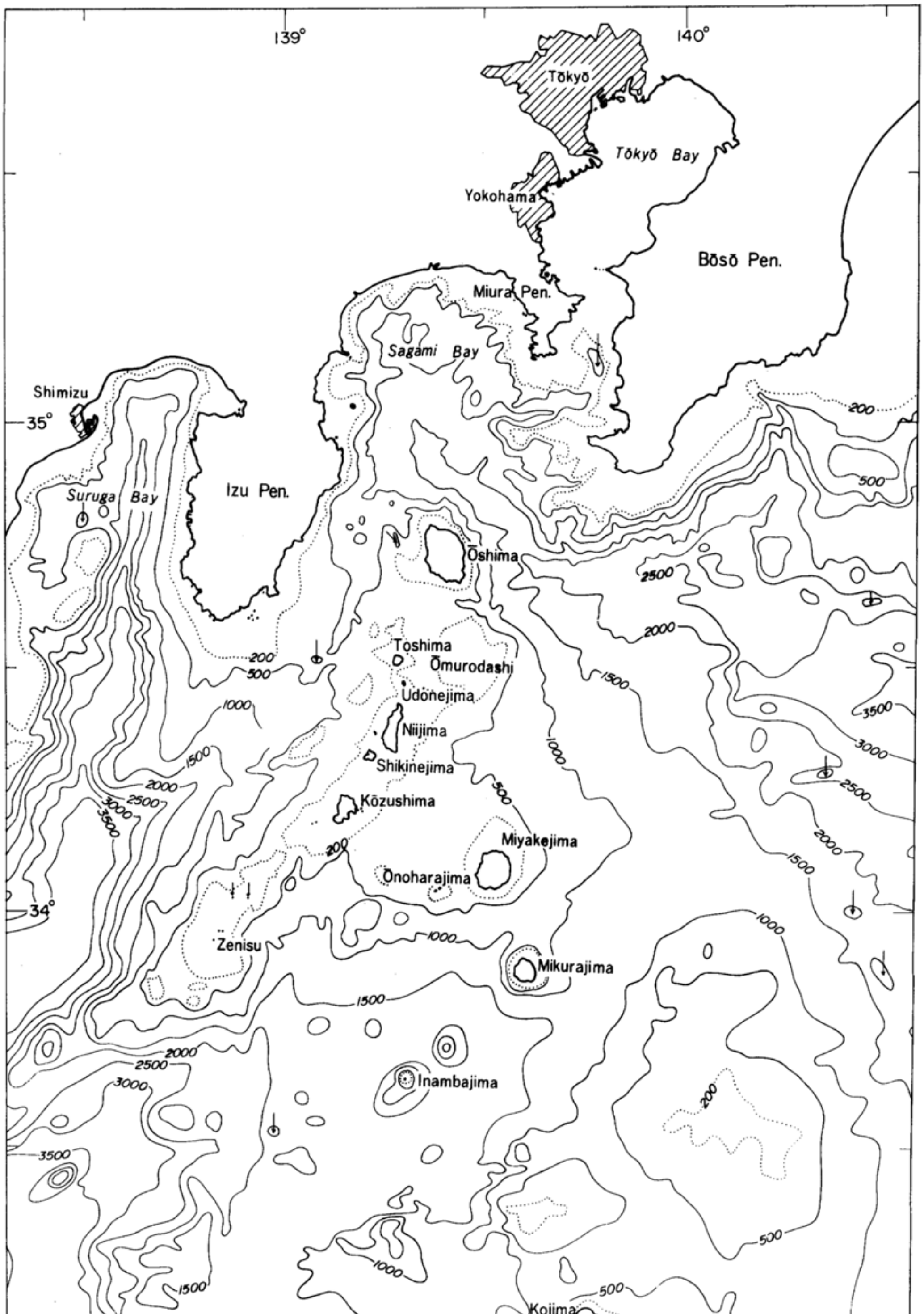

Fig. 1. Locality map of the Izu Islands region on the basis of Ocean Sounding Charts G 1406 and G 1506 published in 1974 by Maritime Safety Agency, Japan.

constituting Miyakejima volcano are olivine basalts, pyroxene-olivine basalts, pyroxene basalts and pyroxene andesites. Aphyric types are not common. Most of the basalts contain phenocrysts of anorthite to bytownite (10-30 vol. %) and less conspicuous ones of ferromagnesian minerals in groundmasses consisting of bytownite to labradorite, clinopyroxene, iron ore, cristobalite and interstitial glass. The andesites have phenocrysts of bytownite to labradorite, pyroxene and titaniferous magnetite in finer-grained groundmasses consisting of labradorite to andesine, clinopyroxene, iron ore and interstitial felsic mesostasis or glass sometimes with tridymite or cristobalite or both as cavity fill. All the rocks of Miyakejima do not contain orthopyroxene as a groundmass constituent and belong to the pigeonitic rock series of KUNO (1950).

(2) Ōnoharajima volcano:

Ōnoharajima which includes several volcanic islets and stacks lies about 10km off the western coast of Miyakejima at 34°03′N and 139°23′E (Fig. 1). They are composed of augite-hypersthene andesite lava with a number of cognate inclusions of more mafic character, and may be erosion remnants of a lava dome or domes. The andesite contains phenocrysts of anorthite to andesine, hypersthene, augite and titanomagnetite in a groundmass consisting of andesine, orthopyroxene, clinopyroxene, iron ore, tridymite, glass and apatite and is of the hypersthenic rock series of KUNO (1950). The cognate inclusion contains phenocrysts of anorthite to andesine, augite and bronzite to hypersthene in a ground mass consisting of plagioclase, bronzite to hypersthene, augite, iron ore and tridymite.

(3) Mikurajima volcano:

Mikurajima is situated about 220km south-southwest of Tokyo at 33°52′N and 139°37′E (Fig. 1). The island is a dissected stratovolcano of basalt and andesite with three andesite lava domes on the flank. Rocks constituting Mikurajima volcano are olivine basalt, augite-olivine basalt, olivine-augite-hypersthene andesite and hypersthere-augite andesite all of which contain abundant calcic plagioclase phenocrysts. Aphyric types are not common. The basalts contain plagioclase, clinopyroxene, iron ore and cristobalite and/or felsic mesostasis as groundmass constituents. The andesites comprise plagioclase, clinopyroxene, iron ore, silica minerals and rare apatite as groundmass constituents. These basalts and andesites are of the pigeonitic rock series of KUNO (1950). An augite-hypersthene andesite lava flow (?) of the main stratovolcano contains phenocrysts of plagioclase, hypersthene, augite and titanomagnetite in a groundmass consisting of plagioclase, clinopyroxene, iron ore, tridymite together with orthopyroxene whose presence characterizes the hypersthenic rock series of KUNO (1950).

(4) Inambajima volcano:

Inambajima is situated about 40km southwest of Mikurajima at 33°39′N and 139°18′E. The island is a very small, almost bare rock of felsic andesite roughly 120m by 70m by 74m high and may be remnant of a lava dome. Inambajima volcano is composed of felsic andesite of the hypersthenic rock series which contains phenocrysts of plagioclase, hypersthene, augite and titanomagnetite in a groundmass consisting of plagioclase, clinopyroxene, iron ore and a little orthopyroxene which are filled with a silica mineral, possibly tridymite.

EXPERIMENTAL

All the samples used in this study were collected by one of the authors (N.I.) except for an Inambajima sample which was donated by Prof. Magoshichi Sato of Tokai University. The sampling localities are summarized in Appendix 1. The specimens in Appendix 1 are arranged in chronological order on the basis of stratigraphy of each volcano.

Samples were analyzed with an inductively coupled plasma optical emission spectrometer (HIRANO *et al.*, 1980; ONUMA *et al.*, 1981). The ICP-OES method is of great advantage to treat many rock samples accurately and precisely. The accuracy of the method checked by several geochemical standard rocks (AGV-1,

Table 1. Analytical results of determination for Ca, Sr and Ba in several geochemical standard rocks by ICP-OES method

Standard rocks	Ca (ppm) This work	Ca (ppm) Certified value	Sr (ppm) This work	Sr (ppm) Certified value	Ba (ppm) This work	Ba (ppm) Certified value
AGV-1	34500	35000*	675	657*	1230	1208*
BCR-1	47400	49500*	331	330*	679	675*
G-2	13400	13900*	486	479*	1920	1870*
GSP-1	13800	14400*	234	233*	1310	1300*
JB-1	63500	66300**	448	435**	500	490**
JG-1	15300	15700**	185	184**	483	462**

*: FLANAGAN (1973).
**: ANDO (1978).

Table 2. Precision for determination of Ca, Sr and Ba in a geochemical standard rock (JG-1) by ICP-OES method

Run		Ca (ppm)	Sr (ppm)	Ba (ppm)
1	Av. of 19	15500	180	470
	S.D.*	190	3.1	6.0
2	Av. of 19	15700	183	461
	S.D.	220	8.0	15.7
3	Av. of 36	15700	180	460
	S.D.	380	2.2	8.3
Average		15500 (c.v. 15700**)	180 (c.v. 184**)	460 (c.v. 462**)
	S.D.	240	4.7	10.9

*: *Standard deviation.*
**: *Certified value from* ANDO *(1978).*

BCR-1, G-2, GSP-1, JB-1 and JG-1), and the precision of the method inspected by a geochemical standard rock (JG-1) are shown in Tables 1 and 2, respectively.

RESULTS AND DISCUSSIONS

The results obtained in this work are summarized in Table 3, and two series of SB systematics from Miyakejima and Ōnoharajima volcanoes and from Mikurajima and Inambajima volcanoes are shown in Figs. 2 and 3, respectively.

As shown in Fig. 2, Sr/Ca - Ba/Ca plots of rocks from Miyakejima volcano make a curve growing upward from basalts to andesites, suggesting existence of crystal fractionation process in a "magma chamber". The crystal fractionation process is controlled by plagioclase and clinopyroxene crystallization in terms of Sr/Ca and Ba/Ca ratios. Removal of these minerals causes small increase in Sr/Ca ratio and large increase in Ba/Ca ratio of the silicate melts, while olivine crystallization does not change the slope because olivine does not accept these large cations.

An andesite and a cognate inclusion in the andesite from Ōnoharajima volcano make a different systematics situated over Miyakejima systematics, as shown in Fig. 2. Ōnoharajima systematics also suggests the existence of a "magma chamber" in which plagioclase and clinopyroxene crystallization prevailed. The parallelism between the two series of SB systematics indicates that the crystal factionation processes are very similar to each other in terms of plagioclase and clinopyroxene crystallization. However, the two series of SB systematics are quite different in terms of Sr/Ca ratio. The difference is considered to have been caused by the different degrees of partial melting of mantle material, as is discussed later.

Table 3. Ca, Sr, Ba contents and Sr/Ca, Ba/Ca ratios of volcanic rocks of Miyakejima, Ōnoharajima, Mikurajima and Inambajima, the Izu Islands, Japan

Sample	Rock type	Ca (ppm)	Sr (ppm)	Ba (ppm)	Sr/Ca	Ba/Ca
Miyakejima volcano						
NI57073004	Augite-olivine basalt	74600	241	130	3.23×10^{-3}	1.74×10^{-3}
NI57073001	Augite-olivine basalt	74100	240	132	3.24×10^{-3}	1.78×10^{-3}
NI57073108	Hypersthene-bearing augite-olivine basalt	85800	257	95.4	3.00×10^{-3}	1.11×10^{-3}
NI58032011	Hypersthene-augite andesite	55200	250	222	4.53×10^{-3}	4.02×10^{-3}
NI74112701	Olivine-bearing hypersthene-augite andesite	44500	247	276	5.55×10^{-3}	6.20×10^{-3}
NI57072303	Hypersthene-augite andesite	49900	236	272	4.73×10^{-3}	5.45×10^{-3}
NI58032512	Hypersthene-bearing olivine-augite basalt	67700	246	155	3.63×10^{-3}	2.29×10^{-3}
NI57072408	Aphyric basalt	70700	237	159	3.35×10^{-3}	2.25×10^{-3}
NI57073006	Aphyric basalt	63700	239	188	3.75×10^{-3}	2.95×10^{-3}
NI57080611c	Olivine- and augite-bearing basalt	57600	247	225	4.29×10^{-3}	3.91×10^{-3}
NI57080611b	Hypersthene-augite-olivine basalt	62500	249	205	3.98×10^{-3}	3.28×10^{-3}
NI62090902	Hypersthene- and olivine-bearing augite basalt	55200	242	235	4.38×10^{-3}	4.26×10^{-3}
Ōnoharajima volcano						
NI57072505	A cognate inclusion in augite-hypersthene andesite (NI57072504)	68900	313	115	4.54×10^{-3}	1.67×10^{-3}
NI57072504	Augite-hypersthene andesite	52500	305	169	5.81×10^{-3}	3.22×10^{-3}
Mikurajima volcano						
(1) Main stratovolcano						
NI60092710	Augite-hypersthene andesite	51600	298	217	5.78×10^{-3}	4.21×10^{-3}
NI60091401	Augite-olivine basalt	69400	246	124	3.54×10^{-3}	1.79×10^{-3}
NI60092406	Hypersthene-augite andesite	39800	263	274	6.61×10^{-3}	6.88×10^{-3}
NI60091112	Aphyric andesite	56100	250	165	4.46×10^{-3}	2.94×10^{-3}
NI60092401	Augite-bearing hypersthene andesite	75600	295	155	3.90×10^{-3}	2.05×10^{-3}
(2) Lava dome group						
NI60091805	Olivine-augite-hypersthene andesite	60500	254	168	4.20×10^{-3}	2.78×10^{-3}
Inambajima volcano						
NI62060801c	Augite-hypersthene andesite	51900	306	226	5.90×10^{-3}	4.35×10^{-3}

As shown in Fig. 3, basalts and andesites from Mikurajima volcano make an SB systematics with a gentle slope, suggesting that plagioclase and clinopyroxene crystallization proceeded within a "magma chamber". Inambajima volcano provides only an andesite to that we can not define SB systematics from the volcano.

Figure 4 shows a comparison of SB systematics so far obtained from volcanoes of the Izu Islands. A line with a slope of 45° through chondrites is a hypothetical partial melting line introduced by ONUMA (1981) and ONUMA and HIRANO (1981). We define the intersection of the partial melting line and a given SB systematics as "SB index" which is a measure of degree of partial melting for the "primary magma" generated in the mantle. The larger SB index corresponds to the smaller degree of partial melting, and vice versa.

Figure 4 suggests that the major difference in magmatism operated beneath the Izu Islands region is characterized by the difference in the degree of partial melting of mantle material with chondritic Sr/Ca and Ba/Ca ratios. The four volcanoes in Ōshima are composed of a "primary magma" with the largest degree of partial melting, and its derivatives evolved from the "primary magma" by crystal fractionation

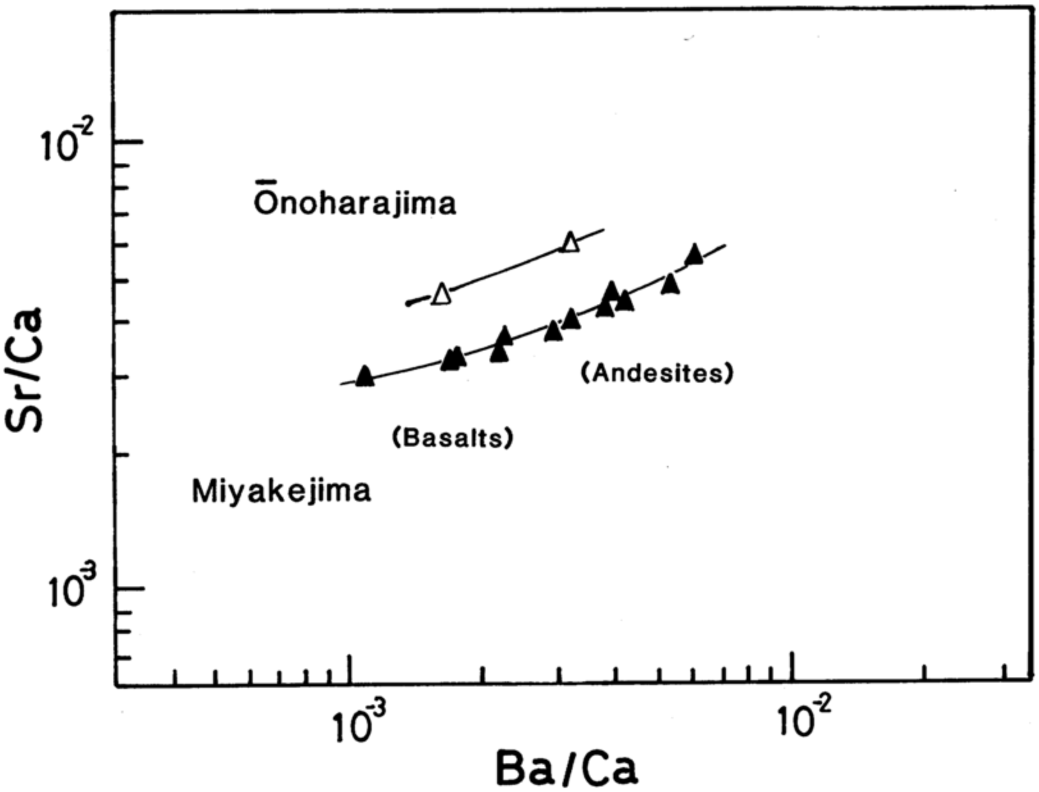

Fig. 2. Sr/Ca - Ba/Ca systematics defined by volcanic rocks from Miyakejima and Ōnoharajima volcanoes. (▲: Miyakejima, △: Ōnoharajima).

within a "magma chamber" before ascent to the surface. "Primary magmas" generated beneath Miyakejima and Mikurajima (and maybe Inambajima) volcanoes are the same in terms of the degree of partial melting of mantle material, since the two series of SB systematics from Miyakejima and Mikurajima volcanoes converge at the intersection of the partial melting line as shown in Fig. 4. The degree of partial melting for Miyakejima and Mikurajima volcanoes is smaller than that of the four volcanoes in Ōshima, since the SB index for the former volcanoes is larger than that for the latter volcanoes. The difference in magmatism beneath Miyakejima and Mikurajima is characterized by the difference of crystal fractionation process in the "magma chamber". Plagioclase/clinopyroxene ratio in cumulates left in the "magma chamber" for Mikurajima may be smaller than that for Miyakejima. The difference in the course of fractional crystallization may have been caused by the difference of water contents of "magma chambers". Ōnoharajima volcano shows the largest SB index in this region, indicating the smallest degree of partial melting of mantle material.

Volcanoes (Ōshima, Miyakejima and Mikurajima) situated on the volcanic front provide rocks of the pigeonitic rock series, while volcanoes (for example, Ōnoharajima) situated behind it give rocks of the hypersthenic rock series. Figures 2 and 4 suggest that major chemical difference in the two rock series is caused by different degrees of partial melting of a common mantle material with chondritic Sr/Ca and Ba/Ca ratios. The degrees of primary basalt magmas for the pigeonitic rock series (PRS) are larger than that for the hypersthenic

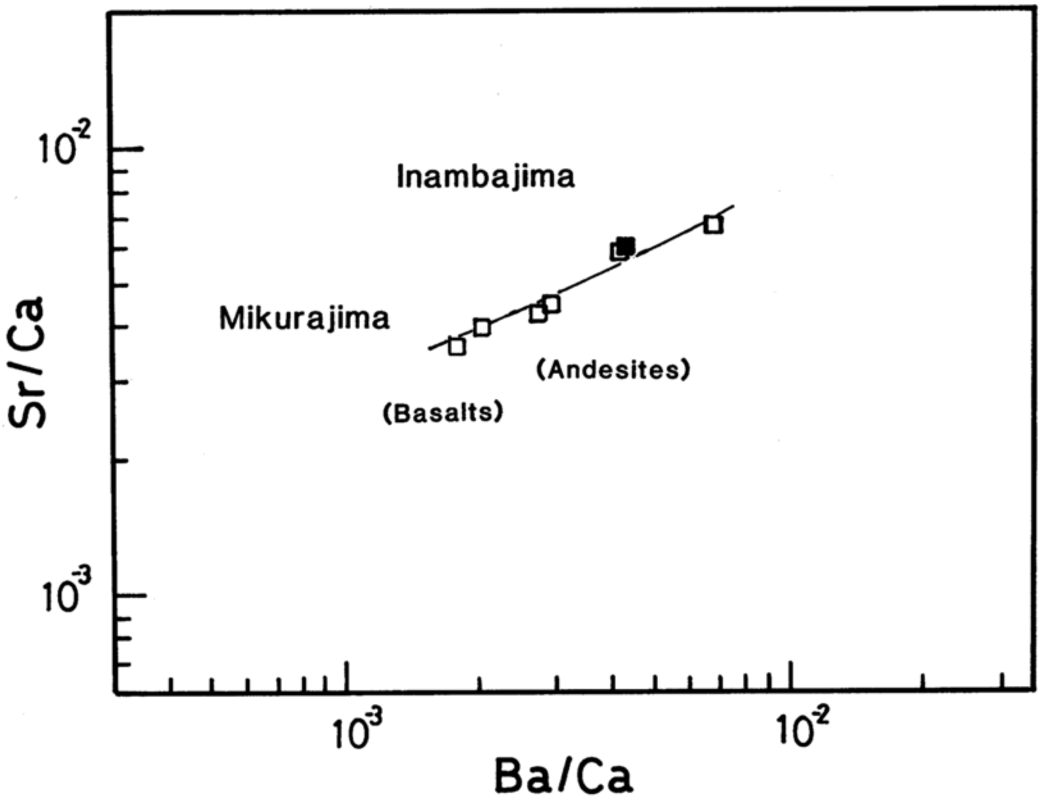

Fig. 3. Sr/Ca - Ba/Ca systematics defined by volcanic rocks from Mikurajima and Inambajima volcanoes. (□: Mikurajima, ■: Inambajima).

rock series (HRS). In Mikurajima (PRS) *vs.* Inambajima (HRS) system (Fig. 3), however, we cannot give an additional definite conclusion because of the poor data on Inambajima. The fractional crystallization processes in "magma chambers" for the two different rock series, are, more or less, similar to each other in terms of plagioclase/clinopyroxene crystallization, as indicated by the parallelism of the SB systematics given by the two different rock series.

It should be noted that Ōshima, Miyakejima and Mikurajima aligned parallel to the Izu-Ogasawara Trench down to the south show different degrees of partial melting of mantle material. In the Miyakejima-Ōnoharajima system oblique to the Izu-Ogasawara Trench, there is a difference in the degree of partial melting between the two islands. On the other hand, there seems to be no difference in the degree of partial melting in Mikurajima-Inambajima system oblique to the Izu-Ogasawara Trench. Therefore, there is no relationship between the degree of partial melting and the distance from the Izu-Ogasawara Trench in this region.

Acknowledgements—This work was supported in part by Grant-in-Aid for Scientific Research, No. 504112 and No. 56110005 (for one of the authors, N.O.) from the Ministry of Education, Science and Culture, Japan.

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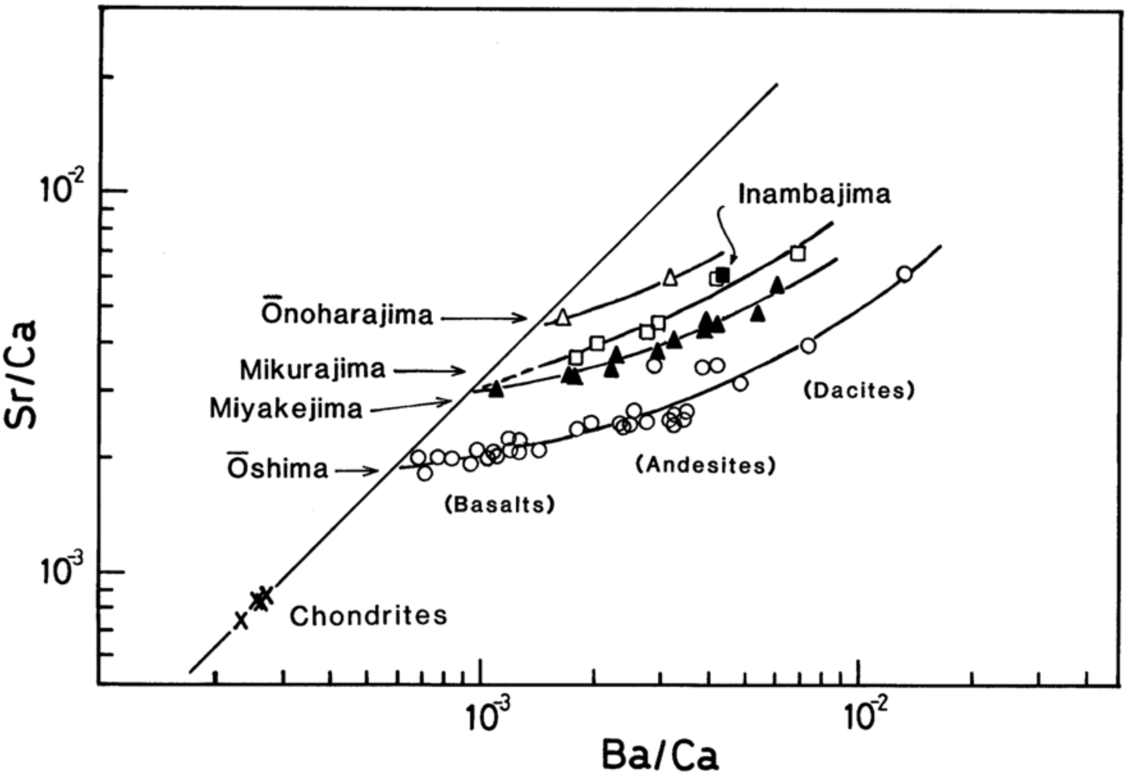

Fig. 4. Comparison of Sr/Ca - Ba/Ca systematics of volcanoes in the Izu Islands.

○: *Ōshima (ONUMA et al., 1981).*
▲: *Miyakejima (This work).*
□: *Mikurajima (This work).*
■: *Inambajima (This work).*
△: *Ōnoharajima (This work).*

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Appendix 1. Sampling localities

Miyakejima volcano		
NI57073004	A lava flow exposed on the sea-cliff about 300m north of Ako on the western coast	
NI57073001	A lava flow exposed on the sea-cliff about 700m north of Ako on the western coast	ISSHIKI (1960), p.22, Table 2, no.1
NI57073108	A lava flow exposed on the sea-cliff about 350m south-southeast of Izunzaki on the western coast	
NI58032011	A lava flow exposed at Izu on the northwestern foot	
NI74112701	A bomb exposed on a roadcut about 100m north of Naganehachiman on the western foot	
NI57072303	A lava flow exposed on the sea-cliff southwest of Tsubota on the southern coast	
NI58032512	A lava flow exposed on a roadcut about 700m east of Igaya on the northwestern flank	
NI57072408	Lava flow of 1535? exposed at Benkenemisaki on the east-southeastern coast	ISSHIKI (1960), p.22, Table 2, no.5
NI57073006	Lava flow of 1643? exposed at Imasaki on the western coast	ISSHIKI (1960), p.23, Table 2, no.6
NI57080611c	The lower part of composite lava flow of 1874 exposed between Kamitsuki and Tosa on the northern foot	ISSHIKI (1960), p.23, Table 2, no.9
NI57080611b	The middle part of composite lava flow of 1874 exposed between Kamitsuki and Tosa on the northern foot	ISSHIKI (1960), p.23, Table 2, no.8
NI62090902	Lava flow of August, 1962 on the northeastern flank	
Ōnoharajima volcano		
NI57072505	A cognate inclusion in dome lava exposed at Ōne	
NI57072504	Dome lava exposed at Ōne	ISSHIKI (1960), p.23, Table 2, no.11
Mikurajima volcano		
(1) Main stratovolcano		
NI60092710	A lava flow? exposed on the sea-cliff on the southwestern coast	ISSHIKI (1980), p.13, Table 1, no.1
NI60091401	A lava flow exposed on the sea-cliff north of Uranne on the western coast	ISSHIKI (1980), p.13, Table 1, no.2
NI60092406	A float of welded spatter found about 1km north of Oyama	ISSHIKI (1980), p.13, Table 1, no.4
NI60091112	A dike exposed on the sea-cliff a little east of Tokkurine on the northern coast	ISSHIKI (1980), p.13, Table 1, no.5
NI60092401	A dike exposed about 0.4km southeast of Oyama	ISSHIKI (1980), p.13, Table 1, no.6
(2) Lava dome group		
NI60091805	Dome lava of Yasukajigamori about 1.2km southwest of Nangō	ISSHIKI (1980), p.13, Table 1, no.7
Inambajima volcano		
NI62060801c	Dome lava exposed at the northeastern tip	