Bulletin of the Geological Survey of Japan, vol, 43 (7), p. 421-456, 1992

Petrographic and geochemical along-arc variations of volcanic rocks on the volcanic front of the Izu-Ogasawara (Bonin) Arc

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YUASA Makoto and NOHARA Masato (1992) Petrographic and geochemical along-arc variations of volcanic rocks on the volcanic front of the Izu-Ogasawara (Bonin) Arc. *Bull. Geol. Surv. Japan,* vol. 43 (7), p. 421-456, 11fig., 3tab.

Abstract: The Shichito-Iwojima Ridge is divided into two parts based on the rock chemistry of volcanic islands and submarine volcanoes. This division corresponds to the topography. The volcanic rocks of the southern part (Nishinoshima to Minami-Iwojima volcanoes) are higher in alkali contents than those of the northern part (Oshima to Sofugan volcanoes). The rocks from seamounts in the Nishinoshima Trough have different chemical characteristics than the surrounding volcanoes. Sr isotope ratios of the rocks are low relative to the surroundings. They are chemically divided into four groups. Variation trends of incompatible elements for each group are different. This fact suggests that there is a difference in primary magma composition among these groups.

In the southern part of the ridge, K_2O, P_2O_5, Ba and Sr contents tend to increase gradually from north to south, and reach maximum at Minami-Iwojima and Iwojima volcanoes. The SB diagram shows the lowest degree of partial melting of source mantle in those two volcanoes. $^{87}Sr/^{86}Sr$ ratios also vary in the along-arc direction. The highest ratios are at Minami-Iwojima volcano and the lowest in the Nishinoshima Trough. Four segments are defined by the increasing or decreasing trend of the ratios along the arc. In this saw-toothed variation, the lower parts correspond to structural gaps. There is a systematic difference in the ratios between the younger and older seamounts in the Nishinoshima Trough, in spite of their closeness in geographical location. This suggests temporal changes in the composition of magma source, the fluid phase derived from subducting slab, or the tectonic stress field.

1. Introduction

1.1 Across- and along-arc variation of arc volcanism

Island arc volcanoes, produced at convergent plate boundaries, distribute as a chain or a zone parallel to the trench. The most intensive and productive part of the arc volcanism is restricted to a narrow belt called the "volcanic front" (Sugimura, 1958, 1960).

Island arc volcanism is characterized by central eruptions and formation of volcano clusters in a chain. This is different from mid-oceanic ridge volcanism at divergent plate boundaries where fissure eruptions predominate. Hot-spot volcanism, a characteristic intraplate volcanic activity, shows a

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Keywords: Izu-Ogasawara Arc, Bonin Arc, along-arc variation, petrography, Shichito-Iwojima Ridge, submarine volcano, seamount, SB systematics, Sr isotope ratio, petrochemistry, Sofugan Tectonic Line, Nishinoshima Trough, Shichiyo Seamounts, caldera, alkaline volcanic rock, volcanic front, Ohmachi Seamount, alkalinity of volcanic rocks

similarity to island arc volcanism in that it has a central eruption type forming a chain, but the volcanoes along the chain are not simultaneously active as in the island arc volcanoes. The arc volcanic chain seems to be accompanied with a plate subduction. Studies of island arc volcanic rocks demonstrated transverse systematic changes in the chemical compositions of volcanic rocks in relation to the distances from the trench axis (e.g. Kuno, 1966) and to the dip angle of the Wadati-Benioff Zone (e.g. Gill, 1981). The number of volcanic edifices tends to decrease from the volcanic front to the backarc side, suggesting that the magma generation rate decreases toward the backarc side.

In addition to the above across-arc variations, along-arc variations in the configuration of volcanoes and chemistry of volcanic rocks are also important aspects in the study of arc volcanism. Two kinds of variations exist; one is the segmentation of the arc itself and the other is the gradual change in morphological and petrochemical properties of volcanoes along the arc or within a segment.

The origin of these variations for different regions has been discussed as shown below.

Origin of segmentation

(1) Fingering of subducting plate
Central America (Carr *et al.*, 1982)

(2) Change of crustal thickness
South America (Katsui, 1972)

(3) Rift breaking into arc
Philippines (Defant *et al.*, 1988)

Origin of gradual change in segments

(1) Different degree of partial melting
Indonesia (Nishimura and Suparka, 1986)

(2) Mantle heterogeneity
Lesser Antilles (Brown *et al.*, 1977)

These examples show the effects of different behaviors of the subducting plates or different properties of the underlying mantle along the arcs. Arc-trench systems in the western Pacific are often accompanied with backarc basins as one of important elements on their continental side. Yuasa (1985) suggested a possibility that the opening of backarc basins affecting segmentation of the arc.

1.2 Previous studies on across- and along-arc variations of Izu-Ogasawara (Bonin) Arc

The Izu-Ogasawara Arc is one of the arc-trench systems in the western Pacific and emerges as several volcanic islands and reefs arranged north to south along its central axis. There are across- and along-arc chemical variations of volcanic rocks in the Izu-Ogasawara arc (Kuno, 1959; Yuasa and Tamaki, 1982; Yuasa, 1983, 1985; Uto, 1983; Notsu *et al.*, 1983; Notsu, 1985). Uto (1983) summarized the previous work for volcanic rocks from the northern part of the arc and showed the across-arc chemical variation of the rocks. His conclusions are as follows. Incompatible elements including K, Rb, Ba, and light REE increase from the volcanic front toward the backarc side, whereas $^{87}Sr/^{86}Sr$, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios decrease toward the backarc. Yuasa and Tamaki (1982) divided the volcanic rocks along the Shichito-Iwojima Ridge into two groups in terms of their alkalinity; low-alkaline in the northern part (Oshima to Sofugan islands) and high-alkaline in the southern part (Nishinoshima to Minami-Iwojima islands). Yuasa (1983 and 1985) concluded that a major fault, the Sofugan Tectonic Line, is separating the northern and southern parts on the basis of contrasting geological and geophysical characteristics in addition to the rock chemistries. He also suggested that the along-arc variation may be ascribed to the different modes of subduction of the Pacific Plate or differential opening of the backarc basins (Shikoku and Parece Vela basins). These studies are based mainly on the rock chemistry of emerged volcanic islands. Because the arc is mostly submerged, data from the submarine part are essential for discussion of the along-arc variation.

The subducting Pacific Plate is possibly split along the Sofugan Tectonic Line similar to the Cocos Plate subducting beneath Central America. The different alkali contents of volcanic rocks between the northern and southern parts of the Izu-Ogasawara Arc may be ascribed to the difference in subduction angle of the descending plate. Notsu *et al.* (1983) stated that the contamination of volcanic rocks from crustal material is negligible and the underlying mantle is rather homogeneous beneath the Izu-Ogasawara Arc based on the restricted range in Sr isotope ratios of volcanic rocks. If the mantle is homogeneous through the arc the differences in alkali contents, especially that of K, would indicate different degree of partial melting of the mantle. The possibility, however, has to be examined in connection with submarine geologic data.

In this paper the along-arc variation in petrochemical characteristics of seamounts on the volcanic front of the Izu-Ogasawara Arc is described.

2. Petrographic and geochemical descriptions of volcanic rocks from seamounts

The samples described here were dredged or grabbed from seamounts during the scientific cruises of R/V Hakurei-maru (GH84-2 to GH87-3) for the purpose of research on hydrothermal activity in the island arc (Nakao *et al.,* 1990). Locations of the dredge and grab sampling sites are given in Fig. 1. The descriptions of submarine topographic features of seamounts are presented elsewhere (Yuasa *et al.,* 1991).

2.1 Submarine calderas in the northern arc

Aramaki and Ui (1978) pointed out that the proportion of acid volcanic rocks is small in the Quaternary volcanic rocks of the Izu-Ogasawara Arc. Quaternary acid volcanic rocks occur mainly in the backarc volcanoes such as Niijima and Kozushima islands. On the volcanic front of the arc only two examples were known; one is the Myojinsho Reef where a submarine eruption formed a new island in 1952 (Morimoto and Ossaka, 1955), and the other is described at the lower slope of Higashiyama Volcano on Hachijojima Island (Isshiki, 1959). Therefore, less acid volcanic rocks had been regarded to be the characteristic rock types along the volcanic front of the Izu-Ogasawara Arc. Subsequently, acid volcanic rocks were dredged and grabbed from several seamounts (Omurodashi; Hamuro *et al.,* 1983, Kurose Hole; Yuasa *et al.,* 1981), and obtained from Kaitoku Seamount, a newly erupted seamount (Tsuchide *et al.,* 1985). Recently, submarine geologic surveys were carried out in this region and five calderas were found (Higashi-Aogashima, Kita-Bayonnaise, Sumisu, Minami-Sumisu and Torishima calderas: Murakami and Ishihara, 1985; Yuasa and Murakami, 1985; Taylor *et al.,* 1990). Four of them yielded acid volcanics (dacitic and rhyolitic pumice). As described in another paper (Yuasa *et al.,* 1991), these calderas are mostly submerged and only small parts of the sommas emerge above sea level (e.g. Sumisujima Island and Bayonnaise Rocks). These acid rocks had been neglected in the estimation of Aramaki and Ui (1978).

2.1.1 *Kurose Hole*

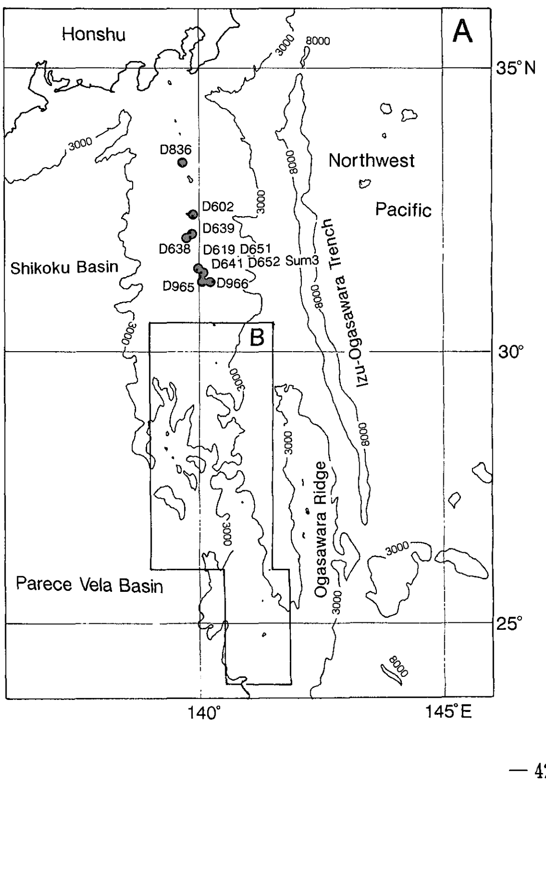
Large amounts of dacitic pumice and algal limestone were recovered by dredge D836 from the inner wall of Kurose Hole. Dacitic pumice is composed of phenocrysts of plagioclase and brownish green hornblende with minor orthopyroxene set in a fibrous glassy matrix. Olivine phenocrysts are rarely included in a less porous variety.

2.1.2 *Higashi-Aogashima Caldera (Daini- and Daisan-Aogashima Knolls)*

Two dredge sites located on the wall (D602) and outer slope (D603) of the caldera just to the east of Aogashima Island yielded andesite, dacitic pumice and altered volcanic breccia. The positions correspond to the flank of the Daini-Aogashima Knoll. Sample D602-5 is porphyritic andesite with large (2mm) plagioclase glomerocrysts. Subordinate orthopyroxene and minor amounts of clinopyroxene and opaque minerals occur in a microcrystalline groundmass of the same minerals. Sample D602-12 is dacitic pumice including phenocrysts of plagioclase and orthopyroxene and minor amounts of olivine, quartz and opaques. Fine-grained plagioclase and quartz phenocrysts are corroded.

2.1.3 *Kita-Bayonnaise Caldera (Myojin Knoll)*

Two dredges were made on this caldera seamount; dredge D638 on the outer slope of the western wall, and dredge D639 on the inner slope of the northeast wall. Large amounts of rhyolitic pumice and calcareous rocks were recovered from the sites. Majority of pumice contains plagioclase, clinopyroxene and orthopyroxene phenocrysts with rare hornblende. In places, hornblende diorite and other igneous xenoliths containing hornblende with radial growth textures are included in the pumice. A fist-sized, rounded cobble of orthopyroxene



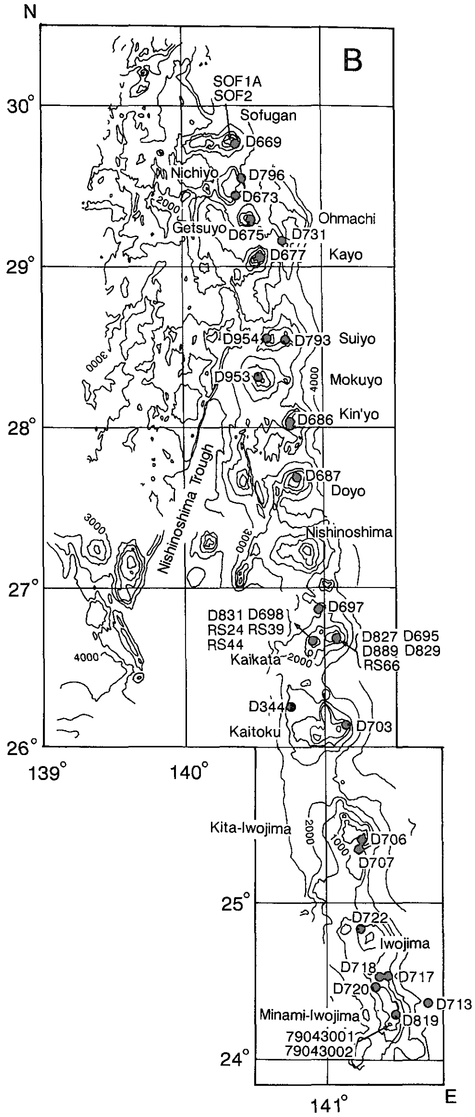


Fig. 1 Sampling localities of northern part (A) and central and southern part of the Izu-Ogasawara Arc (B).
Solid circles with number show sampling sites. Prefix letters mean sampling methods as follows; D: dredge, RS: grab sampler. Others are original sample numbers on land; Sum3: Sumisujima Is., SOF1A and SOF2: Sofugan Is., 79043001 and 79043002: Minami-Iwojima Is. Contour lines in Fig. 1 (A) are 3000 and 8000 m showing the topographic outline of the arc. Contour interval is 500 m in Fig. 1 (B).

-clinopyroxene andesite was also obtained from the D638 site.

2.1.4 *Sumisu Caldera and Sumisujima Island (Sumisujima Volcano)*

Dredges on the outer slope (D652 on the east and D619 on the west), on the wall (D651), and on the central cone (D641) of the caldera were carried out. Dredge D618 is situated at the bathymetric high on the western flank.

Various kinds of volcanic rock were dredged from the caldera wall and slope. Large boulders of conglomerate recovered from the outer slope (D619) consist of clasts of andesite, basalt, quartz diorite, pumice and limestone with a fine~medium-grained calcareous matrix. Sample D619-6 is slightly altered andesite with zoned plagioclase phenocrysts and subordinate clinopyroxene and orthopyroxene phenocrysts. Orthopyroxene phenocrysts are mantled by reaction rims of clinopyroxene. Minor opaques are dispersed through the groundmass and small amounts of secondary epidote are observed. Groundmass mineral assemblage is plagioclase, clinopyroxene, quartz and opaques. A sample of plagioclase-phyric basalt (D652-1) was recovered also from the outer slope, which includes plagioclase glomerocrysts (2mm) and subordinate clinopyroxene and olivine phenocrysts. Olivine phenocrysts are mantled with reaction rims of clinopyroxene. The groundmass is intersertal in texture and composed of plagioclase, clinopyroxene and fine mesostasis.

Large angular blocks of basalt and rhyolite were dredged from the inner wall (D651). Sample D651-2 contains phenocrysts of plagioclase, clinopyroxene, orthopyroxene and rare olivine in a porous groundmass. D651-3 is plagioclase-phyric basalt containing abundant large (2-3mm) plagioclase glomerocrysts and discrete phenocrysts with subordinate clinopyroxene and rare olivine phenocrysts in an intersertal groundmass. Olivine phenocrysts are mantled with the reaction rim of clinopyroxene.

From the central cone, large amounts of dacite blocks were recovered. Sample D641-m has a fine-grained groundmass consisting of plagioclase, clinopyroxene and cryptocrystalline material with abundant small vesicles. Sparse phenocrysts of plagioclase, orthopyroxene, clinopyroxene and opaque minerals are found. The dredge haul is mono-lithologic.

Cobble size fragments of pumice and andesite were recovered from a high on the west flank of the caldera. Sample D618-3 is medium-grained andesite with plagioclase, clinopyroxene, and orthopyroxene phenocrysts. The groundmass is hyalopilitic and composed of plagioclase, clinopyroxene, opaque minerals and glass.

Several rock specimens taken from the shore of Sumisujima Island by B. Taylor (Hawaii Institute of Geophysics, University of Hawaii) are olivine-bearing dolerite and olivine basalt. Analyzed sample Sum-3 (Table 1) is plagioclase-phyric dolerite with glomerocrysts of plagioclase (2-4mm) and rare olivine microphenocrysts set in an ophitic groundmass consisting of plagioclase, clinopyroxene and opaque minerals.

2.1.5 *Minami-Sumisu Caldera (Daisan-Sumisu Knoll)*

Acid volcanic rocks were recovered from two dredge sites on the Minami-Sumisu Caldera, D965 on the caldera wall and D966 on the slope of a satellite cone on the eastern flank.

D965-2 is a large agglomeratic boulder consisting of rhyolite with fine-grained phenocrysts of plagioclase, orthopyroxene, clinopyroxene and opaques set in a porous groundmass. D965-3 is pumiceous dacite with sparse plagioclase and clinopyroxene phenocrysts. D966-1 is pumiceous rhyolite with thin (1mm) manganese oxide coating. It contains plagioclase and green hornblende phenocrysts.

2.2 Chemical characteristics of the caldera volcanoes

Volcanic rocks from the calderas show a wide range in composition from basalt to rhyolite (Table 1). Dacitic and rhyolitic volcanic rocks, mainly pumice, occur on all the submarine calderas. Basaltic rocks, 50 to 52% in SiO_2 content, were obtained only from the somma of Myojinsho and Sumisu calderas. Both calderas show a bimodal chemistry for silica contents. Fig. 2 shows major element oxides versus silica for these rocks. Chemical compositions of volcanic rocks from Kozushima Island situated on the backarc side of the arc (Isshiki, 1982) and average trends of Japanese granitoids (Aramaki *et al.*, 1972) along with the compositions of acid rocks from Omurodashi (Hamuro *et al.*, 1983) and Hachijojima (Isshiki, 1959) are shown in the same diagram for comparison.

Over a long distance (about 350km) from Omurodashi to Minami-Sumisu Caldera, the compositions of these volcanic rocks are restricted within a narrow range. Compared with the volcanic rocks of Kozushima Island, the caldera volcanic rocks have trends of lower K_2O and Al_2O_3 contents and higher TiO_2, FeO* (total iron as FeO) and CaO contents. Chemical compositions of these rocks show an extremely low K_2O content and slightly high contents of TiO_2, FeO*, MgO CaO and Na_2O compared with the average value of Japanese granitoids. The

Table 1 Chemical compositions and CIPW norms for the volcanic rocks from the caldera volcanoes in the northern part of the Shichito-Iwojima Ridge. Kurose: Kurose Caldera, Aoga: Higashi-Aogashima Caldera, N-Bayo: Kita-Bayonnaise Caldera (Myojin Knoll), Sms: Sumisu Caldera (Sumisujima Volcano), S-Sms: Minami-Sumisu Caldera. Asterisks are for XRF analysis of major elements.
CIPW norms are calculated on water-free basis.
Analysts: Japan Analytical Center (major elements by wet analysis) and M. Yuasa (major elements by XRF and minor elements by XRF and AA).

Sp. No.	D836-1 Kurose	D602-5 Aoga	D602-12 Aoga	D638-2 N-Bayo	D639-1 N-Bayo	Sum-3 Sms	D619-6 Sms	D641 Sms	D641-m Sms	D651-2 Sms	D651-3 Sms	D652-1 Sms	D965-2 S-Sms	D965-3 S-Sms	D966-1 S-Sms
Wt%		*											*	*	*
SiO_2	62.96	57.50	69.65	71.22	73.33	50.43	69.15	68.63	69.00	71.91	49.42	51.41	70.11	69.34	72.93
TiO_2	0.36	0.82	0.36	0.30	0.31	0.79	0.73	0.74	0.76	0.51	0.71	0.60	0.49	0.32	0.31
Al_2O_3	14.63	16.07	12.97	13.27	12.81	17.53	13.81	13.80	13.73	13.13	19.30	18.34	14.46	12.69	12.88
Fe_2O_3	1.10	2.79	0.90	0.83	0.46	2.55	1.85	1.72	1.43	1.99	2.47	1.90	1.61	0.96	0.83
FeO	1.03	7.62	1.99	1.64	1.87	8.32	3.27	3.31	3.53	2.17	7.90	7.24	2.02	1.16	1.20
MnO	0.13	0.22	0.11	0.11	0.10	0.19	0.17	0.19	0.19	0.16	0.19	0.17	0.14	0.08	0.09
MgO	4.29	2.62	2.35	1.40	0.72	6.04	1.35	1.21	1.57	1.03	5.54	6.42	0.89	1.19	0.41
CaO	2.22	8.33	2.71	2.42	2.08	11.59	3.73	4.31	3.87	3.10	11.60	11.24	3.58	3.56	2.57
Na_2O	4.13	2.93	4.00	4.55	4.45	1.91	4.59	4.34	4.25	4.22	1.65	1.89	4.03	3.73	3.84
K_2O	1.22	0.23	0.64	0.77	0.86	0.26	0.79	0.58	0.63	0.81	0.19	0.21	0.90	1.14	1.18
P_2O_5	0.10	0.08	0.09	0.08	0.07	0.05	0.19	0.19	0.19	0.10	0.06	0.05	0.11	0.05	0.04
H_2O+	5.83	0.48	3.26	2.63	2.31	0.17	0.18	0.75	0.35	0.38	0.37	0.41	0.98	5.15	3.17
H_2O-	0.42	-	0.29	0.20	0.15	0.15	0.10	0.31	0.09	0.13	0.11	0.13	-	-	-
Total	98.42	99.70	99.32	99.42	99.52	99.98	99.91	100.08	99.59	99.64	99.51	100.01	99.33	99.36	99.45
ppm															
Ni	16	8	12	20	5	30	0	0	0	1	23	32	7	5	4
Co	2	25	4	5	3	42	19	25	18	15	49	58	3	0	2
Cr	1	16	0	0	0	54	8	0	9	5	32	57	14	7	11
V	15	209	24	18	8	394	40	26	41	23	366	285	23	21	19
Cu	10	30	105	26	8	129	6	1	5	18	121	124	0	10	6
Zn	70	91	66	61	55	70	85	92	95	85	73	61	73	44	44
Rb	20	4	10	13	14	4	9	-	11	13	7	8	12	16	17
Sr	221	181	106	153	144	194	170	-	200	169	178	135	186	141	130
Y	31	24	46	37	38	17	45	-	40	46	17	16	30	32	32
Zr	155	56	121	181	172	38	113	-	122	142	35	40	115	129	127
%															
Q	25.07	15.61	35.22	35.03	38.72	3.11	28.98	30.03	30.34	35.91	3.57	4.22	34.27	36.29	41.07
C	2.95		1.03	0.77	0.97								0.62		0.74
or	7.82	1.37	3.95	4.71	5.24	1.54	4.69	3.46	3.75	4.83	1.13	1.25	5.41	7.15	7.24
ab	37.92	24.99	35.34	39.86	38.79	16.22	38.98	37.09	36.27	36.02	14.10	16.08	34.68	33.50	33.75
an	11.24	30.26	13.42	11.89	10.16	38.62	14.80	16.62	16.67	14.62	45.13	41.16	17.33	15.41	12.97
wo-di		4.54				7.83	1.06	1.55	0.60	0.10	5.25	6.09		1.25	
di-en		1.74				4.18	0.50	0.69	0.28	0.06	2.76	3.45		0.87	
fs-di		2.87				3.39	0.54	0.86	0.32	0.04	2.33	2.38		0.28	
en-hy	11.59	4.84	6.11	3.61	1.85	10.92	2.87	2.36	3.66	2.53	11.17	12.63	2.25	2.28	1.06
fs-hy	0.68	7.96	2.63	2.11	2.81	8.86	3.06	2.96	4.12	1.77	9.43	8.73	1.86	0.74	1.22
mt	1.73	4.08	1.36	1.25	0.69	3.71	2.69	2.52	2.09	2.91	3.62	2.77	2.37	1.48	1.25
il	0.74	1.57	0.71	0.59	0.61	1.51	1.39	1.42	1.46	0.98	1.36	1.15	0.95	0.64	0.61
ap	0.25	0.19	0.22	0.19	0.17	0.12	0.44	0.44	0.44	0.23	0.14	0.12	0.26	0.12	0.10

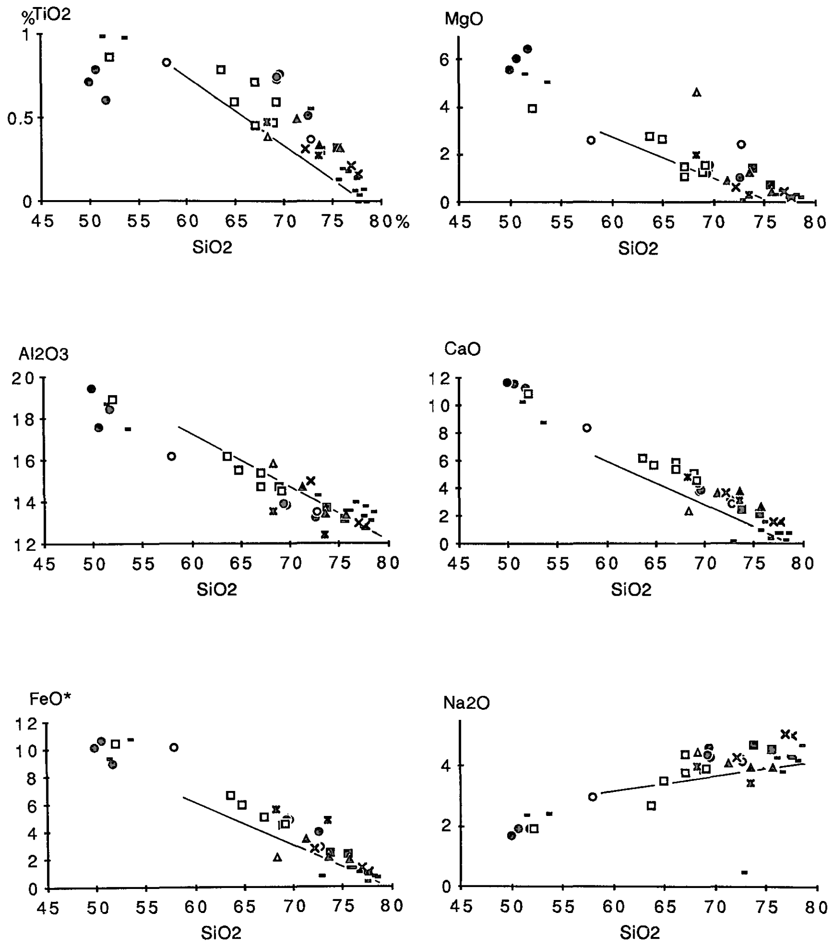


Fig. 2 Harker diagram for rocks from the caldera volcanoes in the northern part of the Shichito-Iwojima Ridge. Solid lines show the average trend of Japanese granitoids (Aramaki *et al.,* 1972). In the K_2O-SiO_2 and total alkali-SiO_2 diagrams, discriminative lines by Gill (1981) and Kuno (1968) are shown in broken lines, respectively. Abbreviations of the fields; H : high-K andesite, M : medium-K andesite, L : low-K andesite, HA : high-alkali tholeiite, LA : low-alkali tholeiite. Chemical compositions of the rocks from the Myojinsho (Morimoto and Ossaka, 1955 and 1970) including the Bayonnaise Rocks (Morimoto *et al.,* 1955), Omurodashi (Hamuro *et al.,* 1983), Hachijojima (Isshiki, 1959) and Kozushima volcanoes (Isshiki, 1982) are plotted in the same diagrams for comparison.

extremely low K characterizes the chemistry of volcanic rocks along the volcanic front in the northern part of the Izu-Ogasawara Arc.

2.3 Central part of the arc

The Izu-Ogasawara Arc is divided into two parts by the Sofugan Tectonic Line (Yuasa, 1985). The sea floor expression of the Tectonic Line is a deep trough trending NNE-SSW with a linear cliff on the west side. There are nine large seamounts on the volcanic front in the trough and they are named Ohmachi, Sawa and Shichiyo (Seven-days) seamounts. These seamounts are

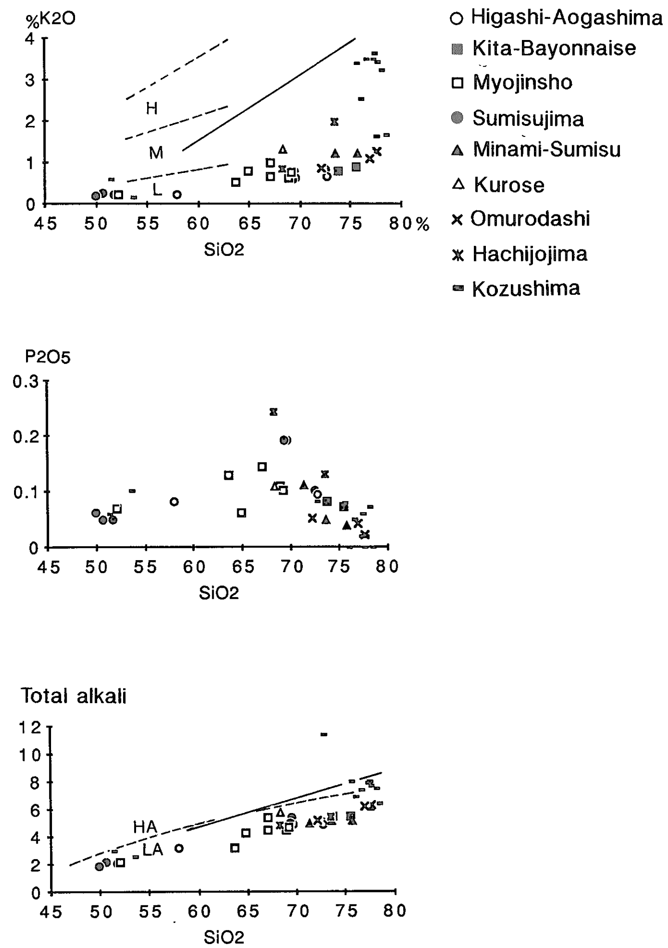


Fig. 2 continued

divided into three groups on the basis of topographic features and seismic profiling (Yuasa *et al.,* 1991), or four groups on the basis of magnetic anomaly data (Yamazaki *et al.,* 1991). The geological meanings of both divisions are consistent with each other except for one seamount (Getsuyo Seamount). Here we assign them to three groups based on both divisions; older (Nichiyo, Ohmachi and Sawa), younger (Getsuyo, Kayo, Kin'yo and Doyo) and intermediate-type (Suiyo and Mokuyo). We regard the Getsuyo Seamount as a young one from its topographic and geochemical features, although it has a slightly different magnetic pattern compared to the other younger seamounts. The Suiyo and Mokuyo seamounts are similar to the older group based on their topographic features. However, as they show complicated and unique magnetic anomaly patterns unlike the other older and younger seamount groups, we classify them as an independent group. Sofugan Island is included here because of its similar features in topography and petrography to the seamounts in the trough. As the island is a Quaternary volcano, it may be included in the younger seamount group.

2.3.1 *Older seamounts (Nichiyo, Ohmachi and Sawa)*

Andesitic rocks were recovered from two dredge sites on the southeast (D673) and east (D796) slopes of the Nichiyo Seamount. D673 contains a large block of volcanic sandstone coated on one side with thick manganese oxide and several clasts of conglomerate. Sample D673-5 is a clast of volcanic conglomerate. This clast consists of pebbles of porphyritic and slightly porous andesite which contains phenocrysts of plagioclase, clinopyroxene, orthopyroxene and opaques set in a microcrystalline groundmass. Clinopyroxene phenocrysts are anhedral and have embayments. D796 also recovered many volcanic conglomerates. Sample D796-5 is a clast of the conglomerate. The phenocryst minerals are the same as those of D673-5 but orthopyroxene occurs in an intersertal groundmass.

Six dredges were located on the Ohmachi Seamount, the largest in the trough. Fresh igneous rocks were obtained only from D731 on the upper middle part of the fault scarp limiting the west side of the seamount. D731-4 is a porphyritic andesite including large amounts of plagioclase phenocrysts with subordinate clinopyroxene, orthopyroxene and opaques set in a microcrystalline groundmass of the same minerals. In the same haul, a fragment of andesite with pale green hornblende phenocrysts was obtained. The rock is slightly altered. From the lower part of the scarp (D794) several sheared rock fragments were sampled. Fist-sized altered volcanic breccias have slickensides on one side. Rubble of the breccia is inferred to be originally clinopyroxene andesite. Pumpellyite, prehnite, epidote and chlorite occur in the rock as secondary minerals (Yuasa *et al.*, in press). Sawa Seamount is a large high also with a sharp fault scarp on the east side. Large blocks of volcanic sandstone and breccia with manganese oxide coatings were recovered. Rubble of the breccia is altered glassy andesite with phenocrysts of plagioclase and minor clinopyroxene.

As described above, most of the samples recovered from the older seamount are coated with thin or thick manganese oxide. This characteristic suggests that these seamounts are older than the others as previously inferred from bathymetry, seismic profiles and magnetic anomalies.

2.3.2 *Intermediate-type seamounts (Suiyo and Mokuyo)*

Suiyo Seamount has two major peaks on its east and west sides with other small satellitic highs. This characteristic feature seems to have resulted from faulting. Two dredges successfully recovered fresh samples; dredge D793 was located on the eastern peak and D954 on the western peak.

Dredge D793 recovered angular basalts with thin manganese oxide coatings and subrounded boulders of dacitic pumice. Sample D793-2 is plagioclase-phyric basalt with large glomerocrysts of weakly zoned plagioclase (3mm) and subordinate euhedral to skeletal olivine phenocrysts with reaction rims of clinopyroxene. Microphenocrysts of clinopyroxene are also observed. The groundmass is intersertal in texture and consists mainly of microlites of plagioclase, clinopyroxene and olivine.

Dredge D954 recovered many fresh and angular pumice blocks with quenched mafic xenoliths. Sample D954-5 is dacitic pumice with phenocrysts of plagioclase, clinopyroxene, olivine and opaques. Sample D954-8 is a xenolith of coarse-grained porphyritic basalt included in the pumice. The basalt contains phenocrysts of plagioclase, olivine (often corroded), clinopyroxene and opaques set in a groundmass of the same minerals. Sparse megacrysts of plagioclase (7mm) occur in the basalt. Needle-like hornblende and swallow-tail plagioclase occur near the boundary between basalt and pumice.

Mokuyo Seamount also has two peaks, a large peak on the west and a small one on the east. Five dredges were located on the seamount; three on the west and two on the east. In these dredges, only D953 on the west peak recovered large fresh rock samples. Thick slab fragments of hydrothermal manganese oxide were recovered from the lower flanks of both peaks in other dredge hauls (D791 and 792). Samples of D953 are mostly porous basalts with plagioclase, clinopyroxene and embayed olivine phenocrysts, although they have some range of variation in porosity and porphyritic nature. Sample D953-3 is highly vesicular basalt with many small pores. A large amount of phenocrystic plagioclase is observed in sample D953-2. The groundmass of these basalts is generally intersertal in texture and consist of microlites of plagioclase, olivine, clinopyroxene and opaques with minor amounts of interstitial brown glass.

2.3.3 *Younger seamounts (Getsuyo, Kayo, Kin'yo and Doyo)*

Each of these younger seamounts has a conical shape with sharp slopes. No stratified layers are observed on their flanks. Dredges D675, D677, D686 and D687 were situated on the Getsuyo, Kayo, Kin'yo and Doyo seamounts, respectively.

Many angular blocks of porphyritic andesite were sampled in the dredge D675 on the southeast flank of the Getsuyo Seamount. The samples are monolithologic. D675-1 has some glomerocrysts and large phenocrysts of plagioclase and clinopyroxene with subordinate orthopyroxene set in a hyalopilitic groundmass consisting of the same minerals and glass. In places, pale brown hornblende xenocrysts occur with a reaction rim of very fine-grained opaque minerals.

Dredge D677 was situated on the east flank of the Kayo Seamount. Four fist-sized fragments of angular volcanics were recovered. Sample D677-1 is plagioclase-phyric andesite with subordinate clinopyroxene phenocrysts, minor olivine, and rare orthopyroxene microphenocrysts. Olivine microphenocrysts are surrounded by clinopyroxene reaction rims. Orthopyroxene shows parallel intergrowth with clinopyroxene. The groundmass is hyalopilitic in texture and is composed of plagioclase, clinopyroxene, orthopyroxene and glass.

Dredge D686 was also a monolithologic haul. Large angular blocks of slightly vesicular andesite were recovered on the west flank of the Kin'yo Seamount. The samples have onion-like shells. Sample D686-1 is plagioclase-phyric andesite with subordinate clinopyroxene and orthopyroxene phenocrysts and olivine and opaque microphenocrysts. Orthopyroxene is often mantled with clinopyroxene, and olivine microphenocrysts are often rimmed likewise with clinopyroxene. The groundmass is intersertal in texture and consists mainly of plagioclase, clinopyroxene and olivine microlites.

Dredge D687 was located on the upper part of the Doyo Seamount. Angular and subrounded rocks were recovered from this site. Rounded samples show fairly intensive alteration with secondary chlorite, calcite, quartz and clay minerals replacing many of the ferromagnesian minerals. Fresh angular volcanic rocks are relatively large in size. Sample D687-1 is slightly porous basalt with large phenocrysts of plagioclase (3mm) and clinopyroxene (4.5mm) and microphenocrysts of orthopyroxene and rare olivine. The groundmass shows an intersertal texture consisting of microlites of plagioclase, clinopyroxene, olivine, opaques and glass. Sample D687-4 is also a porous basalt. Glomerophyric plagioclase and clinopyroxene and corroded olivine phenocrysts are often observed in an intersertal groundmass similar to D687-1 but with less glass.

2.3.4 *Sofugan Island and its subaqueous part*

Sofugan Island is located at lat. 29°47.5′N, long. 140°20.7′E, in the southernmost part of the Izu Islands. It is a steep sided rock, 99m high above sea level.

Large amounts of volcanic boulders (chemically basaltic andesite) were recovered from the dredge site D669 on the southeast slope. D669-1 is basalt including large phenocrysts of plagioclase (2-4mm) with subordinate orthopyroxene and clinopyroxene, and minor olivine and opaques set in an intergranular groundmass consisting of plagioclase and clinopyroxene. D669-2 has the same mineral assemblage of phenocrysts and groundmass. Sample D669-2 has more olivine phenocrysts than D669-1.

Rocks of the Sofugan Island were described by Aoki (1979) and the chemical composition was reported by Aoki and Ossaka (1974). According to them, the Sofugan rock is olivine-clinopyroxene basalt with 49.85 wt% of SiO_2. Recently, Sofugan Island was visited by a Japan-US scientific team during the submersible ALVIN mission in 1987. Sampled rocks (SOF 1A and SOF 2) by B.Taylor, HIG, are both porphyritic andesites with phenocrysts of plagioclase, clinopyroxene, orthopyroxene and opaques. The groundmass of the rocks is holocrystalline and consists of the same minerals.

2.4 Petrographic and chemical characteristics of volcanic rocks from the central part of the arc

Seamounts in the central part of the arc are classified into two types in terms of occurrence or absence of groundmass orthopyroxene. Occurrence of groundmass orthopyroxene is a characteristic feature common to the volcanoes north of the Sofugan Tectonic Line, such as Sofugan Island, and Ohmachi, Nichiyo, Getsuyo and Kayo seamounts. These rocks are in the hypersthenic rock series (Kuno, 1954). Volcanic rocks of this series have rarely been found in the volcanic front of the Izu-Ogasawara Arc (e.g. Oshima Volcano, Kuno, 1954 and Mikurajima Volcano, Isshiki, 1980), but the present study has discovered large amounts of such rocks. In contrast, groundmass orthopyroxene does not occur in rocks from volcanoes in the trough located south of the tectonic line. Further south, only one example was found at Nishinoshima-shinto (new island) which was formed by recent submarine eruptions (Aoki *et al.*, 1983). Thus the volcanoes north of the Sofugan Tectonic Line are characterized by high percentage of the occurrence of the hypersthenic rock series.

Major oxides vs. SiO_2 variation diagrams are shown in Fig. 3. For the comparison with the north and the south segments, the chemical compositions of Sumisujima and Kaikata volcanoes are plotted in the same figure. These rocks all plot within the low -alkali tholeiite field on the alkali-silica diagram of Kuno (1968). Except for one sample (D954-5 dredged from Suiyo Seamount), SiO_2 contents of the analyzed volcanic rocks in the central part of the arc are lower than 58%. The variation trends of oxides are similar to the caldera rocks, but oxide contents except for CaO show a wider range. The variation trend of the rocks from the seamounts in the Nishinoshima Trough is not as monotonous as that of the caldera volcanoes in the northern arc. The volcanic rocks from the seamount in the trough are rich in alkali components, especially K_2O, relative to the rocks from the northern volcanoes and Sumisujima Volcano (Fig. 3). Potassium data for the seamounts in the trough and Sofugan Volcano are plotted at greater magnification in Fig. 4. K_2O contents are normally positively correlated with those of SiO_2, although for some the trend is not very clear. The rocks of Sofugan Volcano in general have the lowest contents of K_2O and show the smallest positive slope. The rocks of intermediate-type and older seamounts show slightly steeper slopes than that of the Sofugan rocks. K_2O contents of the Kin'yo and Doyo seamounts rocks are higher than those of the other younger seamounts (Getsuyo and Kayo). The chemical compositions of rocks from the Getsuyo and Kayo seamounts plot on the same trend as the Sofugan rocks. Rocks from the younger seamounts including the Sofugan Volcano can be grouped into high- and low-K_2O rocks, and the division corresponds to the petrographic one mentioned above. Of the other oxides, Na_2O, MgO, CaO and FeO* show similarity to the above division shown in K_2O trend.

Table 2 Chemical compositions and CIPW norms of volcanic rocks from the volcanoes on the central and southern parts of the Shichito-Iwojima Ridge.
S-Iwo: Submarine part of Minami-Iwojima Volcano including the Fukutoku-okanoba, Iwo: Submarine part of Iwojima Volcano including a high (D713) south-by-southeast of the island, N-Iwo: Submarine part of Kita-Iwojima Volcano, Kaitoku: Kaitoku Seamount, KC: East peak of Kaikata Seamount, KC(W): older somma west of KC peak, KM: central peak of Kaikata Seamount, Ni-KK: A knoll between Kaikata and Nishinoshima volcanoes, Doyo: Doyo Seamount, Kin'yo: Kin'yo Seamount, Mokuyo: Mokuyo Seamount, Suiyo: Suiyo Seamount, Kayo: Kayo Seamount, Getsuyo: Getsuyo Seamount, Nichiyo: Nichiyo Seamount, Ohmachi: Ohmachi Seamount, Sofu R: Sofugan Island and its subaqueous part.
*: major element analyzed by XRF, **: major element compositions are from Yuasa and Tamaki (1982).
CIPW norms are calculated on water-free basis.
Analysts: Japan Analytical Center (major elements by wet analysis), M. Yuasa (major elements by XRF and minor elements by XRF and AA) and H. Goto (Ba by ICP).

Sp.No.	D819-1 S-Iwo	D717-1 S-Iwo	D718-1 S-Iwo	D720-1 S-Iwo	S43001 S-Iwo **	S43002 S-Iwo **	D819-7 S-Iwo	713-1C Iwo	713-1R Iwo	D722-2 Iwo
Wt%										
SiO_2	62.72	46.87	53.58	48.93	45.55	45.02	46.42	58.36	59.68	58.14
TiO_2	0.57	0.84	0.65	0.81	0.85	0.75	0.74	0.61	0.60	0.96
Al_2O_3	16.25	18.16	18.60	19.91	19.31	19.94	16.63	16.16	16.22	16.13
Fe_2O_3	1.72	4.54	1.93	4.40	5.07	4.49	5.30	2.63	2.37	3.31
FeO	3.02	7.34	7.01	5.96	7.47	7.51	6.65	3.83	3.99	4.08
MnO	0.17	0.22	0.20	0.22	0.25	0.23	0.19	0.18	0.18	0.19
MgO	1.57	6.03	4.14	4.21	5.47	5.56	7.26	2.18	2.08	2.12
CaO	3.18	12.26	8.56	10.82	12.74	13.01	13.93	4.67	4.34	3.71
Na_2O	5.25	2.25	3.20	2.73	1.94	1.87	1.87	4.10	4.34	5.78
K_2O	4.60	0.77	1.22	1.00	0.67	0.63	0.73	3.91	3.99	3.66
P_2O_5	0.24	0.19	0.25	0.21	0.23	0.21	0.12	0.28	0.29	0.61
H_2O+	0.25	0.30	0.54	0.56	0.10	0.04	0.18	2.23	1.49	0.82
H_2O-	0.06	0.12	0.06	0.14	0.04	0.04	0.03	0.66	0.11	0.21
Total	99.60	99.89	99.94	99.90	99.69	99.30	100.05	99.80	99.68	99.72
ppm										
Ni	6	25	13	11	14	15	37	4	3	23
Co	7	43	28	31	39	44	47	13	13	14
Cr	20	27	23	20	12	13	35	5	2	46
V	69	408	223	313	368	362	387	113	125	178
Cu	24	126	88	191	170	179	201	51	51	100
Zn	94	76	75	84	85	84	66	83	86	115
Rb	99	9	18	11	10	10	12	67	84	56
Sr	478	865	840	835	832	823	820	562	611	651
Y	36	19	21	18	15	17	10	33	32	36
Zr	268	43	55	46	36	38	36	234	227	175
Ba	1601	262	550	431	438	396	367	1231	1275	1134
%										
Q	6.07		3.43	0.30	3.98	3.75		6.94	7.01	1.08
ne							0.17			
or	27.38	4.57	7.26	5.96			4.32	23.84	24.04	21.92
ab	44.74	19.14	27.26	23.29	16.49	15.95	15.54	35.80	37.44	49.56
an	7.24	37.38	33.00	39.43	42.19	44.50	34.88	14.59	13.25	7.35
wo-di	2.95	9.40	3.38	5.55	8.26	8.00	14.01	3.10	2.83	3.03
di-en	1.52	5.63	1.64	3.28	4.83	4.58	9.36	1.69	1.44	1.74
fs-di	1.36	3.28	1.68	1.99	3.04	3.07	3.60	1.30	1.31	1.16
en-hy	2.42	2.41	8.74	7.29	2.60	0.54		3.91	3.84	3.61
fs-hy	2.17	1.40	8.96	4.44	1.64	0.36		3.02	3.49	2.41
fo-ol		4.95			4.39	6.19	6.13			
fa-ol		3.18			3.05	4.56	2.60			
mt	2.51	6.62	2.82	6.43	7.38	6.57	7.70	3.93	3.50	4.86
il	1.09	1.60	1.24	1.55	1.62	1.44	1.41	1.20	1.16	1.85
ap	0.56	0.44	0.58	0.49	0.53	0.49	0.28	0.67	0.69	1.43

Table 2 continued

Sp.No.	D722-3 Iwo	D706-3 N-Iwo	D707-1 N-Iwo	D703-1 Kaitoku	D703-2 Kaitoku	D344-7 Kaitoku	D695-2 KC	D695-3 KC	D829-1 KC	D889-1 KC
Wt%										
SiO_2	60.47	55.55	63.10	52.21	55.64	47.67	54.00	56.6	56.14	52.69
TiO_2	0.84	0.97	0.83	0.88	0.76	0.98	0.87	0.87	1.08	1.14
Al_2O_3	16.23	15.16	13.75	19.06	18.06	17.95	17.61	17.11	14.47	15.25
Fe_2O_3	1.91	2.87	1.84	2.89	3.93	4.23	2.69	2.32	2.40	3.13
FeO	4.54	8.58	6.83	6.52	4.72	6.07	7.12	6.26	9.27	10.05
MnO	0.23	0.25	0.26	0.17	0.18	0.18	0.19	0.18	0.22	0.23
MgO	1.60	3.52	1.45	3.80	3.47	5.74	2.95	2.58	3.09	4.00
CaO	2.77	7.48	4.01	10.23	8.52	11.63	9.14	7.58	7.12	9.14
Na_2O	6.18	3.67	4.54	2.76	3.21	2.58	3.07	3.68	3.34	3.02
K_2O	4.38	0.86	1.33	0.63	0.84	0.35	0.63	0.91	0.96	0.66
P_2O_5	0.43	0.19	0.32	0.13	0.15	0.21	0.12	0.21	0.19	0.15
H_2O+	0.29	0.67	0.89	0.58	0.42	1.18	1.07	0.24	0.91	0.42
H_2O-	0.04	0.13	0.08	0.07	0.06	0.58	0.11	0.11	0.13	0.07
Total	99.91	99.90	99.23	99.93	99.96	99.35	99.57	98.65	99.32	99.95
ppm										
Ni	4	12	2	14	7	23	7	7	39	25
Co	8	29	11	29	23	30	23	23	30	34
Cr	8	23	2	13	9	115	10	8	74	41
V	78	271	0	305	339	370	339	191	272	399
Cu	22	119	16	142	101	106	150	198	111	224
Zn	120	102	127	77	77	73	82	85	110	107
Rb	83	12	20	10	13	8	15	15	12	9
Sr	395	366	301	255	244	295	264	245	226	240
Y	44	32	51	24	24	25	23	31	34	27
Zr	245	77	127	76	83	55	54	94	89	63
Ba	1200	255	486	120	168	54	235	322	289	256
%										
Q		7.58	18.45	5.34	10.68		8.40	10.42	10.35	4.88
or	25.99	5.13	8.00	3.75	4.99	2.12	3.78	5.47	5.77	3.92
ab	52.51	31.34	39.10	23.52	27.30	22.37	26.40	31.68	28.76	25.69
an	3.62	22.55	13.44	38.03	32.56	37.26	32.94	27.95	22.03	26.25
wo-di	3.07	5.69	1.95	5.11	3.74	8.54	5.16	3.72	5.28	7.66
di-en	1.26	2.39	0.54	2.63	2.31	5.51	2.22	1.60	1.94	3.15
fs-di	1.83	3.33	1.51	2,35	1.20	2.45	2.94	2.11	3.44	4.56
en-hy	2.10	6.46	3.14	6.90	6.38	8.75	5.25	4.93	5.89	6.86
fs-hy	3.05	9.02	8.80	6.16	3.32	3.90	6.98	6.51	10.46	9.93
fo-ol	0.45					0.27				
fa-ol	0.73					0.13				
mt	2.78	4.20	2.71	4.22	5.73	6.28	3.96	3.42	3.54	4.56
il	1.60	1.86	1.60	1.68	1.45	1.91	1.68	1.68	2.09	2.18
ap	1.00	0.44	0.75	0.30	0.35	0.50	0.28	0.49	0.45	0.35

Sp.No.	D827-1 KC	D827-2 KC	RS44-3 KC(W)	D831-1 KM	D698-1 KM	RS24-2 KM	RS39-1 KM	RS66-1 KC	D697-1 NI-KK	D687-1 Doyo
Wt%	*	*						*		
SiO_2O_3	53.79	53.38	60.64	51.39	49.13	51.54	51.61	51.02	52.78	51.00
TiO_2	1.26	1.01	0.91	0.80	0.86	0.93	0.79	0.90	0.78	0.81
Al_2O_3	14.51	16.89	14.81	19.50	17.39	17.56	19.54	18.61	19.21	18.14
Fe_2O_3	2.90	2.81	1.51	2.89	3.34	2.80	2.42	2.56	2.88	2.74
FeO	10.32	8.34	7.66	6.93	8.86	8.69	7.18	8.37	6.57	6.26
MnO	0.24	0.20	0.20	0.21	0.23	0.26	0.22	0.21	0.20	0.17
MgO	3.58	3.46	2.09	3.56	5.97	4.19	3.70	3.99	3.34	5.21
CaO	8.15	9.26	5.9	10.59	11.24	10.01	10.53	10.76	9.39	10.97
Na_2O	3.08	2.94	4.08	2.99	2.10	2.85	2.87	2.56	2.82	2.46
K_2O	0.76	0.59	1.17	0.42	0.33	0.39	0.43	0.38	0.68	0.70
P_2O_5	0.16	0.11	0.22	0.12	0.09	0.12	0.11	0.09	0.13	0.15
H_2O+	0.95	0.91	0.45	0.47	0.39	0.60	0.46	0.52	1.00	0.81
H_2O-	-	-	0.04	0.08	0.05	0.05	0.10	-	0.20	0.32
Total	99.69	99.91	99.68	99.95	99.98	99.99	99.96	99.97	99.98	99.74
ppm										
Ni	63	27	16	23	15	36	17	21	7	41
Co	33	30	21	28	43	31	26	33	27	30
Cr	123	43	36	44	7	69	23	27	5	81
V	334	325	135	253	399	262	226	303	241	344
Cu	192	149	85	92	151	55	106	133	76	113
Zn	116	93	105	79	74	93	82	82	82	66
Rb	12	8	17	6	4	6	6	6	9	11
Sr	230	252	232	344	285	335	345	326	254	326
Y	31	23	41	19	17	22	21	20	24	21
Zr	77	62	129	47	38	42	44	46	63	58
Ba	266	203	351	134	566	168	107	96	167	120
%										
Q	7.34	7.12	14.07	3.32	1.14	3.62	3.51	3.57	6.86	3.15
or	4.55	3.52	6.97	2.50	1.96	2.32	2.56	2.26	4.07	4.20
ab	26.39	25.13	34.81	25.45	17.85	24.28	24.43	21.78	24.16	21.11
an	23.82	31.46	18.79	38.78	37.22	34.19	39.40	38.38	38.22	36.90
wo-di	6.71	5.94	3.87	5.55	7.60	6.27	5.19	6.14	3.38	7.22
di-en	2.55	2.52	1.23	2.65	4.00	2.82	2.43	2.75	1.62	4.21
fs-di	4.27	3.42	2.77	2.81	3.37	3.41	2.71	3.36	1.71	2.66
en-hy	6.48	6.18	4.01	6.27	10.93	7.68	6.85	7.24	6.80	8.95
fs-hy	10.84	8.39	9.01	6.65	9.20	9.27	7.64	8.86	7.17	5.66
fo-ol										
fa-ol										
mt	4.26	4.12	2.21	4.22	4.86	4.09	3.53	3.73	4.23	4.03
il	2.42	1.94	1.74	1.53	1.64	1.78	1.51	1.72	1.50	1.56
ap	0.38	0.26	0.51	0.28	0.21	0.28	0.26	0.21	0.30	0.35

Table 2 continued

Sp.No.	D687-4 Doyo	D686-1 Kin'yo	D953-1 Mokuyo	D953-2 Mokuyo	D953-3 Mokuyo	D953-4 Mokuyo	D954-5 Suiyo	D954-8 Suiyo	D793-2 Suiyo	D677-1 Kayo
Wt%					*	*				
SiO_2	52.76	53.40	52.40	52.31	52.86	53.19	68.24	51.10	51.33	53.97
TiO_2	0.82	0.76	0.93	0.91	1.10	1.09	0.41	0.64	0.72	0.68
Al_2O_3	18.71	17.65	15.77	16.71	15.43	14.95	15.25	17.13	18.51	18.20
Fe_2O_3	2.39	2.63	2.25	2.21	2.59	2.49	1.28	3.61	2.28	2.58
FeO	6.65	6.54	8.91	8.62	8.78	9.50	2.71	6.12	7.17	6.81
MnO	0.17	0.18	0.21	0.20	0.12	0.21	0.13	0.18	0.18	0.18
MgO	4.20	4.73	4.95	4.57	4.64	4.59	1.19	6.93	4.67	3.97
CaO	10.31	10.17	10.21	10.53	9.62	9.39	4.54	11.54	11.29	9.71
Na_2O	2.64	2.58	2.71	2.67	2.81	2.87	4.19	1.91	2.35	2.60
K_2O	0.64	0.64	0.53	0.49	0.52	0.46	1.03	0.32	0.44	0.46
P_2O_5	0.15	0.14	0.14	0.13	0.14	0.13	0.09	0.07	0.08	0.10
H_2O+	0.37	0.45	0.62	0.54	0.97	0.80	0.63	0.24	0.71	0.47
H_2O-	0.08	0.10	0.10	0.10	-	-	0.05	0.06	0.13	0.10
Total	99.89	99.97	99.73	99.99	99.58	99.67	99.74	99.85	99.86	99.83
ppm										
Ni	18	25	35	37	37	32	12	49	35	17
Co	27	30	33	31	34	36	5	34	30	28
Cr	24	32	49	50	50	54	26	75	66	21
V	330	344	361	360	363	384	62	328	299	298
Cu	89	127	146	142	137	136	16	124	141	120
Zn	69	68	85	83	91	92	61	64	76	74
Rb	14	15	7	6	7	7	15	5	5	7
Sr	305	296	239	239	223	235	201	209	222	187
Y	23	21	20	21	24	28	32	14	19	20
Zr	58	75	64	63	74	75	109	44	50	56
Ba	144	233	67	62	77	77	175	51	93	148
%										
Q	5.64	6.68	4.12	4.21	5.90	5.98	27.82	4.72	3.97	8.69
or	3.80	3.80	3.16	2.91	3.12	2.75	6.14	1.90	2.63	2.74
ab	22.46	21.96	23.16	22.74	24.11	24.56	35.79	16.23	20.08	22.16
an	37.52	34.89	29.59	32.37	28.35	26.85	19.95	37.39	39.04	36.90
wo-di	5.40	6.24	8.62	8.08	7.98	8.10	0.92	8.21	7.10	4.58
di-en	2.80	3.42	4.08	3.75	3.80	3.63	0.42	5.33	3.65	2.28
fs-di	2.46	2.59	4.42	4.24	4.07	4.43	0.49	2.32	3.27	2.21
en-hy	7.73	8.43	8.37	7.70	7.92	7.94	2.57	12.01	8.10	7.68
fs-hy	6.79	6.38	9.07	8.71	8.49	9.70	3.02	5.24	7.26	7.45
fo-ol										
fa-ol										
mt	3.48	3.84	3.29	3.22	3.81	3.65	1.87	5.26	3.34	3.77
il	1.57	1.45	1.78	1.74	2.12	2.09	0.79	1.22	1.38	1.30
ap	0.35	0.33	0.33	0.30	0.33	0.30	0.21	0.16	0.19	0.23

Sp.No.	D675-1 Getsuyo	D673-5 Nichiyo	D796-5 Nichiyo	D731-4 Ohmachi	D669-1 Sofu R.	D669-2 Sofu R.	SOF-1A Sofu R.	SOF-2 Sofu R.
Wt%							*	*
SiO_2	57.59	56.50	53.86	57.68	53.58	53.21	55.85	55.55
TiO_2	0.66	0.61	0.75	0.72	0.71	0.78	0.85	0.85
Al_2O_3	17.33	16.23	15.95	17.93	19.28	18.84	17.39	17.37
Fe_2O_3	2.57	2.47	3.13	3.83	3.53	2.57	3.07	3.64
FeO	4.75	5.47	6.89	3.20	5.36	7.12	6.22	5.67
MnO	0.16	0.16	0.18	0.20	0.17	0.18	0.18	0.17
MgO	3.91	4.35	4.93	3.44	3.44	3.22	3.23	3.25
CaO	8.47	8.69	9.58	8.33	10.15	9.97	8.50	8.44
Na_2O	2.97	2.78	2.19	3.20	2.59	2.64	3.04	3.12
K_2O	0.50	0.89	0.58	0.71	0.46	0.45	0.52	0.52
P_2O_5	0.12	0.13	0.09	0.15	0.10	0.10	0.11	0.11
H_2O+	0.49	1.21	1.61	0.49	0.26	0.49	0.59	0.73
H_2O-	0.07	0.25	0.22	0.17	0.14	0.09	-	-
Total	99.59	99.74	99.96	100.05	99.77	99.66	100.63	100.55
ppm								
Ni	23	17	40	7	8	17	15	16
Co	22	25	32	18	25	29	21	21
Cr	54	39	85	10	7	21	17	28
V	238	239	302	188	296	345	217	217
Cu	57	82	136	51	40	159	245	131
Zn	67	65	81	82	67	76	91	87
Rb	13	19	9	15	5	7	7	8
Sr	229	258	184	329	216	194	173	173
Y	23	26	22	31	23	25	29	29
Zr	69	72	54	98	48	51	64	64
Ba	115	127	79	121	153	167	123	119
%								
Q	14.15	11.89	10.21	14.72	9.63	8.06	12.01	12.08
or	2.98	5.35	3.48	4.22	2.74	2.68	3.11	3.11
ab	25.38	23.94	18.83	27.24	22.05	22.55	25.99	26.75
an	32.80	29.69	32.50	32.66	39.87	38.58	32.61	32.28
wo-di	3.69	5.56	6.92	3.31	4.23	4.46	3.87	3.93
di-en	2.20	3.18	3.81	2.45	2.38	1.98	1.92	2.13
fs-di	1.31	2.14	2.84	0.54	1.68	2.46	1.87	1.66
en-hy	7.64	7.85	8.67	6.17	6.24	6.12	6.20	6.07
fs-hy	4.55	5.28	6.47	1.36	4.42	7.62	6.03	4.74
fo-ol								
fa-ol								
mt	3.76	3.64	4.61	5.59	5.15	3.76	4.50	5.35
il	1.27	1.18	1.45	1.38	1.36	1.50	1.63	1.64
ap	0.28	0.31	0.21	0.35	0.23	0.23	0.26	0.26

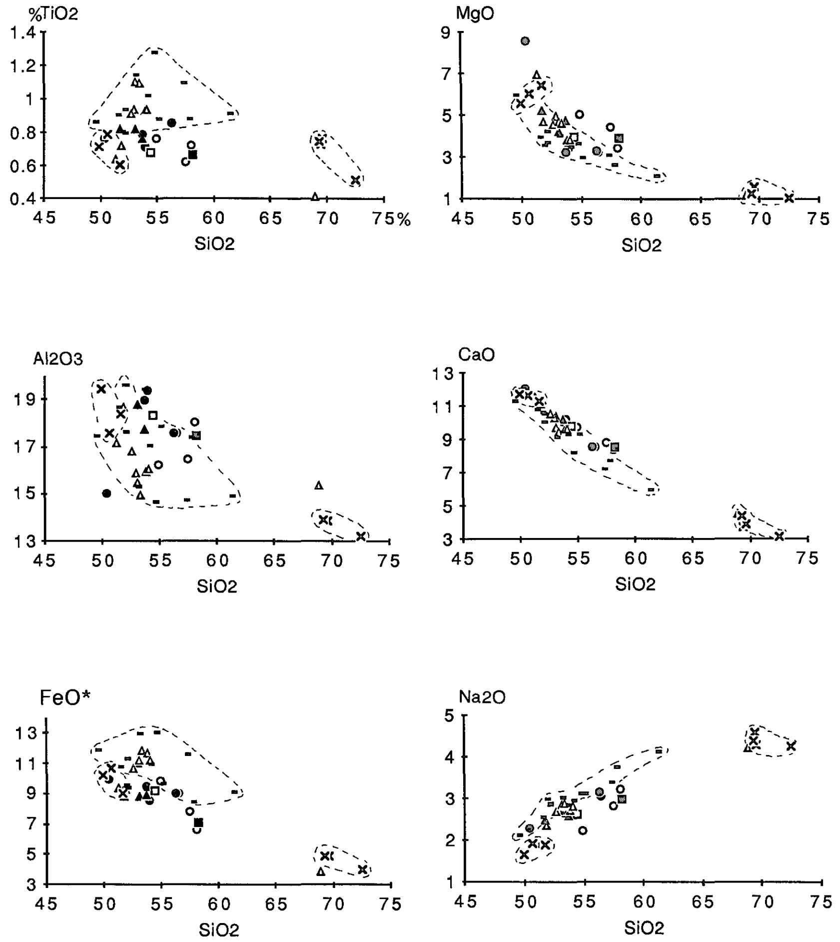


Fig. 3 Harker diagram for rocks from Sofugan Volcano and the seamounts in the Nishinoshima Trough, central part of the Shichito-Iwojima Ridge. In the K_2O-SiO_2 and alkali -SiO_2 diagrams, discriminative lines by Gill (1981) and Kuno (1968) are drawn, respectively. Abbreviations of the fields as follows ; M : medium-K andesite, L : low-K andesite, A : alkali basalt, HA : high-alkali tholeiite, LA : low-alkali tholeiite. Chemical compositions of rocks from the Sumisujima Volcano (Sumisu Caldera) and Kaikata Seamount are also plotted for comparison. An analysis from Sofugan Island (Aoki and Ossaka, 1974) is included in this figure.

2.5 Southern part of the arc

The southern half of the Izu-Ogasawara Arc comprises six large composite volcanoes from Nishinoshima to Minami-Iwojima islands. They are all discrete large composite volcanoes, and are separated into two groups, Nishinoshima to Kaitoku and Kita-Iwojima to Minami-Iwojima, by the Iwo Canyon. This extends from the Parece Vela Basin on the west to the boundary between Kaitoku Seamount and Kita-Iwojima Island. The relief of the trough is smaller than that of en echělon valleys crossing the arc in the northern part of the arc.

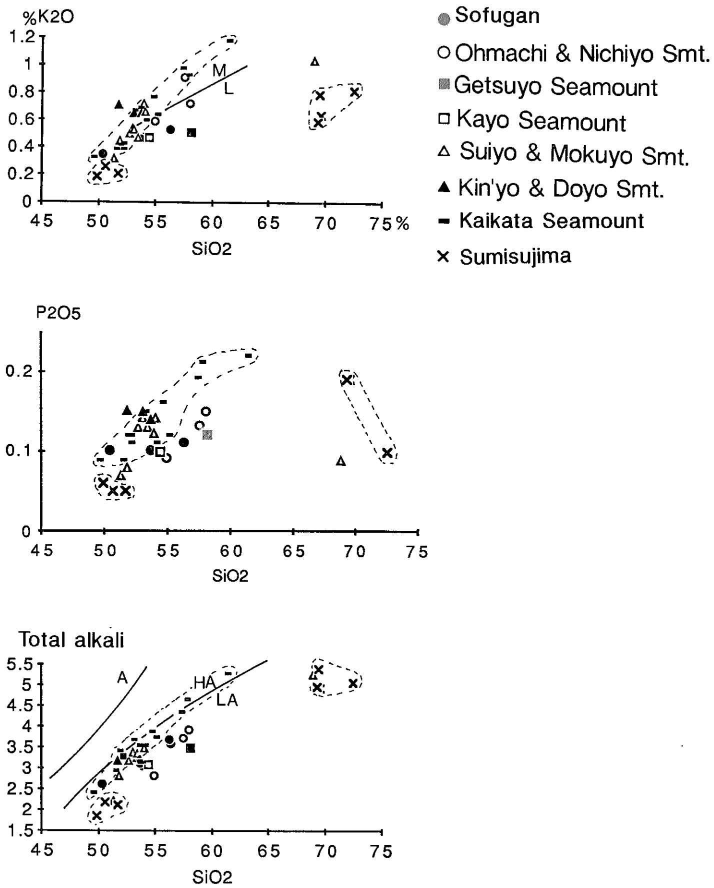


Fig. 3 continued

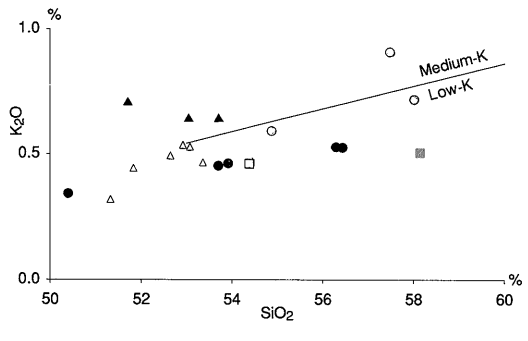


Fig. 4 Part of the K_2O-SiO_2 diagram in Fig. 3 for the rocks from Sofugan Volcano and seamounts in the Nishinoshima Trough. Symbols are the same as in Fig. 3.

2.5.1 *Nishinoshima Volcano*

Nishinoshima Volcano erupted in 1973 and formed a new island adjoining the older island. Petrographic descriptions given by Aoki *et al.* (1983) are briefly cited below. Nishinoshima Island (subaerial part) is constructed mainly of andesitic rocks. These are hypersthene-augite andesite with or without olivine phenocrysts. Hypersthene occurs in the groundmass of the new lava, whereas pigeonite occurs as both phenocryst and groundmass mineral in the older rocks. An olivine basalt lava was reported from the west flank (older part) of the island (Aoki *et al.*, 1983).

2.5.2 *Kaikata Volcano*

Dredge sites D695 and D829 were located on the southern and western inner walls of the new caldera of KC peak. Large angular blocks of altered and non-altered volcanic rocks were recovered in dredge D695. One altered rock (D695-1), 56×45×25 cm in size, is plagioclase-phyric andesite with phenocrysts of pyroxene pseudomorphed. This sample shows fairly intense alteration with secondary quartz, sericite, montmorillonite and chlorite. Pyrite occurs as disseminated minute grains with quartz in the groundmass and as veinlets with gangue quartz in cavities. Sample D695-2 is an andesite rather fresh and porous with phenocrysts of plagioclase and minor clinopyroxene with opaque microphenocrysts set in a microcrystalline groundmass consisting of the same minerals. Sample D695-3 may be a fragment of columnar-jointed dike rock. It is relatively coarse-grained with plagioclase, clinopyroxene, and orthopyroxene phenocrysts and opaque microphenocrysts set in a subophitic groundmass consisting of plagioclase, clinopyroxene and minute opaques. Secondary calcite occurs in the groundmass. The samples of D829 are mostly monolithologic angular fragments of andesite and rare bleached rocks. Sample D829-1 is a nearly aphyric andesite with sparse phenocrysts of plagioclase, clinopyroxene, orthopyroxene and opaques. The phenocrystic minerals occur often as glomerocrysts. The groundmass shows a slightly porous and intersertal texture and is composed of plagioclase, clinopyroxene and opaques.

Dredge D889-1 was situated on the central cone in the caldera. Deep-sea towing side-scan sonar and deep-sea TV systems found a crater-like depression on the top of the cone and a white crab colony on a small high in the depression. During the towing survey, several fragments of volcanic rock with native sulfur in the cavities accidentally entered into the towing vehicle. Sample D889-1 is olivine basalt or basaltic andesite with phenocrysts of plagioclase, subordinate skeletal olivine and minor clinopyroxene set in an intersertal groundmass of the same minerals and opaques. Inside the caldera, basaltic rocks were recovered only from the central cone.

Dredge D827 was located on the eastern outer slope of the caldera. Samples are porous andesite with small phenocrysts of plagioclase, clinopyroxene and opaques set in an intersertal groundmass of the same minerals (e.g. sample D827-1). Sample D827-2 includes skeletal olivine microphenocrysts in addition to the above minerals.

RS44 samples recovered by grab sampler from the inner wall of the older caldera are fist-sized angular volcanic blocks. Sample RS44-3 is dark gray dacite, the most acid rock of all fresh samples collected from the Kaikata Seamount. The phenocrysts are plagioclase and clinopyroxene with minor orthopyroxene and opaques set in a hyalopilitic groundmass with plagioclase and clinopyroxene.

Samples recovered from the KM peak (RS24-2, RS39-1, RS66-1 , D698-1 and D831-1) are nearly aphyric to plagioclase-phyric basalt including phenocrysts and microphenocrysts of plagioclase, clinopyroxene, olivine and opaques. Olivine phenocrysts are common in all samples. The olivine phenocrysts often show embayed or skeletal form and are sometimes rimmed with clinopyroxene. There are many varieties of groundmass texture. The groundmass of sample RS24-2 shows intersertal texture and consists of microlites of the phenocryst minerals along with mesostasis. Samples RS39-1 and RS66-1 have a microcrystalline groundmass consisting of the same minerals described above. Sample D698-1 is a porous, seriate-textured basalt with a microcrystalline groundmass of the same minerals as above. Most phenocrysts of D831-1 show subhedral shape. Groundmass minerals in the rock are equigranular (0.03 mm) plagioclase and clinopyroxene with minor amounts of interstitial cryptocrystalline materials.

There are some satellitic cones to the north of the Kaikata Seamount. Dredge D697 was situated on one of the cones between Nishinoshima and Kaikata volcanoes. Sample D697-1 is plagioclase-phyric basaltic andesite with a small amount of olivine and linopyroxene phenocrysts and opaque microphenocrysts. The groundmass shows intersertal texture and consists of fine-grained microlites of the same minerals and minor amounts of inter-stitial brownish glass.

2.5.3 *Kaitoku Volcano*

Kaitoku Volcano has three major peaks. Three dredges were located on the individual peaks. Fresh volcanic rocks were recovered only from the east peak (D703), where a submarine eruption occurred in 1984. Sample D703-1 is plagioclase-phyric basalt with clinopyroxene and olivine phenocrysts. Olivine phenocrysts are mantled by clinopyroxene reaction rims. The groundmass consists of plagioclase, clinopyroxene, olivine and opaques with intersertal texture. Sample D703-2 is an angular fragment of andesite with large plagioclase and subordinate clinopyroxene and orthopyroxene phenocrysts and opaque microphenocrysts set in a microcrystalline groundmass consisting of plagioclase, clinopyroxene and opaques.

Dredge D344 was situated on the lower slope of the northwest flank. Sample D344-7 is a fine-grained basalt with minor amounts of small phenocrysts of plagioclase and olivine, both elongated in shape, and clinopyroxene microphenocrysts. The groundmass is intersertal in texture and is composed of plagioclase, clinopyroxene, olivine, and opaques with interstitial cryptocrystalline materials.

2.5.4 *Kita-Iwojima Volcano*

Kita-Iwojima Island is one of the peaks of a submerged large composite volcano and is situated on its eastern part. Two dredges located on the volcano successfully recovered fresh lava blocks in addition to various small fragments of pumice, scoria, hornblende diorite, hornblende tonalite, altered volcanics, and sedimentary rocks. Dredge D706 was located on the southwestern slope of Kita-Iwojima Island and D707 on a small cone to the southwest. Sample D706-3 is slightly vesicular andesite with microphenocrysts of plagioclase, clinopyroxene, olivine and opaque minerals set in an intersertal groundmass of the same minerals with minor amounts of interstitial mesostasis. Sample D707-1 is hyalocrystalline dacite with sparse small phenocrysts of plagioclase, clinopyroxene (some of them are pigeonitic augite) and opaques. The groundmass is hyalopilitic in texture and is composed of plagioclase, clinopyroxene and glass.

2.5.5 *Iwojima Volcano*

Trachyandesite of Iwojima Island has been known for a long time as an alkaline rock on the volcanic front (e.g. Honma, 1925 ; Tsuya, 1936 and 1937 ; Isshiki, 1976 ; Stern *et al.*, 1984). Two dredges were carried out on the volcano ; Dredge D722 on a satellite cone northwest of the island and Dredge D723 on an isolated high on the northwest slope of the island.

An altered andesitic boulder, some fresh cobbles of benmoreitic trachyte and minor amounts of pumice and scoria were dredged from the satellitic cone northwest of Iwojima Island. Benmoreitic trachyte (D722-2) contains a minor amount of phenocrysts of plagioclase with microphenocrysts of olivine, clinopyroxene and opaque minerals. The groundmass has a flow texture with microlites of plagioclase (oligoclase), clinopyroxene and opaques. Sample D722-3 is also benmoreitic trachyte with the same phenocrystic mineral assemblage but it is more porphyritic than the above. Abundant sieve-textured large plagioclase phenocrysts are characteristic, and plagioclases are often poikilitically enclosed in olivine and clinopyroxene phenocrysts. Olivine microlites are also found in a hyalopilitic groundmass consisting of oligoclase, clinopyroxene and glass.

Subangular boulders of conglomerate with thin (<1mm) manganese coats were recovered from the isolated high (D723) on the northwest slope of the island. Sample D723-1 is a clast of the conglomerate cemented by calcareous material. The rock is an altered basalt, reddish in color, with phenocrysts of plagioclase (3 mm), orthopyroxene, clinopyroxene and abundant small opaques. Clay minerals occur in the plagioclase phenocrysts. Orthopyroxene phenocrysts are often red-colored along the cleavage. The groundmass consists mainly of plagioclase with minor opaques and clinopyroxene. Secondary zeolitic minerals occur in places.

2.5.6 *Minami-Iwojima Volcano*

Minami-Iwojima Island is the southernmost island of the Izu-Ogasawara Arc. Recently, Yuasa and Tamaki (1982) and Fukuyama (1983) visited the island in 1979 and 1982, respectively, and described basaltic rocks there. Yuasa and Tamaki (1982) indicated that the rocks are augite-olivine basalt with a transitional nature between alkaline basalt and tholeiitic basalt. Fukuyama (1983) showed that the volcano consists of alkaline rocks such as ankaramite, olivine basalt, etc. Though trachyandesitic rocks have been well known from Iwojima Island as mentioned above, the basalt with alkaline affinity is the first discovery from the volcanic front of Japan (Fukuyama, 1983).

Eight dredges were performed on the submarine part of Minami-Iwojima Volcano; four dredges (D717-D720) on the northern side, three (D714, D715 and D819) on the center, and one (D713) on the eastern isolated high.

There is one more isolated high 19km west of the volcanic axis. Rounded pumice and manganese oxide plates were recovered there (D716). Pumice may not be *in situ* and the high is inferred to be an older seamount than Iwojima Volcano because of the occurrence of hydrogenous manganese oxide.

A piece of glassy lava was dredged from a small cone 28km east of the volcano (D713). Sample D713-1 is benmoreitic trachyte with phenocrysts of large plagioclase and subordinate clinopyroxene and opaques and minor olivine microphenocrysts. Clinopyroxene phenocrysts often show sector-twined structure and poikilitically enclose plagioclase crystals. The rock is quench-textured with swallow-tailed plagioclase (oligoclase) and dendritic clinopyroxene in a glassy groundmass.

From the central part of the volcano, many pumice samples were dredged. Petrographically they are benmoreitic pumice with phenocrysts of plagioclase, clinopyroxene and olivine set in a glassy groundmass with oligoclase microlites. Their petrography is similar to the 1986 and older pumice erupted from Fukutoku-okanoba (Ossaka *et al.*, 1986; Fukuyama, 1983). Dredge D819 was performed on the upper slope of Fukutoku-okanoba after the 1986 eruption. Sample D819-1 is benmoreitic trachyte pumice including many small xenoliths. Phenocrysts of the pumice are plagioclase, clinopyroxene, olivine and opaques. D819-8 is also benmoreitic trachyte (lava ?) with the same phenocrystic minerals but it is not so porous as D819-1. Sample D819-7 is a xenolith of dolerite which consists of plagioclase, clinopyroxene (sector-twined), olivine and opaques. Colorless glass fills up the miarolitic cavities. Although these pumice samples have very similar petrographic and chemical features to the floating pumice near the volcano or found along the shore of Chichijima Island after the 1986 eruption, it is not clear whether or not they are the products of Fukutoku-okanoba 1986 eruption.

Fragments of basaltic lava (D717, D718 and D720) and boulders of conglomerate (D719) were recovered from small cones on the northern part of the volcano. Samples D717-1 and D720-1 are porphyritic basalts with phenocrysts of plagioclase, sector-twined clinopyroxene, olivine and opaques set in an intersertal groudmass consisting of the same minerals. Thin carbonate veins are observed in the sample D720-1. Sample D718-1 is also a porphyritic and seriate-textured basalt with the same phenocrystic minerals set in a hyalopilitic groundmass though it is more enriched in silica.

2.6 Petrographic and chemical characteristics

The northern three volcanoes, Nishinoshima, Kaikata and Kaitoku, are composed mainly of hypersthene-augite andesite with subordinate augite-olivine basalt, whereas the volcanoes in the southern segment, Volcano Islands, lack rocks containing orthopyroxene phenocrysts, except for one sample obtained from a high called Kaise-nishinoba in the northwest neighborhood of Iwojima Island. Since the high is located on the west of the axis of the volcanic chain and the rocks are covered by thin ferromanganese coatings, it must be a seamount older than the front volcanoes. Alkaline rocks characteristically occur in the Iwojima (benmoreitic trachyte) and Minami-Iwojima (alkali -olivine basalt) islands, in the Volcano Islands segment. Benmoreitic trachyte was also collected from D713 and D722 sites, located to the southeast and the northwest of Iwojima Island, respectively. These localities including Iwojima Island where benmoreitic trachyte occur show liner arrangment (Fig.26 of Yuasa *et al.*, 1991). This liner arrangement intersects the direction of highs on both Minami- and Kita-Iwojima volcanoes obliquely and is rather similar to the northern Mariana trend. Petrographic variation along the arc axis is also recognized to the north of this area. As to the seamounts in the Nishinoshima Trough, clinopyroxene-olivine basalt is dominant on the southern side of the Sofugan Tectonic Line, whereas orthopyroxene-clinopyroxene andesite on the northern side.

2.6.1 *Chemistry of Nishinoshima to Kaitoku volcanoes (northern segment)*

Fig. 5 shows the variation of major oxides vs. silica for the rocks from the northern segment in the southern arc. Na_2O, K_2O and P_2O_5 increase with increasing SiO_2, whereas Al_2O_3, FeO*, MgO and CaO decrease. On the alkali-SiO_2 diagram of Kuno (1968), these rocks plot near the boundary between high -alkali and low-alkali tholeiite fields. The variation trend of the rocks on the diagram crosses the boundary and the alkali contents are higher than the boundary in the high silica region and vice versa. The alkali contents of the northern three volcanoes are distinctly higher than those of the Hachijojima and Sofugan islands. The difference in alkaline contents between the northern and southern parts of the arc shown by Yuasa and Tamaki (1982) is also recognized in Fig. 5 which include new analyses for the Kaikata and Kaitoku seamounts. As compared with the rocks of the northern part of the arc no particular difference in other oxide contents exists except that TiO_2 content is slightly lower than that of Hachijojima Island. K_2O contents plot mostly in the medium-K andesite field (Gill, 1981) and its extrapolated range, and partly in the low-K andesite field in the low silica range. No particular difference in variation trends exists among the three volcanoes.

2.6.2 *Chemistry of Volcano Islands volcanoes*

Volcano Islands are located on the southernmost part of the volcanic front of the Izu-Ogasawara Arc and characterized by the occurrence of alkaline volcanic rocks.

Fig. 6 shows major element oxides vs. SiO_2 variation diagrams. Na_2O and K_2O increase, whereas Al_2O_3, FeO*, MgO and CaO decrease with increasing SiO_2 contents. It is obvious that the alkali element and P_2O_5 contents of the Minami-Iwojima and Iwojima volcanoes are conspicuously higher than the other volcanoes. In contrast, CaO, MgO and FeO* contents of both volcanoes are lower than the others. In the K_2O-SiO_2 diagram, K_2O values for given SiO_2 contents are clearly separated into three groups in order to increasing

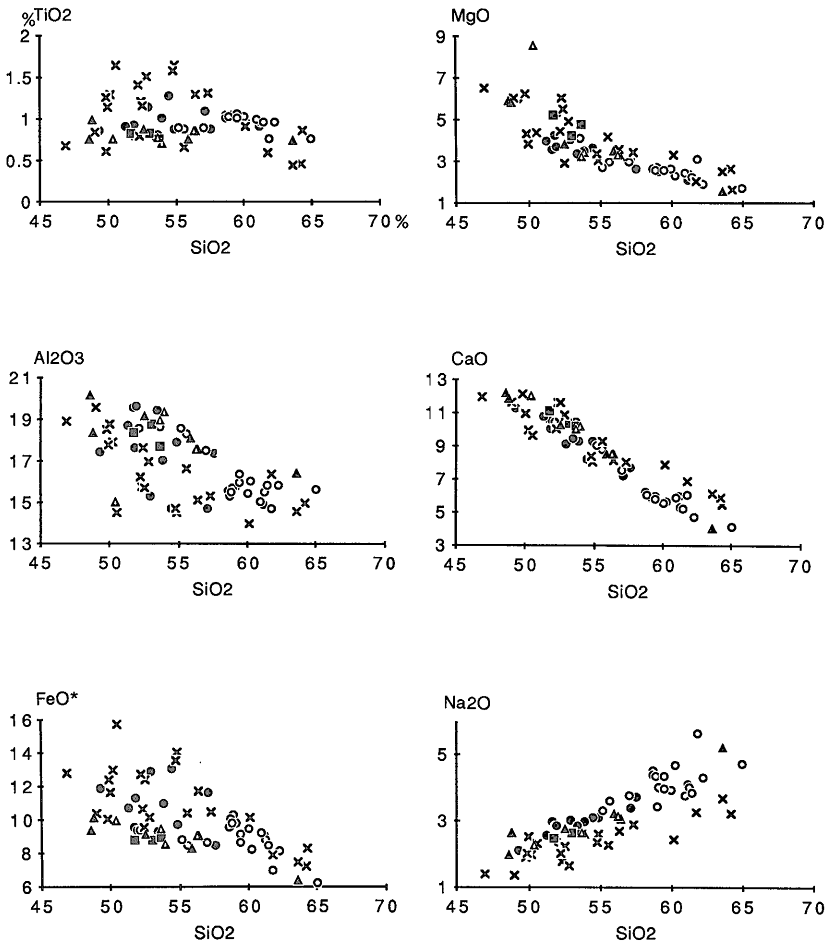


Fig. 5 Harker diagram for rocks from Nishinoshima (Aoki *et al.*, 1983), Kaikata, and Kaitoku (including the data from Tsuchide *et al.*, 1985) seamounts on the southern part of the Shichito-Iwojima Ridge. In the K_2O-SiO_2 and alkali-SiO_2 diagrams, discriminative lines by Gill (1981) and Kuno (1968) are drawn, respectively. Abbreviations of the fields as follows; M : medium-K andesite, L : low-K andesite, A : alkali basalt, HA : high -alkali tholeiite, LA : low-alkali tholeiite. Chemical compositions of the rocks from the younger (Kin'yo and Doyo) seamounts in the Nishinoshima Trough and Hachijo Volcano (Isshiki, 1959) are plotted for comparison.

contents; Iwojima and higher silica content rocks of Minami-Iwojima, lower silica content rocks of Minami-Iwojima, and other volcanoes. This separation is also observed in total alkali and Na_2O contents. CaO and FeO* contents of Iwojima and Minami -Iwojima volcanoes are also separated from the other volcanoes. In the alkali vs. SiO_2 diagram the rocks of Iwojima Island all plot in the alkaline volcanic field, those of Minami -Iwojima Volcano in both the alkaline and high-alkali tholeiite fields, and those of Kita -Iwojima Volcanoes plot in the high-alkali tholeiite field.

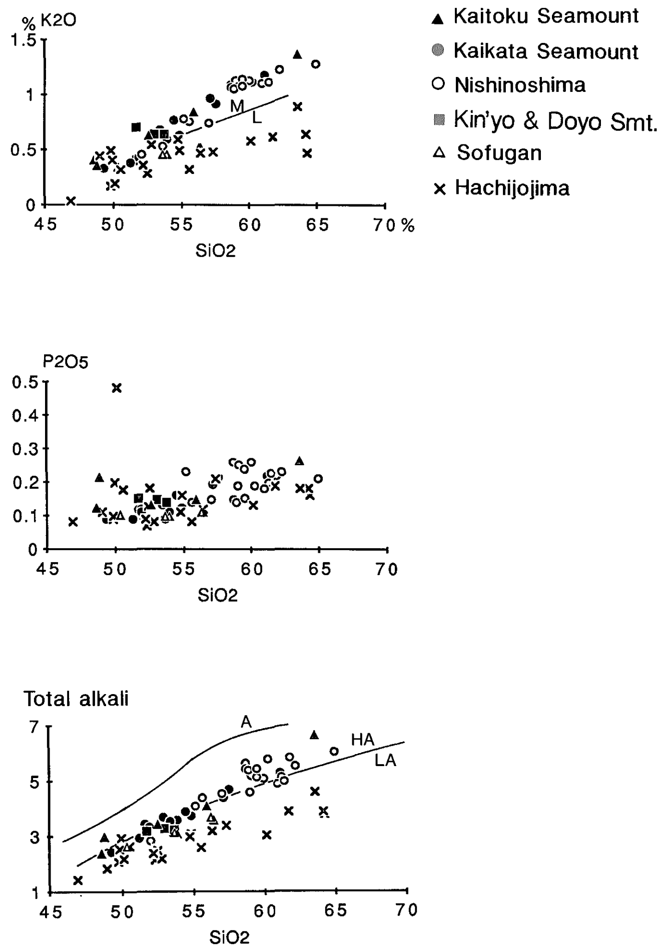


Fig. 5 continued

3. Regional geochemical characteristics

3.1 Chemical segmentation of the volcanic front

3.1.1 *Division into north and south segments in terms of alkali content*

As mentioned earlier, the volcanic front of the Izu-Ogasawara Arc is divided into two, the north and the south segments based mainly on rock chemistry of islands. It is known that the volcanic rocks of the south segment (Nishinoshima to Minami-Iwojima islands) are higher in alkali contents than those of the north (Oshima to Sofugan) (Yuasa and Tamaki, 1982 ; Yuasa, 1985). This is also supported by the new data from the submarine rocks (Fig. 7). In addition, the new chemical data reveal that the south segment can be subdivided into Iwojima and Minami-Iwojima volcanoes and Kita-Iwojima to Nishinoshima volcanoes. The former is richer in alkali contents than the latter. In Fig. 7, the data from the northern Mariana Arc (Ikeda and Yuasa, in prep.) are also plotted. Their total alkali contents are similar to or slightly lower than those of Kita-Iwojima to Nishinoshima volcanoes. The rocks of the seamounts in the Nishinoshima Trough are lower in alkali contents than those of the south segment. This tendency is also shown by K_2O, Ba and Rb of the LIL elements.

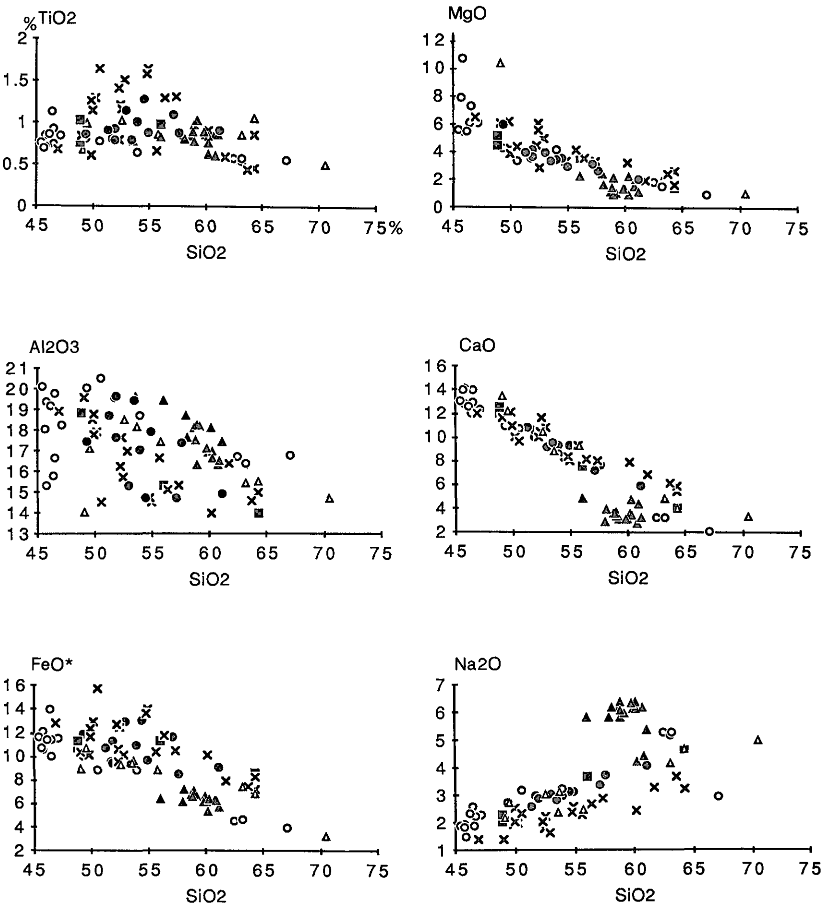


Fig. 6 Harker diagram for rocks from Volcano Islands and its environs in the southern part of the Shichito-Iwojima Ridge. In the K_2O-SiO_2 and alkali-SiO_2 diagrams, discriminative lines by Gill (1981) and Kuno (1968) are drawn, respectively. Abbreviations of the fields as follows; H: high-K andesite, M: medium-K andesite, L: low-K andesite, A: alkali basalt, HA: high-alkali tholeiite, LA: low-alkali tholeiite. Chemical compositions of the rocks from the northern Mariana Arc (Ikeda and Yuasa, in prep), Kaikata Seamount and Sumisujima Volcano (Sumisu Caldera), are plotted for comparison. Data by Fukuyama (1983) for Minami-Iwojima Volcano and Isshiki (1976) for Iwojima Volcano are also plotted.

Although no chemical data were available for the seamounts between Sofugan and Nishinoshima islands in the reports of Yuasa and Tamaki (1982) and Yuasa (1985), the boundary between the north and the south segments of the arc has been delineated in this area. As will be mentioned in the next section, the seamounts between both islands clearly show contrasting characteristics between those to the north of the Sofugan Tectonic Line and those to the south.

3.1.2 *Seamounts in the Nishinoshima Trough*

As mentioned earlier, these seamounts are subdivided into three groups, younger, older and intermediate-types, on the basis of submarine topography, geologic structure

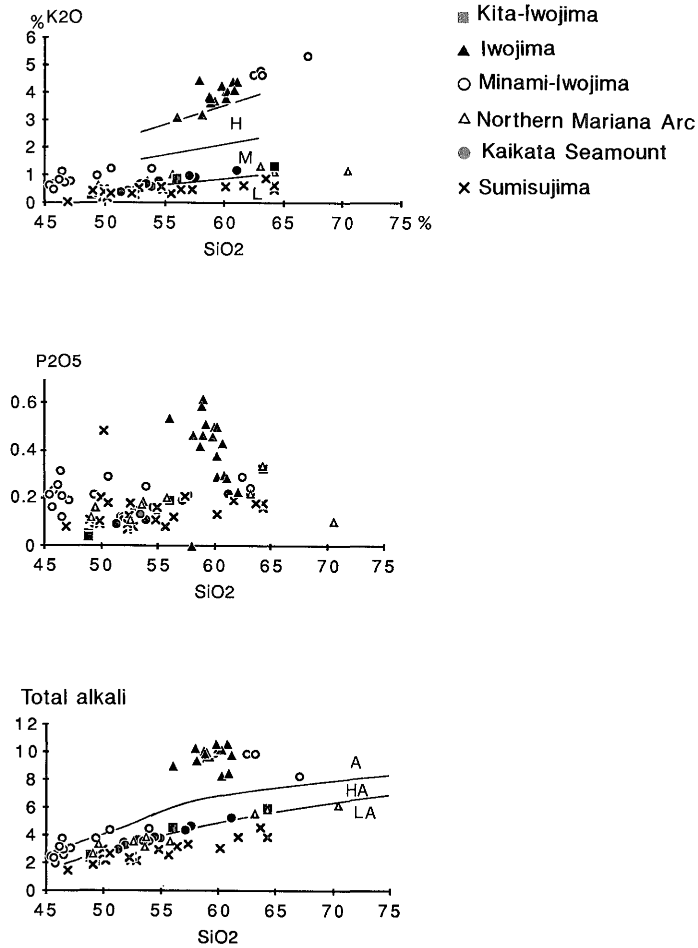


Fig. 6 continued

and magnetic anomaly pattern. Sofugan Volcano is located out side of the trough and resembles the younger volcanoes within the trough in its topography (Yuasa *et al.*, 1991) and dipole-type magnetic anomaly pattern (Yamazaki *et al.*, 1991). There are ten major volcanic edifices in the Nishinoshima Trough including Sofugan Volcano. Although the Nichiyo, Ohmachi and Sawa seamounts have not kept their original volcanic shapes, they are regarded as volcanoes here because they are composed mainly of volcanic rocks.

Except for the Sawa Seamount from which no fresh analyzable rock samples were obtained, these seamounts are chemically divided into four groups corresponding to the above three and Sofugan Volcano. As mentioned before, variation trends of K_2O vs. SiO_2 contents of the above groups are different from each other. Fig. 8 shows variations in K/Rb ratios vs. SiO_2 for each group. The K/Rb ratios of volcanic rocks vary with geological setting and across-arc situation (Jakes and White, 1970) as well as with increasing SiO_2 during crystallization differentiation. In this figure, four different decreasing trends are recognized. Chemical compositions of the rocks from Getsuyo and Kayo seamounts rocks are not included in the discussion because only one datum for each seamount is available, although they plot near the older seamounts area. Compared

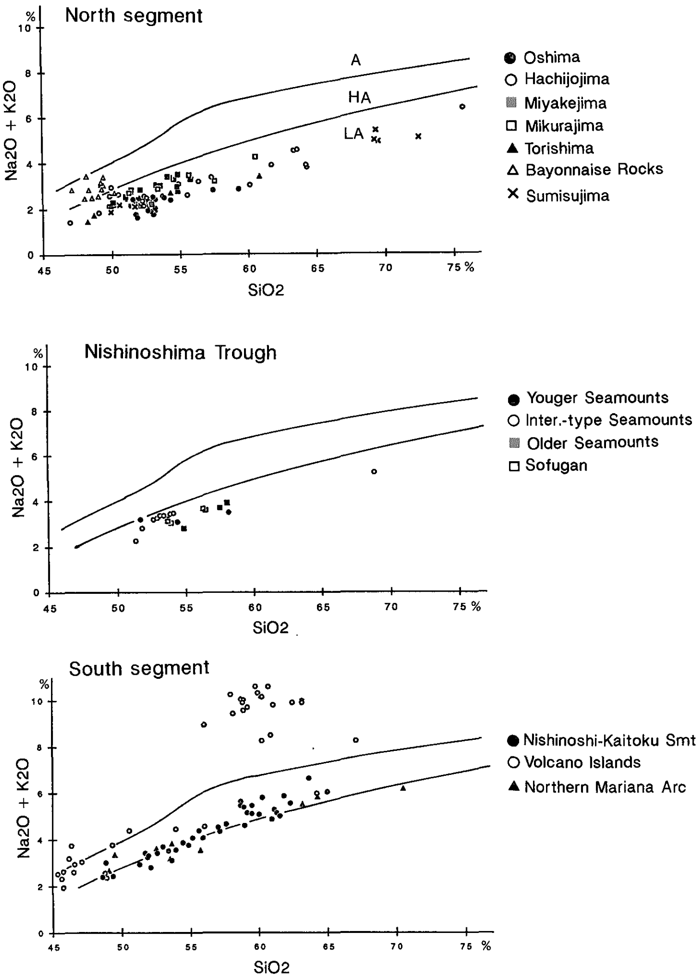


Fig. 7 Alkali-SiO_2 diagrams for the rocks from the north, central and south segments of the Shichito-Iwojima Ridge. Solid lines divide the alkali basalt (A), high-alkali tholeiite (HA) and low-alkali tholeiite (LA) fields (Kuno, 1968). Newly analyzed data in this paper are added to Yuasa and Tamaki (1982).

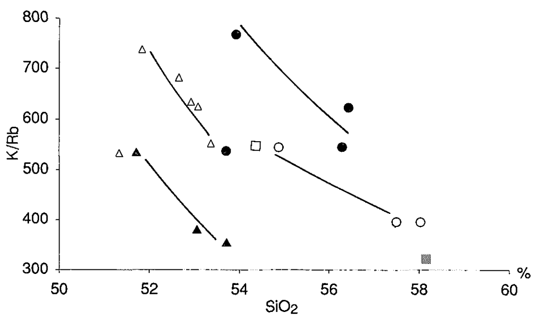


Fig. 8 K/Rb ratio vs. SiO_2 diagram for the rocks of the seamounts in the Nishinoshima Trough and Sofugan Volcano. Symbols are the same as in Fig. 3.

with each group for the same SiO_2 value, the rocks of Sofugan Volcano have the higher ratios whereas younger seamounts (Kin'yo and Doyo) show lower ratios. The trends of intermediate-type and older seamounts are plotted between them. This indicates two remarkable changes of the K/Rb ratios with time and in space. The rocks of Sofugan Volcano show higher ratios in K/Rb than those of the younger seamounts in the trough, while with time, the rocks of Sofugan Volcano show high ratios relative to those of the older volcanoes in the trough. On the other hand, the younger seamounts, Kin'yo and Doyo, have the lowest ratios in the figure. The rocks of intermediate-type and older seamounts plot between the two trends of the younger volcanoes. The variations in K/Rb ratios of rocks with time and space in the Nishinoshima Trough area suggest that K/Rb ratio increases from older to younger volcanoes to the north of the Sofugan Tectonic Line and decreases from older to younger ones in the area south of the fault. This suggests that the conditions for magma genesis are contrastingly different between north and south of the Sofugan Tectonic Line around the Nishinoshima Trough. That is, the degree of partial melting of the source mantle increases in north of the fault with time and decreases south of the fault. The primary magma composition of each volcano group is different.

There exist two examples that do not follow these trends in Sofugan Volcano and intermediate-type seamounts, and they are plotted on the chronologically different trends. These two rocks may indicate that the chronologically different magma has used the same passage in the volcano. A similar example is found also in the northern Mariana Ridge, e. g., Nikko Seamount recently erupted in 1979 and the rock dredged from the seamount was dated 4 Ma (Honza *et al.,* 1981). The tectonic setting of the above two volcanoes is similar to that of the Nikko Seamount, i.e. they all exist on the volcanic front just near the tip of backarc rifting. The passage of magma may be easily preservable for a long time in the same place with such a tectonic setting.

The rocks from the three young volcanoes, Getsuyo, Kin'yo and Doyo seamounts, are conspicuously low in Sr isotope ratio (0.70315-0.70331) relative to those from other volcanoes on the volcanic front. These values are the most primitive on the volcanic front of the Izu-Ogasawara Arc and correspond to that of the backarc depression basalt which has a transitional nature between island arc tholeiite and E-type MORB (Ikeda and Yuasa, 1989). It is clear that the interaction between magma and island arc crust is least developed on the three young seamounts on the volcanic front, even if the interaction exists. As shown in the gravity anomaly map by Ishihara and Yamazaki (1991), the Nishinoshima Trough shows a positive free-air gravity anomaly less than 30 mgal in spite of its great water depth of 3500 to 3800m, suggesting the existence of thin crust (Ishihara, 1985; Ishihara and Yamazaki, 1991). These data suggest that the island arc crust underlaying the Nishinoshima Trough is the least developed in the whole Izu-Ogasawara Arc.

3.1.3 *Gradational chemical change along the arc axis in the southern part of the arc*

Fig. 9 shows the along-arc variation in K_2O value (normalized at $SiO_2=60\%$), raw K_2O, Ba, P_2O_5, Rb, and Sr contents. K_2O, Ba, P_2O_5, and Sr contents tend to increase gradually from north to south, and become maximum at Minami-Iwojima and Iwojima volcanoes. At those volcanoes Rb contents show notably high values as well as other incompatible elements. However, except for those volcanoes, Rb contents are lower than about 20 ppm and very constant through the southern part of the arc.

Stern *et al.* (1988) showed along-arc variations in chemical composition of the volcanic rocks for the volcanoes from Mariana Ridge to Volcano Islands. They indicated that Rb,

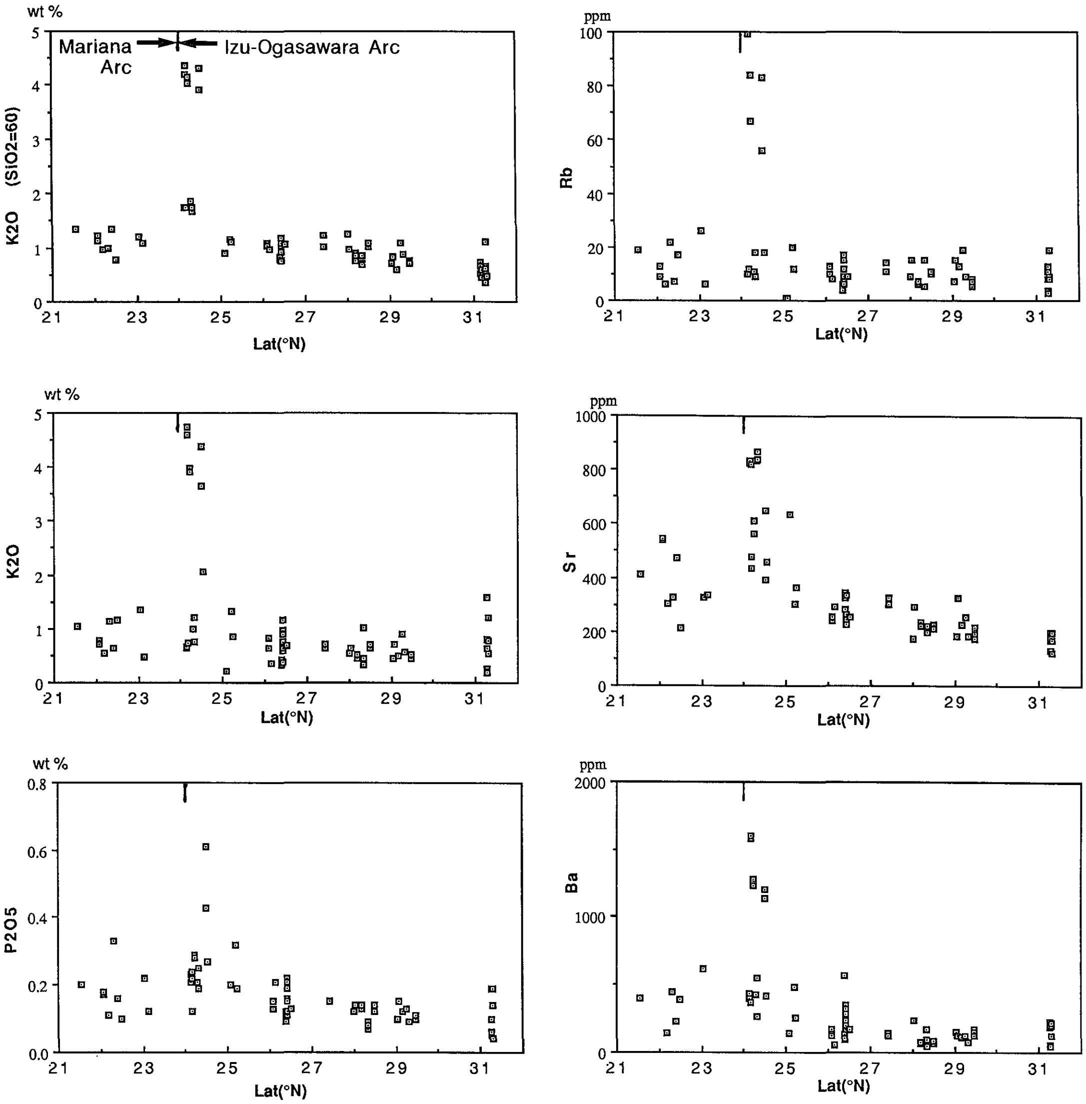


Fig. 9 Along-arc variations in K_2O (normalized to $SiO_2=60\%$), raw K_2O, P_2O_5, Rb, Sr and Ba. Chemical compositions of the rocks from the northern Mariana Arc (21° to 23°N, data from Ikeda and Yuasa, in prep) are also plotted.

Ba, Sr, Ce and $(Ce/Yb)_N$ increase from Mariana to the north as far as Iwojima Island, but further north of Iwojima such an increase is not observed. As far as Fig. 9 is concerned, however, there are no remarkable differences in the variation trends between the volcanoes located north and south of Iwojima Volcano.

3.2 Sr/Ca vs. Ba/Ca systematics

A log-log graph of Sr/Ca vs. Ba/Ca was used to explain petrogenesis by Onuma *et al.* (1981 and 1983). Chemical variation trends on this diagram indicate crystallization differentiation and the diagram is called "Sr/Ca-Ba/Ca diagram" or "SB diagram". Onuma and others drew a line with an inclination of 45°

through chondritic Sr/Ca and Ba/Ca ratios as a hypothetical partial melting line (Onuma *et al.*, 1981), and defined the intersection of the partial melting lline with the crystallization differentiation line as the SB index. A smaller SB index indicates a higher degree of partial melting of source mantle.

Data from the southern part of the arc, Sumisujima in the northern part, and the northern Mariana Arc are shown in Fig. 10. SB systematics of the volcanic rocks from Oshima (Onuma *et al.*, 1981) and Miyakejima (Hirano *et al.*, 1982) are plotted in the same figure for comparison.

In this figure, the alkaline rocks of Minami-Iwojima and Iwojima volcanoes show the lowest degree of partial melting. The rocks around Kita-Iwojima Island show a slightly higher degree of partial melting than the above and nearly the same degree as the rocks of the northern Mariana Ridge. Kaikata and Kaitoku seamount rocks plot in the field of higher melting degree than Mariana and Kita-Iwojima rocks. Of all the volcanoes plotted in the figure, the degree of partial melting at Sumisujima Volcano is the highest and nearly same as the SB systematics of Oshima and Miyakejima volcanoes.

Thus, the degree of partial melting of source mantle varies along the arc axis, i.e. it is lowest in the southernmost Minami-Iwojima and Iwojima volcanoes and increases toward north.

It is difficult to show the SB systematic trend of each volcano group in the Nishinoshima Trough because of insufficient amount of data. Comparing the Sr/Ca ratios, the rocks of younger seamounts show higher ratios in Sr/Ca than those of the intermediate-type and older seamounts, while the rocks of Sofugan Volcano show lower ratios than the latter. As expected from the figure, the degree of partial melting of the source mantle of the younger seamounts (Kin'yo and Doyo seamounts) is smaller than that of intermediate-type seamounts (Suiyo and Mokuyo seamounts), and the partial melting degree of source mantle of Sofugan Volcano is larger than that of older seamounts (Nichiyo and Ohmachi seamounts). This tendency corre-

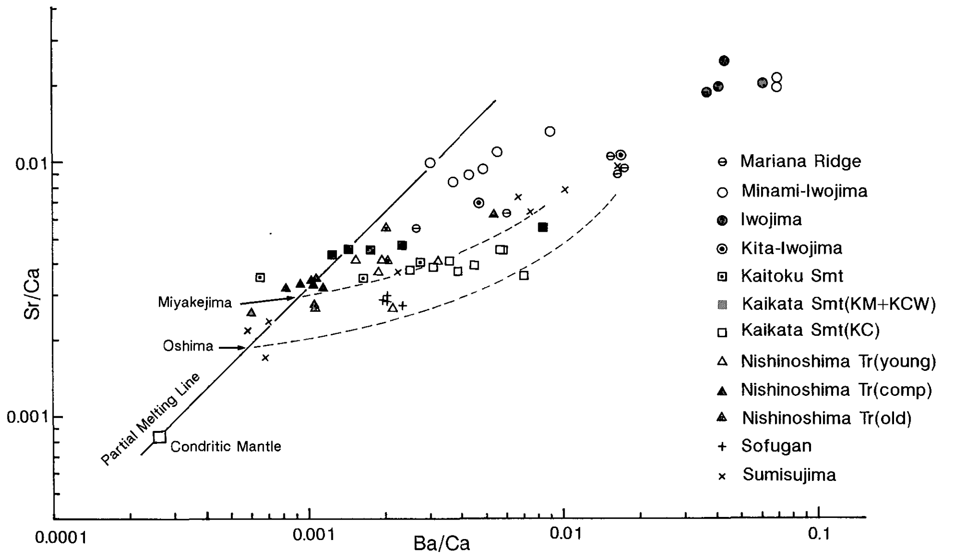


Fig. 10 Sr/Ca vs. Ba/Ca diagram (SB systematics) for the volcanic rocks of the central and southern part of the Izu-Ogasawara Arc. Broken lines show SB systematics for the rocks of Oshima and Miyakejima volcanoes (Onuma *et al.*, 1983).

sponds to that suggested from the consideration of the K/Rb ratios.

3.3 Along-arc variation of $^{87}Sr/^{86}Sr$ ratio

Notsu *et al.* (1983) reported Sr isotope ratios of the Quaternary volcanic rocks mainly from the islands in the Izu-Ogasawara Arc. They indicated that the ratios tend to decrease from the volcanic front (ca. 0.7037) to the backarc side (ca. 0.7033) as has been known in the Tohoku Arc. As for the along-arc variation in this ratio, they pointed out that the ratios decrease from Oshima toward the south and are nearly constant between Mikurajima and Nishinoshima islands, but further to the south the ratios increase from Nishinoshima to Minami-Iwojima islands. The values of the ratio given by them, however, are rather uniform and vary within a narrow range of 0.7034 to 0.7039.

Newly obtained Sr isotope ratios of the rocks along the volcanic front are shown in Table 3 and are plotted on Fig. 11 together

Table 3 $^{87}Sr/^{86}Sr$ ratios of volcanic rocks from the Shichito-Iwojima Ridge. Normalized to E & A=0.7080. Analysts: M. Yuasa and M. Nohara.

Sample No	Island/Seamount	Ratio	2 sigma
Sum-3	Sumisujima	.703354	.000032
D669-2	Sofugan	.703529	.000023
D731-4	Ohmachi Seamount	.703479	.000010
D796-5	Nichiyo Seamount	.703603	.000028
D673-5	Nichiyo Seamount	.703508	.000215
D675-1	Getsuyo Seamount	.703311	.000010
D677-1	Kayo Seamount	.703425	.000020
D954-8	Suiyo Seamount	.703383	.000015
D793-2	Suiyo Seamount	.703448	.000068
D953-1	Mokuyo Seamount	.703343	.000048
D686-1	Kin'yo Seamount	.703151	.000028
D687-1	Doyo Seamount	.703275	.000041
D697-1	Nishinoshima	.703508	.000011
D695-2	Kaikata smt	.703536	.000072
D703-1	Kaitoku smt	.703610	.000038
D706-3	Kita-Iwojima	.703582	.000014
D722-2	Iwojima	.703601	.000013
D713-1	Minami-Iwojima	.703701	.000013

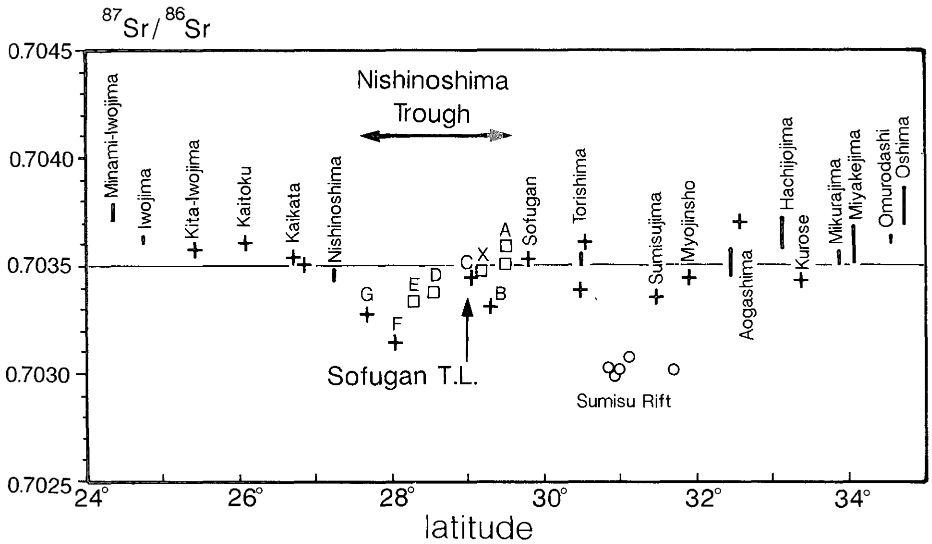


Fig. 11 Along-arc variation of $^{87}Sr/^{86}Sr$ ratios for the volcanic rocks on the Shichito-Iwojima Ridge.
Crosses and bars: younger volcanoes on the volcanic front, open square: older and intermediate-type seamounts in the Nishinoshima Trough, open circle: volcanic rocks from backarc rifts (Ikeda and Yuasa, 1989). Vertical bar shows the initial ratio range of the rocks from the volcano given by Notsu *et al.* (1983).

with the data given by Notsu *et al.* (1983). Data from the backarc rifts (open circle, Ikeda and Yuasa, 1989) are also shown in the figure. Relatively older seamounts in the Nishinoshima Trough (older and intermediate-type seamounts) are distinguishable from the young volcanoes by using open square symbols. Vertical bars are the range of the ratios given by Notsu *et al.* (1983). The ratios vary within a limited range from 0.7032 to 0.7039 throughout the front, but their variation is significant.

From Fig. 11, three characteristic points along the arc are recognized. First, the highest ratios exist at Minami-Iwojima and Oshima on both ends of the arc, and the lowest ratios are in the Nishinoshima Trough at the central part of the arc. Of the lower values, three young volcanoes in the Nishinoshima Trough have the lowest values (0.70315 to 0.70331) in the whole arc. The lowest ratio (0.70315 for Kin'yo Seamount) is within the range of backarc rift rocks (0.70302 to 0.70323 for Sumisu Rift). Similar along-arc variation of Sr isotope ratios is known in the southern Andes, where the ratio falls to the lowest value at the boundary between two petrographic provinces at 37°S (Lopez-Escobar *et al.,* 1985 ; Notsu *et al.,* 1987). Here, the maximum elevation of the Andes changes abruptly from high on the north to low on the south (Lowrie and Hey, 1981), and possible extensions of two fracture zones on the Nazca Plate, Mocha and Valdivia fracture zones, are subducted beneath the Andes at 37-38°S (Herron, 1981). However, Notsu *et al.* (1987) emphasized that the along-arc variation pattern of the ratios correlates neither with the age pattern of the subducting plate nor with the thickness of the continental crust. In the Izu-Ogasawara Arc, changes in geologic and geophysical phenomena, as well as in the mode of subduction of the Pacific Plate, coincide with the lowest Sr ratio.

Second, the Sr isotope ratios of the young volcanoes are lower than those of the older seamounts (0.70334 to 0.70360) in the Nishinoshima Trough. Even if the age effect is taken into consideration, there is still a significant difference between the values of the young and older seamounts. For instance, the present Sr isotope ratio of the Ohmachi Seamount rock is 0.70348. The calculated initial ratio is 0.70342 based on an age of 32 Ma (Yuasa *et al.,* 1988), being smaller only by 0.00006 than the present ratio. Thus, systematic differences in Sr isotope ratios exists between the younger and older seamounts in spite of their close geographical locations. This suggests that the composition of the magma source, the fluid phase derived from subducting slab, and/or the tectonic stress field (Kobayashi, 1986) might have changed with time.

A similar relation of Sr isotope ratios is known in the Northeast Japan, where the ratios of the younger volcanic rocks are lower than the older ones in the time range from 27 Ma to 6 Ma (Nohda and Wasserburg, 1986). It is considered that the effect of crustal contamination became smaller with time (Nohda and Wasserburg, 1986).

Third, four segments are defined by the increasing or decreasing trend of Sr isotope ratio along the arc. The first segment is assigned to the southward decreasing trend from Oshima to Kurose in the north. The second segment starts from Hachijojima Island and the ratios decrease to Sumisujima Island. The third segment is from Torishima Island to Getsuyo Seamount in the Nishinoshima Trough. In contrast to the above three segments, the Sr isotope ratios increase toward the south in the fourth segment from Kin'yo Seamount in the trough to Minami-Iwojima Island in the south,. Three gaps exist between : 1) Kurose and Hachijojima, 2) Sumisujima and Torishima, and 3) Getsuyo and Kin'yo seamounts. These segments except for the third segment are read from Notsu *et al.*'s (1983) Fig.4. They pointed out that such minute variations of Sr isotope ratios might be due to small differences in magma genesis, to changes in the mode of subduction of the Pacific Plate, or to mantle heterogeneity (Notsu *et al.,* 1983). As mentioned before, the mode of the subduction of Pacific Plate changes near the point where the lowest Sr isotope ratio occurs corresponding to the boundary between the third and fourth segments. However, the other two gaps do not correspond to the change in the mode of subduction. This saw-toothed pattern of Sr isotopic variation along the arc may correspond to the position of the structural gap in the arc crust rather than to mantle heterogeneity or change in the fluid phase derived from subducted slab. That is, these gaps coincide with the position of the submarine topographic discontinuities on the volcanic front. There is no necessity for mantle heterogeneity or fluid contents patterns to correspond to the submarine topographic gap of the volcanic front. As expected from the consideration of K/Rb ratio variations, the change in the fluid phase contributing to magma genesis around the Nishinoshima Trough may exist. For instance, the younger seamounts, Kin'yo and Doyo, have lower ratios in K/Rb than the intermediate-type and older seamounts rocks in the trough. The lower ratio is caused by a lower degree of partial melting deeper in the mantle source, where the dehydration of phlogopite occurs (Tatsumi, 1986). On the other hand, as amphibole dehydration occurs at shallower depth, where the degree of partial melting is higher, the K/Rb ratio of the rocks is larger. Although there is a possibility of fluid phase change as mentioned above, it is impossible to explain the whole along-arc variation pattern of Sr isotope ratios by this. Notsu *et al.* (1983) also showed a positive correlation between the Sr isotope ratio and the degree of partial melting estimated by SB diagram for the rocks from Oshima to Hachijojima islands. As indicated in the former section, however, the degree of partial melting of source mantle decreases to the south in the fourth segment. This suggests a negative correlation between them. The along-arc variation of Sr isotope ratio does not seem to correspond to the other geochemical parameters of volcanic rocks in the arc.

The topographic discontinuities suggest structural gaps. For instance, Kurose is on the inferred fault zone north of Hachijojima Island based on the gravimetric data (Ishihara, 1982). The other two gaps correspond to the tectonic valley crossing the arc (Fig. 25 of Yuasa *et al.,* 1991). The Nishinoshima Trough between Getsuyo and Kin'yo seamounts is the largest in size in the arc. Thus, the saw-toothed variation in Sr isotopic ratios along the arc is considered to be connected with the tectonic regime. The tensional field occurs in the structural gap which is an intra-arc depression on the Izu-Ogasawara Arc caused by the northwestward subduction of the Philippine Sea Plate. This coincides with Kobayashi's (1986) suggestion that the degree of mixing between magma and crustal material may be subject to regional tectonic stress and Sr isotope ratios become low in the tensional field because of the magma staying for a shorter time in the crust.

4. Conclusions

1) The volcanic front of the Izu-Ogasawara Arc is divided into two parts based on the rock chemistry of volcanic islands and seamounts. This division corresponds to the topographic one. The volcanic rocks of the southern part (Nishinoshima to Minami-Iwojima volcanoes) are higher in alkali contents than those of the northern part (Oshima to Sofugan volcanoes). The volcanic rocks of the seamounts in the Nishinoshima Trough have chemical characteristics different from the surrounding volcanoes.

2) The seamounts in the Nishinoshima Trough are chemically divided into four groups, younger (north), younger (south), older and intermediate-type ones. Sr isotope ratios of the rocks are low relative to the surroundings, especially the rocks of the younger seamounts show the lowest values on the volcanic front. The variation trend of

incompatible elements for each group is different from each other, suggesting differences in primary magma composition among these groups.

3) In the southern part of the arc, K_2O, P_2O_5, Ba and Sr contents tend to increase gradually from north to south, and become maximum at Minami-Iwojima and Iwojima volcanoes.

4) The degree of partial melting of source mantle varies along the arc axis as shown in terms of SB diagrams, i.e. it is lowest in the southernmost Minami-Iwojima and Iwojima volcanoes and increases to the north.

5) $^{87}Sr/^{86}Sr$ ratios of rocks also vary along the arc. The highest ratios exist at Minami-Iwojima and Oshima volcanoes, both ends of the arc, and the lowest ratio exists in the Nishinoshima Trough at the central part of the arc. Four segments are defined by the increasing or decreasing trend of the ratio along the arc. In this saw-toothed variation, the lower parts correspond to the structural gaps. There exists a systematic difference in the ratio between the younger and older seamounts in the Nishinoshima Trough, in spite of their close geographical location. This suggests temporal changes in the composition of magma source, the fluid phase derived from subducting slab, or the tectonic stress field.

Acknowledgements: We would like to express our sincere thanks to Emeritus Professor Y. Katsui, Hokkaido University, for his continuous guidance, encouragement and a critical reading of the manuscript. Dr. Y. Kawachi, Otago University, Dr. R.M. Conrey, Washington State University, Professors Y. Hariya, M. Kato and S. Yui, Drs. Y. Ikeda and T. Watanabe, Hokkaido University, and T. Moritani, Sumitomo Construction Co., LTD., are also acknowledged for reading the original manuscript and giving many helpful suggestions. Dr. K. Fujioka, Japan Marine Science and Technology Center, read the manuscript and encouraged us. Professor B. Taylor, University of Hawaii, gave us the samples of Sofugan and Sumisujima islands. Chemical analyses of rocks were carried out under the guidance of Messrs. H. Goto (XRF, minor and ICP) and S. Yokota (AA), and Drs. H. Hattori (XRF, major), T. Nakajima (Sr isotope) and T. Shirahase (Sr isotope), Geological Survey of Japan.

We are also grateful to the following persons of the Geological Survey of Japan for their help and cooperation with the experiments and field survey: K. Iizasa, T. Ishihara, N. Isshiki, T. Iwaya, H. Kanaya, K. Kishimoto, F. Murakami, S. Nakao, A. Nishimura, E. Saito, S. Togashi, T. Urabe, A. Usui and T. Yamazaki.

References

(J): in Japanese, (JE): in Japanese with English abstract, (JG): in Japanese with German abstract.

Aoki, H. and Ossaka, J. (1974) *Mysteries of submarine volcanoes-the exploration records of Nishinoshima (Kaiteikazan no Nazo).* Tokai Univ. Press, 250p. (J)

——— and Tokai University Research Group for Marine Volcano (1983) Petrochemistry of the Nishinoshima Islands. *La mer,* vol. 22, p. 248-256.

Aoki, S. (1979) On the topography and bottom character of the insular shelf of Izu Islands and their neighboring banks. *Jour. Toyo Univ. Gener. Educ. (Natural Sci.),* vol. 22, p. 19-46. (JE)

Aramaki, S., Hirayama, K. and Nozawa, T. (1972) Chemical composition of Japanese granites, part 2, variation trends and average composition of 1200 analyses. *Jour. Geol. Soc. Japan,* vol. 78, p. 39-49.

——— and Ui, T. (1978) Major element frequency distribution of the Japanese Quaternary volcanic rocks. *Bull. Volcanol.,* vol. 41, p. 390-407.

Brown, G.M., Holland, J.G., Sigurdsson, H., Tomblin, J.F. and Arculus, R.J. (1977) Geochemistry of the Lesser Antilles volcanic island arc. *Geochim. Cosmochim. Acta,* vol. 41, p. 785-801.

Carr, M.J., Rose, W.I. and Stoiber, R.E. (1982) Central America. in R.S. Thorpe ed., *Andesites,* John Wiley & Sons Ltd., p. 149-166.

Defant, M.J., De Boer, J.Z. and Oles, D. (1988) The western Central Luzon volcanic arc, the Philippines: two arcs derived by rifting? *Tectonophys.*, vol. 145, p. 350-317.

Fukuyama, H. (1983) Geology of Minami-Iwo Volcano, Izu-Bonin Islands, Japan. *Jour. Geogr.,* vol. 92, p. 55-67. (JE)

Gill, J. (1981) *Orogenic andesites and plate tectonics.* Springer-Verlag, Berlin-Heiderberg-New York, 390p.

Hamuro, K., Aramaki, S., Fujioka, K., Ishii, T., Tanaka, T. and Uto, K. (1983) The Higashi-Izu-oki submarine volcanoes, Part 2, and the submarine volcanoes near the Izu Shoto Islands. *Bull. Earthq. Res. Inst.,* vol. 58, p. 527-557. (JE)

Herron, E.M. (1981) Chile margin near lat 38°S: evidence for a genetic relationship between continental and marine geologic features or a case of curious coincidences? *Geol. Soc. Am. Memoir,* vol. 154, p. 755-760.

Hirano, M., Isshiki, N. and Onuma, N. (1982) Sr/Ca-Ba/Ca systematics in Miyakejima, Onoharajima, Mikurajima and Inambajima volcanoes, the Izu Islands, Japan. *Geochem. Jour.,* vol. 16, p. 79-87.

Honma, F. (1925) Geological observation of Sulphur Island, on the Pacific. *Chikyu (The Globe),* 4, 290-309. (J)

Honza, E., Inoue, E. and Ishihara, T. eds. (1981) *Geological investigation of the Ogasawara (bonin) and Northern Mariana Arcs, GH79-2, -3, and -4 Cruises, April -August 1979.* Geol. Surv. Japan, 170p.

Ikeda, Y. and Yuasa, M. (1989) Volcanisms in nascent back-arc basins behind the Shichito Ridge and adjacent areas in the Izu-Ogasawara arc, northwest Pacific: evidence for mixing between E-type MORB and island arc magmas at the initiation of back-arc rifting. *Contr. Miner. Petrol,* vol. 101, p. 377-393.

——— and ——— (in prep) Origin of alkaline volcanism on the volcanic front of the Izu-Mariana arc, northwest Pacific: implication for mantle metasomasism.

Ishihara, T. (1982) Gravity anomalies northeast of Hachijojima Island. Geological investigation of the northeast of Hachijojima Island, northern part of Ogasawara Arc, July-August 1980 (GH80-4 Cruise). *Geol. Surv. Japan Cruise Report,* no. 16, p. 20-24.

——— (1985) Gravity anomaly. in *1984 F.Y. report for Investigation of heavy metal resources accompanied with submarine hydrothermal activity,* Geol. Surv. Japan, 21. (J)

——— and Yamazaki, T. (1991) Gravity anomalies over the Izu-Ogasawara (Bonin) and northern Mariana Arcs. *Bull. Geol. Surv. Japan,* vol. 42, p. 687-701.

Isshiki, N. (1959) *Explanatory text of the geological map of Japan, Hachijojima, scale 1 : 50,000,* Geol. Surv. Japan, 58p. (JE)

——— (1976) Geology and petrography of Iwo-jima (Sulphur Island), Volcano Island. *Rept. Nat. Cent. Disaster Prevention,* no. 23, p. 5-16. (JE)

——— (1980) *Geology of the Mikurajima, Inambajima and Zenisu districts.* Quadrangle Series, Scale 1: 50,000, Geol. Surv. Japan, 35p. (JE)

——— (1982) *Geology of the Kozushima districts*. Quadrangle Series, Scale 1: 50,000, Geol. Surv. Japan, 75p. (JE)

Jakes, P. and White, A.J.R. (1970) K/Rb ratios of rocks from island arcs. *Geochim. Cosmochim. Acta,* vol. 34, p. 849-856.

Katsui, Y. (1972) Late Cenozoic volcanism and petrographic provinces in the Andes and Antarctica. *Jour. Fac. Sci., Hokkaido Univ.,* ser. 4, vol. 15, p. 27-40.

Kobayashi, Y. (1986) Quaternary arc volcanism and its bearing on tectonics. *Bull. Volcanol. Soc. Japan,* ser. 2, vol. 30, p. S137-S152. (JE)

Kuno, H. (1954) *Volcanoes and volcanic rocks.* Iwanami Zensho 196, Iwanamishoten, Tokyo, 255p. (J)

——— (1966) Lateral variation of basalt magma type across continental margins and island arcs. *Bull. Volcanol.,* vol. 29, p. 165-222.

——— (1968) Comment to "Rocks of the oceanic region -1. High-alumina basalts-"

by Aoki, H. and Ito, M. *Earth Science (Chikyu Kagaku),* vol. 22, p. 195-199. (J)

Lopez-Escobar, L., Moreno, H., Tagiri, M., Notsu, K. and Onuma, N. (1985) Geochemistry and petrology of lavas from San Jose volcano, Southern Andes (33°45′ S). *Geochem. Jour.,* vol. 19, p. 209-222.

Lowrie, A. and Hey, R. (1981) Geological and geophysical variations along the western margin of Chile near lat 33° to 36°S and their relation to Nazca plate subduction. *Geol. Soc. Am. Mem.,* vol. 154, p. 741-754.

Morimoto, R., Fisher R.L. and Nasu, N. (1955) Bathymetry and Petrography of the Bayonnaise Rocks, Japan. *Proc. Japan Acad,* vol. 31, p. 637-641.

——— and Ossaka, J. (1955) The 1952-1953 submarine eruption of the Myojin Reef near the Bayonnaise Rocks, Japan (1). *Bull. Earthq. Res. Inst.,* vol. 33, p. 221-250.

——— and ——— (1970) The 1970 activity of Myojin Reef. *Jour. Geogr.,* vol. 79, p. 301-320. (JE)

Murakami, F. and Ishihara, T. (1985) Submarine calderas discovered in the northern part of Ogasawara Arc. *Earth Monthly,* vol. 7, p. 638-646. (J)

Nakao, S., Yuasa, M., Nohara, M. and Usui, A. (1990) Submarine hydrothermal activity in the Izu-Ogasawara Arc, western Pacific. *Rev. Aqua. Sci.,* vol. 3, p. 95-115.

Nishimura, S. and Suparka, S. (1986) Tectonic development of East Indonesia. *Jour. Southeast Asian Earth Sci.,* vol. 1, p. 45-57.

Nohda, S. and Wasserburg, G.J. (1986) Trends of Sr and Nd isotopes through time near the Japan Sea in northeastern Japan. *Earth Planet. Sci. Lett.,* vol. 78, p. 157-167.

Notsu, K. (1985) Geochemistry of volcanic rocks from the Izu-Ogasawara Arc. *Earth Monthly,* vol. 7, p. 652-656. (J)

———, Isshiki, N. and Hirano, M. (1983) Comprehensive strontium isotope study of Quaternary volcanic rocks from the Izu-Ogasawara arc. *Geochem. Jour.,* vol. 17, p. 289-302.

———, Lopez-Escobar, L. and Onuma, N. (1987) Along-arc variation of Sr-isotope composition in volcanic rocks from the Southern Andes (33°S-55°S). *Geochem. Jour.,* vol. 21, p. 307-313.

Onuma, N., Hirano, M. and Isshiki, N. (1981) Sr/Ca-Ba/Ca systematics in four volcanoes of Oshima, Izu Islands, Japan. *Geochem. Jour.,* vol. 15, p. 315-324.

———, ——— and ——— (1983) Genesis of basalt magmas and their derivatives under the Izu Islands, Japan, inferred from Sr/Ca-Ba/Ca systematics. *Jour. Volcanol. Geotherm. Res.,* vol. 18, p. 511-529.

Ossaka, J., Hirabayashi, J. and Tsuchide, S. (1986) Chemical composition of effusive material of submarine volcano, Fukutoku-okanoba, in 1986. *Abstract Ann. Meeting Geochem. Soc. Japan, 1986,* p. 153. (J)

Stern, R.J., Bloomer, S.H., Lin, P.-N., Ito, E. and Morris, J. (1988) Shoshonitic magmas in nascent arcs: new evidence from submarine volcanoes in the northern Marianas. *Geology*, vol. 16, p. 426-430.

———, Smoot, N.C. and Rubin, M. (1984) Unzipping of the Volcano Arc, Japan. *Tectonophysics,* vol. 102, p. 153-174.

Sugimura, A. (1958) Marianen-Japan-Kamtschaka Orogen in Tätigkeit. *Earth Science (Chikyu Kagaku)*, no.37, p. 34-39. (JG)

——— (1960) Zonal arrangement of some geophysical and petrological features in Japan and its environs. *Jour. Fac. Sci. Univ. Tokyo,* ser. II, vol. 12, p. 133-153.

Tatsumi, Y. (1986) Role of induced convection and mantle diapir in the generation of subduction zone magma. *Bull. Volcanol. Soc. Japan,* ser. 2, vol. 31, p. 39-44.

Taylor, B., Brown, G., Fryer, P., Gill, J.B., Hochstaedter, A.G., Hotta, H., Leinen, C. H.M., Nishimura, A. and Urabe, T. (1990) Alvin-SeaBeam studies of the Sumisu Rift, Izu-Bonin arc. *Earth Planet. Sci. Lett.,* vol. 100, p. 127-147.

Terashima, S. (1971) Determination of cobalt, chromium, copper, lithium, nickel, lead, strontium and zinc in silicates by atomic absorption spectrophotometry. *Bull. Geol. Surv. Japan,* vol. 22, p. 245-259. (JE)

——— (1973) Atomic absorption analyses of Be, V, Ba and Rb in rocks and flame emission analysis of Rb. *Bull. Geol. Surv. Japan,* vol. 24, p. 469-486. (JE)

Terashima, S. (1977) X-ray fluorescence determination of chromium, gallium, niobium, lead, rubidium, strontium, yttrium, zinc- and zirconium in rocks. *Bull. Geol. Surv. Japan,* vol. 28, p. 393-399.

Tsuchide, M., Kato, S., Uchida, A., Sato, H., Konishi, N., Ossaka, J. and Hirabayashi, J. (1985) Submarine volcanic activity at the Kaitoku seamount in 1984. *Rept. Hydrogr. Res.,* vol. 20, p. 47-82. (JE)

Tsuya, H. (1936) Geology and petrography of Io-sima (Sulphur Island), Volcano Islands Group. *Bull. Earthq. Res. Inst.,* vol. 14, p. 453-480.

——— (1937) On the volcanism of the Huzi volcanic zone, with special reference to the geology and petrology of Idu and the Southern Islands. *Bull. Earthq. Res. Inst., Tokyo Imp. Univ.,* Vol. 15, p. 215-357.

Uto, K. (1983) Quaternary volcanic rocks from the Izu-Ogasawara Arc. *Earth Monthly,* vol. 8, p. 464-468. (J)

Yamazaki, T., Ishihara, T. and Murakami, F. (1992) Magnetic anomalies over the Izu-Ogasawara (Bonin) Arc, Mariana Arc and Mariana Trough. *Bull. Geol. Surv. Japan,* vol. 42, p. 655-686.

Yuasa, M. (1983) Contrast of geologic and geophysical phenomena between northern and southern parts of the Ogasawara Arc. *Earth Monthly,* vol. 5, p. 458-463. (J)

——— (1985) Sofugan Tectonic Line, a new tectonic boundary separating northern and southern parts of the Ogasawara (Bonin) Arc, northwest Pacific. in N. Nasu *et al.* eds., *Formation of Active Ocean Margins,* Terra Pub. Tokyo, p. 483-496.

———, Inouchi, Y. and Kinoshita, Y. (1981) Bottom samples obtained by dredge and rock-corer from the area northeast of Hachijojima Island, in the northern part of Izu-Ogasawara Arc. *Geol. Surv. Japan, Cruise Report*, no. 16, p. 35-48.

——— and Murakami, F. (1985) Geology and geomorphology of the Ogasawara Arc and the Sofugan Tectonic Line. *Jour. Geogr,* vol. 94, p. 115-136. (JE)

———, ———, Saito, E. and Watanabe, K. (1991) Submarine topography of seamounts on the volcanic front of the Izu-Ogasawara (Bonin) Arc. *Bull. Geol. Surv. Japan,* vol. 42, p. 703-743.

——— and Tamaki, K. (1982) Basalt from Minami-Iwojima Island, Volcano Islands. *Bull. Geol. Surv. Japan,* vol. 33, p. 531-540. (JE)

———, Uchiumi, S., Nishimura, A. and Shibata, K. (1988) K-Ar age of a forearc seamount adjacent to the volcanic front of the Izu-Ogasawara Arc. *Bull. Volcanol. Soc. Japan,* vol. 33, p. 352-353. (J)

———, Watanabe, T., Kuwajima, T., Hirama, T. and Fujioka, K. (in press) Prehnite-Pumpellyite facies metamorphism in oceanic arc basement from Site 791, in the Sumisu Rift, western Pacific. *Proc. ODP, Sci. Results, 126* : College Station, TX (Ocean Drilling Program).

Appendix

Analytical methods

All samples analyzed were sawed into thin slices and broken into small pieces less than 5mm in diameter. Crushed samples were soaked in a beaker filled with distilled water and rinsed in an ultrasonic bath until the water remained clear with addition of $AgNO_3$. Then, samples were crushed in an agate ball-mill or a mortar grinder.

Bulk rock samples were analyzed for major elements mainly by wet chemical analysis (GSJ wet analysis methods) and partly by XRF (Phillips PW1400) techniques using the glass disc method developed by H. Hattori of GSJ. Rb, Sr, Zr and Y were also analyzed by XRF (Toshiba AFC-202F) by the powder disc method (Terashima, 1977). Ni, Co, Cr, V, Cu, and Zn were analyzed by atomic absorption spectrometry (Terashima, 1971, 1973). Ba was measured by ICP technique.

Sr isotope ratios were measured on a VG Isomass 54E double collector mass spectrometer with on-line computer facilities using a single Ta filament. All measurements were normalized to E & A=0.7080.

Bulletin of the Geological Survey of Japan, Vol. 43, No. 7

伊豆・小笠原弧の火山フロント上火山岩の記載岩石学的および地球化学的特徴にみられる島弧軸沿いの変化

湯浅真人・野原昌人

要　旨

伊豆・小笠原弧の火山フロントである七島-硫黄島海嶺は，海面上に顔を出す火山島および海底火山からなり，それらの火山を構成する岩石の化学組成に基づいて南部と北部の二つに分割される．この区分は海底地形の特徴に基づく分割とも対応している．二分されたうちの南部（西之島-南硫黄島）の火山岩は北部（大島-孀婦岩）のそれに比べ，アルカリ元素含有量が高いという特徴がある．両者の間の西之島トラフには従来その概要の明らかでなかった海山群（大町・沢海山および七曜海山列）が分布するが，これらの海山を構成する火山岩類の化学組成は，上記南北の火山岩の特徴と異なっていて，とくにSr同位体比は周囲の岩石のそれに比べ低くなっている．西之島トラフ内海山は，孀婦岩も含め化学組成上4グループに分けられる．各グループの岩石のインコンパチブル元素の変化傾向はそれぞれ異なっていて，これら各グループ間で初成マグマの組成に違いがあったことが示唆される．

七島-硫黄島海嶺南部では，K_2O，P_2O_5，Ba，Srの含有量が北から南に向かって漸増する傾向があり，硫黄島および南硫黄島火山で最大値を示す．SB（Sr/Ca-Ba/Ca）ダイアグラムは，これらふたつの火山でソースマントルの部分溶融度が最小であることを示している．Sr同位体比も島弧軸方向に変化し，北へ向かって増加あるいは減少する4つのセグメントが認められる．各セグメントにおいて相対的に同位体比の低い部分は，地質構造上のギャップの位置に対応している．西之島トラフ内の新期海山と古期海山との間ではSr同位体比に系統的な差があり，新期海山は低い値を示す．このことは，マグマソースの組成，あるいはサブダクションスラブに由来する液相，あるいはテクトニックな応力場に，時間的な変化があったことを示唆している．

（受付：1992年3月24日；受理：1992年4月20日）