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A Strontium Isotopic Study of the Volcanic Rocks of the Myoko Volcano Group, Central Japan

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Abstract. Thirty-one selected volcanic rocks from the Myoko volcano group which comprises a volcanic chain of four independent volcanoes of Quaternary to Recent age are analyzed for $^{87}Sr/^{86}Sr$ ratios. The rocks of the Iizuna volcano, the oldest among the Myoko volcano group, have higher $^{87}Sr/^{86}Sr$ ratios and show a larger scatter ranging from 0.7043_7 to 0.7055_6 than those of other volcanoes. The Kurohime volcanic rocks have a restricted range of $^{87}Sr/^{86}Sr$ ratios ($0.7040_3 \sim 0.7043_5$). $^{87}Sr/^{86}Sr$ ratios of the Myoko volcanic rocks are almost the same in average to those of the Kurohime volcanic rocks, although somewhat varied ranging from 0.7037_8 to 0.7046_1. A single analysis of the Yakeyama volcanic rock yielded a $^{87}Sr/^{86}Sr$ ratio of 0.7042_7. A characteristic pattern in $^{87}Sr/^{86}Sr$ ratios is observed through the volcanic activity of the Myoko volcano group; $^{87}Sr/^{86}Sr$ ratios are high in the early stage of the volcanic activity and then decrease to low values, the late eruptives being characterized by constant $^{87}Sr/^{86}Sr$ ratios. The negative correlation between $^{87}Sr/^{86}Sr$ and Rb/Sr, and positive correlation between $^{87}Sr/^{86}Sr$ and Sr found in the rocks of the Iizuna volcano are interpreted to show the occurrence of contamination by materials with high $^{87}Sr/^{86}Sr$ ratios (>0.7056), low Rb/Sr ratios (<0.01) and high Sr contents (>300 ppm). Sialic crustal contamination may have played only a minor role.

Introduction

Petrogenesis of andesites and associated volcanic rocks occurring in island arc and continental margin environments has recently been discussed using Sr isotopes as a natural tracer (Ewart and Stipp, 1968; Church and Tilton, 1973; Gill and Compston, 1973; James et al., 1975a, b; Whitford, 1975). In immature island arcs in oceanic regions and also in one continental margin, e.g., the Cascade Range, Sr isotopic ratios of andesitic rocks are generally low (<0.7040) and are believed to reflect those of the source region where magmas were generated. On the basis of these low $^{87}Sr/^{86}Sr$ ratios, it has been proposed that andesitic magmas are directly derived from an upper mantle material and that crustal materials play an insignificant role. However, in mature island arcs such as Japanese Islands and New Zealand, and also in the continental margin such as South America, a fairly thick continental crust exists beneath volcanoes. Therefore, Sr isotopic ratios measured on volcanic rocks from these areas may not necessarily indicate the $^{87}Sr/^{86}Sr$ ratio of the source region of magma generation, because various degrees of crustal contamination are expected to occur. In these environments, Sr isotopic data may offer information on contamination which occurred before magmas reached surface rather than indicate $^{87}Sr/^{86}Sr$ ratios of primary magmas. Before drawing any hypothesis or conclusion on the genesis of andesites and associated rocks based on Sr isotopic data, it is important to study the variation of Sr isotopic composition in different eruptions of a single volcano or volcano group which has been throughly investigated geologically. For this purpose, we determined Sr isotopic compositions of the volcanic rocks of the Myoko volcano group which comprises a volcanic chain of four independent volcanoes of Quaternary to Recent age and is mainly composed of andesite of calc-alkaline rock series.

Summary of Geology and Volcanic History of the Myoko Volcano Group

The Myoko volcano group, consisting of the Iizuna, Kurohime, Myoko and Yakeyama volcanoes, is situated in the northern part of Central Japan (Fig. 1). The geology of the Myoko volcano group was recently described in detail by one of the authors (Hayatsu, 1976, 1977). Therefore, only a brief summary will be given here.

The volcanic cones extend northwards, arranged at a nearly equal interval of approximately 8 km and become younger northwards in age. Volcanic activity commenced in the Pleistocene and continues to the present. It is assumed that about 5×10^5 years have elapsed since the start of the volcanic activity of the Iizuna volcano until the building of the Yakeyama volcano of which principal activity was in historic time. The volcanoes of the Myoko volcano group are typical stratovolcanoes, except for the dome-shaped Yakeyama volcano. They are similar to each other in shape, but are rather different from each other in growth history, petrography and other features. The volcanic histories of the Iizuna, Kurohime and Myoko volcanoes are presented in the form of table (Tables 1–3).

The Myoko volcano group is composed of high-alumina basalts and associated calc-alkaline andesites and dacites. Volcanic rocks of the Myoko volcano group are invariably porphyritic with plagioclase as the dominant phenocryst. Andesitic volcanism is dominant, occurring in the form of lava flows, pyroclastic flow deposits and air-fall pyroclastic deposits. Basaltic and dacitic eruptives are limited and their volume relative to andesitic eruptives is small.

The Iizuna volcano, the oldest among the Myoko volcano group, started its activity in the Middle Pleistocene and the volcanic activity is divided into two stages based on a remarkable unconformity between them. All eruptives from the Iizuna volcano are covered by those from the Kurohime volcano. Eruptive materials from the Kurohime volcano are successively covered by those of the third, fourth and probably second stages of the Myoko volcano. The volcanic history of the Myoko volcano is much more complex compared with those of the Iizuna and Kurohime volcanoes. The Myoko volcano is divided into the old Myoko and the Myoko volcano based on a remarkable unconformity between them. The eruptives of the old Myoko volcano are invariably hydrothermally altered. The volcanic rocks of the second, third and fourth stages change their composition from basalt, through andesite, to dacite with the growth of the volcano. In the volcanic rocks of the Myoko volcano, especially in those of the fourth stage, xenolithic inclusions of sediments (siltstone, sandstone, etc.) derived from the basal Neogene strata are commonly observed.

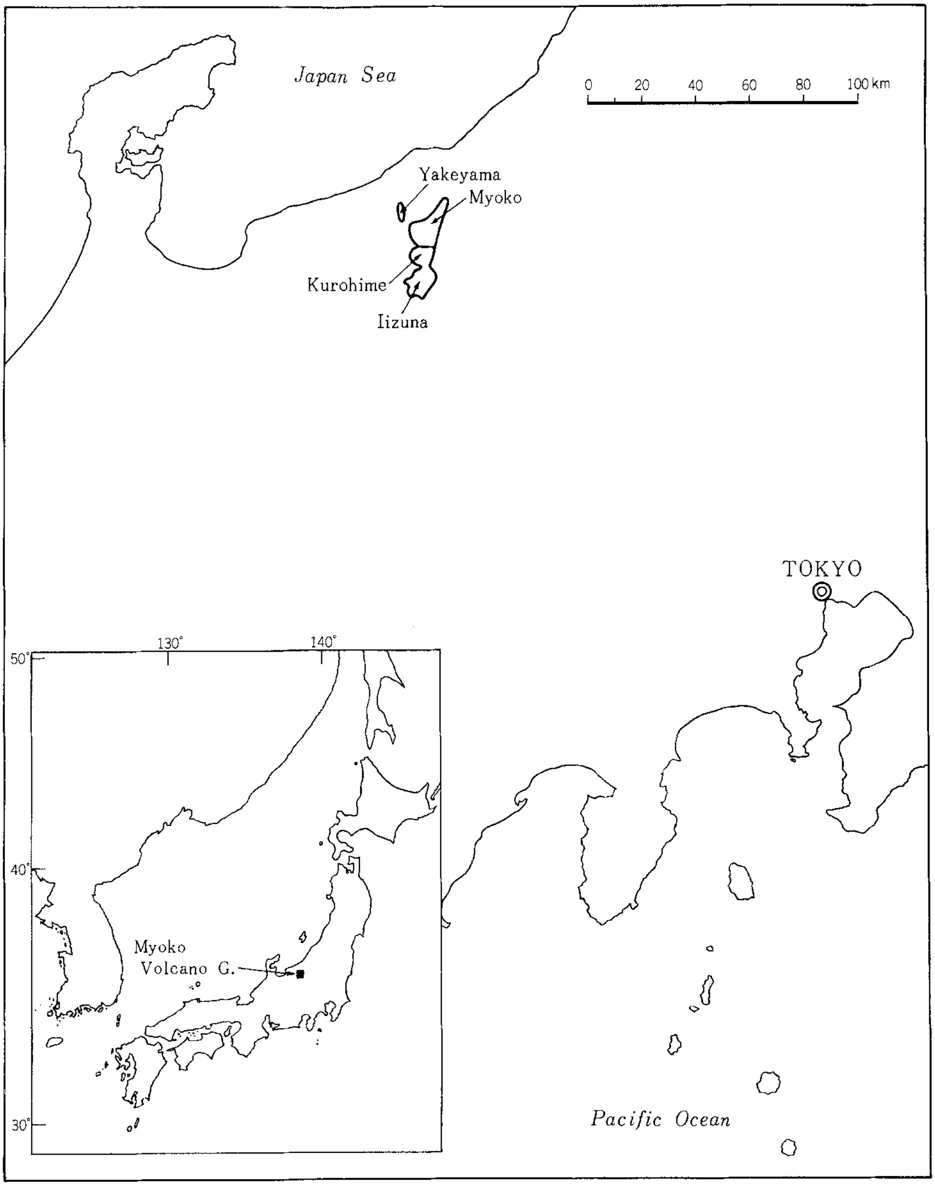

Fig. 1. Index map

All eruptive rocks of the Yakeyama volcano are intermediate and acid andesite with abundant hornblende phenocrysts. The lithofacies are rather uniform. No basalt is present in contrast to other volcanoes.

Analytical Methods

Sr isotopic analyses were performed during the period between June 1974 and November 1975 on a 30 cm JEOL 05RB mass spectrometer with a digital output at Kyushu University. Nine

Table 1. Stratigraphical succession of the Iizuna volcano

				Samples	Remarks	Rock type
Pleistocene	IInd stage	Central cone stage		IZ 72-1 Hy-ho andesite (L) IZ 101 Au-hy andesite (L)	Six parasitic lava domes formed on northwest flank each sample represents different dome	Ho andesite ↑
		Caldera stage			Mudflow deposits	
		Stratovolcano stage	Later	IZ 134-I Ol-ho bg hy andesite (P.f.) IZ 182 Au-hy andesite (L) IZ 214-2 Au-hy andesite (L) IZ 212-2 Au-hy andesite (L)	Pyroclastic flow deposits cover Iizunayama lava Iizunayama lava lavas and pyroclastics most extensive distribution uniform in lithofacies	Ho-px andesite ↑ Px andesite ↑
			Earlier	IZ 165 Au-ol basalt (P.f.) IZ 59 Hy-ol-au basalt (L) IZ 135-1 Au-ol basalt (L) IZ 166 Au-ol basalt (P.f.)	Iizuna basalt thick scoria deposit accompanied by lava flow limited exposure covered by Iizunayama lava	Px-ol basalt
	Ist stage			IZ 119-1 Ho-hy andesite (L) IZ 49 Hy andesite (L)	Lava and pyroclastics limited exposure covered discordantly by eruptives of second stage	Ho andesite Px andesite
Pliocene	Basement					

Ol = Olivine; Au = Augite; Hy = Hypersthene; Ho = Hornblende; Px = Pyroxene; bg = bearing; (L) = Lava; (P.f.) = Pyroclastic fall deposit; Qz = Quartz

analyses of Eimer and Amend standard carbonate made during this period gave a mean $^{87}Sr/^{86}Sr$ value of $0.7080_3 \pm 0.0001_3 (2\sigma)$. This places a limit of $0.0001_3 (2\sigma)$ on the precision of an individual run. Rb and Sr concentration data reported in the present paper are quoted from Yanagi and Ishizaka (1977). Both Rb and Sr concentrations were determined by the standard isotope dilution methods. The precision estimated from replicate analyses of standard samples is 2% for Rb and 1% for Sr.

Analytical Results

Analytical data for $^{87}Sr/^{86}Sr$ ratios, and Rb and Sr concentrations of 31 selected volcanic rocks from the Iizuna, Kurohime, Myoko and Yakeyama volcanoes are presented in Table 4. They are ordered stratigraphically for each volcano. All Sr isotopic results, except for the sample of the siltstone xenolith, are plotted in Figure 2 in stratigraphical order.

Table 2. Stratigraphical succession of the Kurohime volcano

			Samples	Remarks	Rock type
Pleistocene	Central cone stage		KH 354 Ol-ho bg au-hy andesite (L)	Volcanic activity in caldera repeated effusion of lava flows to form central cone	Ho-px andesite ↑
	Caldera stage			Mudflow deposit	
	Young stratovolcano stage	Later substage	KH 292 Qz-ol bg au-hy-ho andesite (P.f.) KH 295 Au-hy andesite (L)	Mainly lava flow with subordinate pyroclastics variable lithofacies Long pause of activity between earlier and later substages distinctly differ from each other in quantity	Ho-px andesite Px andesite ↑
		Earlier substage	KH 31-a Au-hy andesite (L) KH 206 Au-hy andesite (L)	Thick lava flow with small amount of pyroclastics total volume much larger than those of later substage constitute most of volcano uniform lithofacies	Px andesite ↑
	Old stratovolcano stage		KH 205-1 Ol-au basalt (L)	Small volume limited exposure lava flow and pyroclastics covered by eruptives of young stratovolcano	Ol-px basalt
Pliocene	Basement				

The Iizuna volcanic rocks have higher $^{87}Sr/^{86}Sr$ ratios and show a larger scatter in $^{87}Sr/^{86}Sr$ ranging from 0.7043_7 to 0.7055_6 compared with the rocks of other volcanoes. $^{87}Sr/^{86}Sr$ ratios of the Iizuna basalts are generally lower than those of the andesites. The values of the Iizunayama lava (andesite) which constitutes most of the volcano are uniform, averaging 0.7052_6. Two andesite samples from different lava domes show distinct $^{87}Sr/^{86}Sr$ ratios, suggesting a distinct variation of $^{87}Sr/^{86}Sr$ from dome to dome.

The Kurohime volcanic rocks have $^{87}Sr/^{86}Sr$ ratios ranging from 0.7040_3 to 0.7043_5. This restricted range of relatively low ratios is in contrast to the Iizuna volcanic rocks which have a wider range of higher ratios. The eruptive rocks of the Kurohime volcano show no Sr isotopic variation within a single stage in contrast to those of the Iizuna volcano which show fairly a large isotopic heterogeneity. The small isotopic difference between the eruptives of the earlier substage and those of other stages may be real.

Table 3. Stratigraphical succession of the Myoko volcano

				Samples	Remarks	Rock type
Holocene	Myoko volcano	IVth stage	Central cone stage	MK 60-A-1 Hy-ho andesite (P.f.) MK 226 Ho bg au-ol-hy andesite (L)	4990±110 year B.P. Ho andesite overwhelmingly predominant	Ho andesite (dacite) Px andesite ↑ Px-ol basalt
Pleistocene			Caldera stage			
			Stratovolcano stage	MK 322 Hy-au-ol basalt (L)	Exceedingly small volume	
		IIIrd stage		MK 323 Ol bg au-hy-ho andesite (P.f.) MK 489-15 Hy bg au-ol basalt (L) MK 489-1 Ol-hy-au basalt (P.f.)	Ejection of scoria fall followed by alternate eruption of lava and bomb finally eruption of pyroclastic flow 24,550±700 year B.P.	Ho andesite (dacite) ↑ Px andesite ↑ Px-ol basalt ↑ Ol-px basalt
		IInd stage		MK 539-1 Ol bg au-hy-ho andesite (P.f.) MK 545-1 Au-hy andesite (L) MK 547-1 Hy-au-ol basalt (L)	Basic scoria tuff followed by basic and intermediate lava and pyroclastics finally eruption of pyroclastic flow	Ho andesite (dacite) ↑ Px andesite ↑ Px-ol basalt
		Ist stage		MK 50 Au-hy-ho andesite (P.f.) MK 546-2 Hy-au andesite (L) MK 546-1 Ho-ol bg au-hy andesite (L)	Thick lava and subordinate amount of pyroclastics cover Old Myoko volcanics with a remarkable unconformity	Ho andesite Px andesite
	Old Myoko volcano				Altered to show sap greenish grey color	Px andesite Px-ol basalt
Miocene	Basement					

$^{87}Sr/^{86}Sr$ ratios of the Myoko volcanic rocks are almost the same in average to those of the Kurohime volcanic rocks, although the ratios of the Myoko volcanic rocks are somewhat varied ranging from 0.7037_8 to 0.7046_1. A single analysis of the Yakeyama volcanic rock yielded a value of 0.7042_7 which is indistinguishable from $^{87}Sr/^{86}Sr$ ratios of the rocks of the later stages of the Myoko volcano.

Table 4. Analytical data of the Iizuna-Kurohime-Myoko-Yakeyama volcanic rocks

Sample No.	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Sr/^{86}Sr$ 2σ
YK 1-2-3	55.8	364	0.153	$0.7042_7 \pm 0.0002_8$
MK 60-A-1	67.9	297	0.229	$0.7042_0 \pm 0.0001_2$
MK 226	48.1	361	0.133	$0.7042_9 \pm 0.0001_6$
MK 322	31.8	393	0.081	$0.7043_6 \pm 0.0001_7$
MK 323	65.8	284	0.232	$0.7043_8 \pm 0.0003_4$
MK 489-15	40.4	350	0.115	$0.7042_3 \pm 0.0002_3$
MK 489-1	24.1	318	0.076	$0.7037_8 \pm 0.0001_6$
MK 539-1	60.5	250	0.242	$0.7039_9 \pm 0.0002_7$
MK 545-1	37.5	260	0.144	$0.7043_4 \pm 0.0000_8$
MK 547-1	24.4	307	0.079	$0.7041_7 \pm 0.0002_4$
MK 50	56.5	238	0.237	$0.7046_1 \pm 0.0001_7$
MK 546-2	47.7	360	0.133	$0.7039_5 \pm 0.0000_8$
MK 546-1	33.1	279	0.119	$0.7038_5 \pm 0.0002_4$
KH 354	25.5	360	0.071	$0.7040_3 \pm 0.0001_9$
KH 292	60.6	265	0.229	$0.7040_7 \pm 0.0000_7$
KH 295	26.8	303	0.088	$0.7040_6 \pm 0.0001_0$
KH 31-a	25.0	348	0.072	$0.7043_4 \pm 0.0001_0$
KH 206	22.7	334	0.068	$0.7043_5 \pm 0.0001_6$ $0.7043_5 \pm 0.0000_3$
KH 205-1	12.1	296	0.041	$0.7040_7 \pm 0.0001_0$
IZ 72-1	32.2	277	0.116	$0.7043_7 \pm 0.0001_9$
IZ 101	15.9	323	0.049	$0.7052_5 \pm 0.0002_8$
IZ 134-1	6.29	455	0.014	$0.7055_6 \pm 0.0001_6$
IZ 182	27.0	384	0.070	$0.7052_5 \pm 0.0003_0$
IZ 212-2	21.0	390	0.054	$0.7051_5 \pm 0.0003_4$
IZ 214-1-1	16.2	413	0.039	$0.7053_9 \pm 0.0001_7$
IZ 165	19.5	332	0.059	$0.7044_8 \pm 0.0001_6$
IZ 59	11.0	295	0.037	$0.7048_1 \pm 0.0002_0$
IZ 135-1	5.15	445	0.012	$0.7049_5 \pm 0.0001_4$
IZ 166	3.65	338	0.011	$0.7046_8 \pm 0.0003_4$
IZ 119-1	37.7	423	0.089	$0.7051_4 \pm 0.0001_7$
IZ 49	14.7	319	0.046	$0.7048_0 \pm 0.0003_9$
Xenolith	52.0	465	0.112	$0.7048_6 \pm 0.0001_3$

IZ, KH, MK and YK denote Iizuna, Kurohime, Myoko and Yakeyama, respectively

As can be seen in Figure 2, a characteristic pattern in $^{87}Sr/^{86}Sr$ ratios is observed through the volcanic activity from the Iizuna, through the Kurohime and Myoko, to the Yakeyama volcano. $^{87}Sr/^{86}Sr$ ratios are high in the early stage of the volcanic activity and then decrease to low and fixed values (0.7040 ~ 0.7043). A considerable Sr isotopic variation is observed in the eruptive

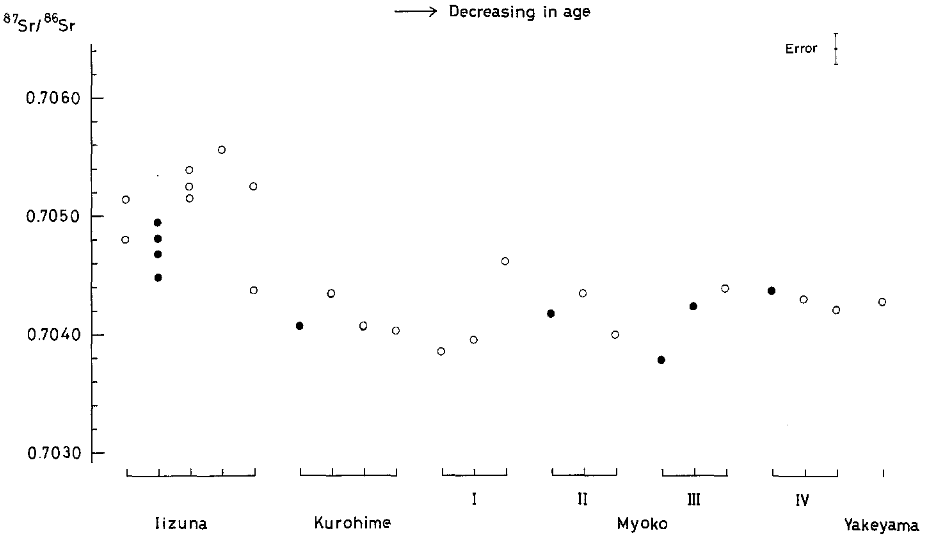

Fig. 2. Variation of $^{87}Sr/^{86}Sr$ ratios of the rocks of the Myoko volcano group in accordance with stratigraphical succession; Solid: basalt; Open: andesite

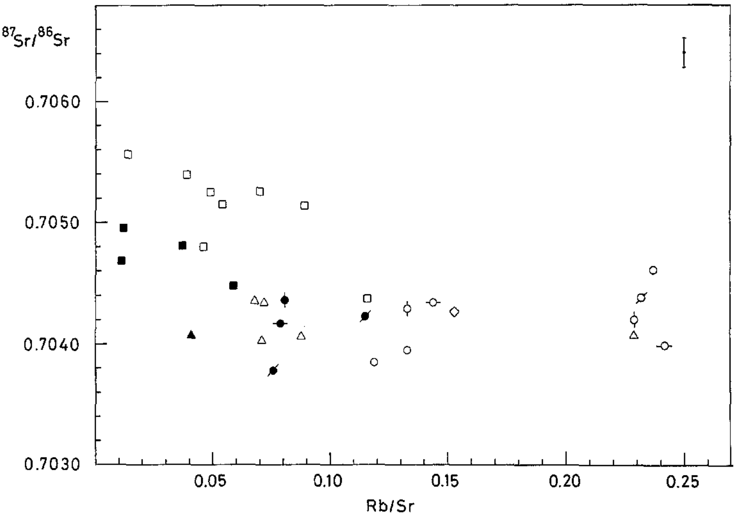

Fig. 3. $^{87}Sr/^{86}Sr$ versus Rb/Sr plots for the Iizuna, Kurohime, Myoko and Yakeyama volcanic rocks. (□) Iizuna; (△) Kurohime; (○) Myoko Ist stage; (-○-) Myoko IInd stage; (ø) Myoko IIIrd stage; (ϕ) Myoko IVth stage; (◇) Yakeyama. Solid: basalt; Open: andesite

rocks from the first stage to the initial phase of the third stage of the Myoko volcano. After the initial phase of the third stage, $^{87}Sr/^{86}Sr$ ratios practically stay constant at around 0.7043 until the last eruptives of the Myoko volcano group during the period of approximately 2.5×10^4 years. This indicates that the volcanic rocks erupted during this period were derived from isotopically

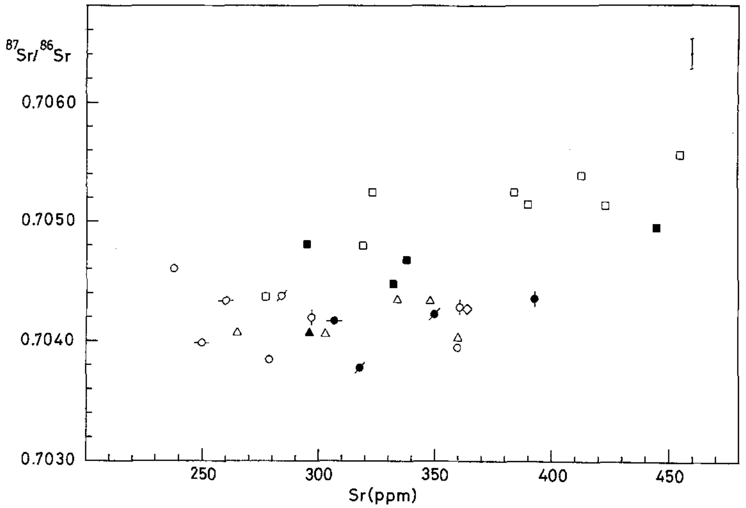

Fig. 4. Variation of ^{87}Sr/^{86}Sr versus Sr contents for the Iizuna, Kurohime, Myoko and Yakeyama volcanic rocks. Symbols as in Figure 3

homogeneous magmas. Thus, Sr isotopic ratios of the eruptive rocks of the Myoko volcano group, as a whole, decreased with decreasing in age and reached a common value at the later stages.

The data of the rocks of the Myoko volcano group are plotted on ^{87}Sr/^{86}Sr versus Rb/Sr and ^{87}Sr/^{86}Sr versus Sr diagram in Figures 3 and 4 respectively. On this isochron diagram, the data of the Iizuna volcanic rocks define two negative trends, one for basalts and the other for andesites. The negative correlation is more obvious for the andesites than for the basalts. Comparing these two trends at the same Rb/Sr ratio, the andesites are higher in ^{87}Sr/^{86}Sr ratios than the basalts. Moreover, there is a weak positive correlation between ^{87}Sr/^{86}Sr ratios and Sr contents (Fig. 4) and again it is distinct for the andesites. For the rocks of the Kurohime, Myoko and Yakeyama volcanoes, no correlation exist between ^{87}Sr/^{86}Sr and Rb/Sr or between ^{87}Sr/^{86}Sr and Sr contents in contrast to those of the Iizuna volcano, although the rocks of the first stage of the Myoko volcano exhibit a positive correlation between ^{87}Sr/^{86}Sr and Rb/Sr.

An unmetamorphosed siltstone xenolith yielded a relatively low ^{86}Sr/^{86}Sr ratio of 0.7048_6.

Discussion

As shown in Figure 2, scatter in Sr isotopic ratios well outside range of experimental error exists in each volcano of the Myoko volcano group, although the degree of the scatter differs from one volcano to the other. An especially large scatter in ^{87}Sr/^{86}Sr ratios, together with their high values, is striking in the volcanic rocks of the Iizuna volcano. This kind of isotopic heterogeneity within the eruptive rocks from a single volcano could arise either by wall-rock contamination or by several isotopically distinct magmas and mixture of these magmas. First we will consider the former case. As can be seen in Figures 3 and 4, there is a negative correlation between $^{87}Sr/^{86}Sr$ and Rb/Sr, and a weak positive correlation between $^{87}Sr/^{86}Sr$ and Sr for the rocks of the Iizuna volcano. These relations are the reverse of those normally encountered when sialic crustal materials are incorporated (e.g., Faure and Powell, 1972). Provided that the higher the $^{87}Sr/^{86}Sr$ ratios, the more the volcanic rocks were contaminated, the correlations in Figures 3 and 4 would indicate that Rb/Sr ratios decrease and Sr concentrations increase with increasing contamination. This would require that the contaminant have $^{87}Sr/^{86}Sr$ ratios greater than 0.7056, Rb/Sr ratios less than 0.01, Sr content greater than 300 ppm and hence Rb content less than 3 ppm. The contaminant with these geochemical characteristics is clearly different from normal crustal materials and excludes the possibility of old crustal materials with high Rb/Sr ratios. As a canditate for such unusual contaminant, we suggest mafic rocks such as those found as accidental inclusions in Cenozoic alkali basalt of Utajima, an islet off the Japan Sea coast of Southwest Japan, which have low Rb/Sr ratios (0.00077–0.0072), high Sr contents (198–1006 ppm) and relatively high $^{87}Sr/^{86}Sr$ ratios ($\sim$0.7050) (Ishizaka et al., 1977). They suggested that the Utajima inclusions may be crystallization residiuum which constitutes the lower crust beneath the Utajima and that this kind of residiuum is expected to occur extensively at depth beneath Central Japan.

From another point of view, we will re-examine the contaminant of the Iizuna volcanic rocks. The frequency distribution of Rb/Sr ratios in andesites and basalts from island arcs and corresponding orogenic belts, of which $^{87}Sr/^{86}Sr$ ratios are less than 0.7037, has a distinct peak at about 0.023 (Yanagi, 1975). The abundance of volcanic rocks with Rb/Sr ratio of about 0.01 is very restricted in island arcs. Almost all other volcanic rocks in island arcs, basalts and andesites with $^{87}Sr/^{86}Sr$ ratios higher than 0.7037, and dacites and rhyolites, have higher Rb/Sr ratios than 0.023. Therefore it may be assumed that primary magmas, basaltic or andesitic, have Rb/Sr ratios of about 0.02, where their $^{87}Sr/^{86}Sr$ ratios are less than 0.7037. Some of the Iizuna volcanic rocks (IZ 166, IZ 135-1 and IZ 134-1) have Rb/Sr ratios less than 0.02 and have $^{87}Sr/^{86}Sr$ ratios distinctly higher than 0.7037. We assume these high $^{87}Sr/^{86}Sr$ ratios resulted from wall-rock contamination. If so, it may follow that the contamination proceeded with slight decrease or without significant variation of Rb/Sr ratios in magmas. Since partition coefficient of Rb between a magma and its residiuum is very small and close to zero, Rb concentration in magma continues to increase during the contamination. Therefore the above condition, the contamination without significant variation of Rb/Sr ratio, implies that the Sr concentration increases at almost the same rate as that of Rb during the contamination. This condition is expressed by the following equation,

$$\frac{\Delta \ln C_L^{Rb}}{\Delta x} \leqq \frac{\Delta \ln C_L^{Sr}}{\Delta x}$$

where C_L^{Rb} and C_L^{Sr} are concentrations of Rb and Sr in the magma, respectively, x is an amount of the contaminant incorporated into the magma. When the contamination is approximated by zone melting, this equation is expressed by the following equation,

$$\frac{C_{\mathrm{B}}^{\mathrm{Rb}}}{C_{\mathrm{L}}^{\mathrm{Rb}}}-\gamma^{\mathrm{Rb}}\leqq\frac{C_{\mathrm{B}}^{\mathrm{Sr}}}{C_{\mathrm{L}}^{\mathrm{Sr}}}-\gamma^{\mathrm{Sr}} \quad \text{or} \quad \frac{C_{\mathrm{B}}^{\mathrm{Rb}}}{C_{\mathrm{B}}^{\mathrm{Sr}}}\leqq\frac{C_{\mathrm{L}}^{\mathrm{Rb}}}{C_{\mathrm{L}}^{\mathrm{Sr}}}-\frac{C_{\mathrm{L}}^{\mathrm{Rb}}}{C_{\mathrm{B}}^{\mathrm{Sr}}}(\gamma^{\mathrm{Sr}}-\gamma^{\mathrm{Rb}})$$

where γ^{Rb} and γ^{Sr} are partition coefficients, respectively, for Rb and Sr between magma and residiuum. $C_{\mathrm{B}}^{\mathrm{Rb}}$ and $C_{\mathrm{B}}^{\mathrm{Sr}}$ are concentrations of Rb and Sr in the contaminanat, respectively. This equation is approximated as follows, because γ^{Rb} is very close to zero,

$$\frac{C_{\mathrm{B}}^{\mathrm{Rb}}}{C_{\mathrm{B}}^{\mathrm{Sr}}}\leqq\frac{C_{\mathrm{L}}^{\mathrm{Rb}}}{C_{\mathrm{L}}^{\mathrm{Sr}}}-\gamma^{\mathrm{Sr}}\cdot\frac{C_{\mathrm{L}}^{\mathrm{Rb}}}{C_{\mathrm{B}}^{\mathrm{Sr}}}.$$

In the case of the Iizuna, $\frac{C_{\mathrm{L}}^{\mathrm{Rb}}}{C_{\mathrm{L}}^{\mathrm{Sr}}}=0.01$, then $\frac{C_{\mathrm{B}}^{\mathrm{Rb}}}{C_{\mathrm{B}}^{\mathrm{Sr}}}<0.01$.

This is the same as previous conclusion derived from Figure 3.

In connection with the negative correlation found in Figure 3, the difference in $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratio between the basalts and andesites should be explained with no effect to the above conclusion. A rate of variation of $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratio during contamination depends on the difference in $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratio between the magma and the contaminant, and partition coefficient of Sr between the magma and its residiuum (Yanagi, 1975).

A magnitude of the partition coefficient of Sr depends almost on an abundance and Ab content of plagioclase in the residiuum (Yanagi, 1975). The partition coefficient increases with the increase of the abundance and of the Ab content of plagioclase. Since an andesitic magma has more plagioclase and less mafic mineral components than a basaltic magma, plagioclase may safely be assumed to be more abundant and richer in Ab content in the residiuum from the andesitic magma than from the basaltic magma under similar physical conditions. Therefore the partition coefficient is reasonably expected to be larger for the andesitic magma. This implies that the rate of variation of $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratio during the contamination is larger for the andesitic magma than for the basaltic magma and also implies that Sr concentration to which the magma is changing during the contamination is different between the basaltic and andesitic magmas. The larger the partition coefficient, the lower the Sr concentration becomes. Provided that the partition coefficient of Rb was very low and close to zero for both cases of crystallization of the basaltic and the andesitic magmas and that these two magmas were contaminated with the same material postulated previously, then at the same degree of the contamination, the andesitic magma would be higher in Rb/Sr and also in $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratio than the basaltic magma. In these ways, it is possible to explain the difference in $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratio between the basalts and andesites of the Iizuna volcano and the negative correlation for these volcanic rocks.

Nevertheless, the possibility that the isotopic variation observed in the Iizuna volcanic rocks resulted from several isotopically distinct magmas and mixture of these magmas cannot be ruled out. For example, IZ 72-1 and IZ 101 from two different lava domes have distinct isotopic ratios. This isotopic heterogeneity within lava domes could arise from isotopically distinct magmas.

The Myoko volcanic rocks contain xenoliths of sediments of the basal Neogene strata. All rock types from basalt to dacite of the fourth stage contain them, sometimes up to 6% in volume. Various degrees of pyrometamorphism are observed in the inclusions from practically unmetamorphosed to completely metamorphosed sediments and hence isotopic variations in the volcanic rocks are expected to occur among the rocks of the fourth stage. No Sr isotopic variation which exceeds analytical uncertainty, however, is observed among the rocks of the fourth stage. It is considered that these xenoliths with relatively low $^{87}Sr/^{86}Sr$ ratio little affected the $^{87}Sr/^{86}Sr$ ratios of the Myoko volcanic rocks.

The lack of correlation between $^{87}Sr/^{86}Sr$ and Rb/Sr or between $^{87}Sr/^{86}Sr$ and Sr, except for the rocks of the first stage of the Myoko volcano, as well as low $^{87}Sr/^{86}Sr$ ratios suggests no clear evidence for crustal contamination for the eruptive rocks of the Kurohime and Myoko volcanoes. It is considered that the rocks of the Kurohime, Myoko and Yakeyama volcanoes were formed through crystallization differentiation of magmas isotopically homogeneous with $^{87}Sr/^{86}Sr$ ratios of 0.7042 ± 2.

Conclusions

The first magma, from which the Iizuna eruptive rocks were derived, ascending from the depth in the mantle may have reacted with the wall-rock of the reservoir to various degrees. The reservoir is assumed to exist in the depth of the Earth where the wall-rock has Rb/Sr ratio less than 0.01, Sr content greater than about 300 ppm and $^{87}Sr/^{86}Sr$ ratio larger than 0.7056. Since the origin of the wall-rock material suggested in this paper is a crystallization residiuum from magmas which formed very thick accumlates of volcanic rocks in Central Japan, an extensive occurrence of this kind of residiuum is reasonably expected at depth beneath Central Japan. Although this kind of residiuum is not directly accessible to us, we have provisionally postulated that the residiuum is very akin to the mafic inclusions found in the alkali basalt of Utajima, Southwest Japan. The eruptive rocks derived from such magmas would show a negative correlation between Rb/Sr and $^{87}Sr/^{86}Sr$ and a positive correlation between $^{87}Sr/^{86}Sr$ and Sr. The magmas successively ascended, from which the Kurohime, Myoko and Yakeyama volcanic rocks were derived, might not have reacted with the wall-rocks as deduced from the lack of correlation between Rb/Sr and $^{87}Sr/^{86}Sr$ or between $^{87}Sr/^{86}Sr$ and Sr, and also from low $^{87}Sr/^{86}Sr$ ratios of the Kurohime and Myoko volcanic rocks, although minor contamination with acid crustal materials might have occurred.

High $^{87}Sr/^{86}Sr$ ratios of the volcanic rocks occurring in orogenic belts have usually been ascribed to the contamination with old sialic crustal materials of relatively upper level of the crust. The present study, however, indicates that relatively high $^{87}Sr/^{86}Sr$ ratios also could arise by reaction (or contamination) with mafic wall-rocks which probably constitute lower part of the crust. Fairly thick crust may exist underneath mature island arcs, such as the Japanese Islands. The lower crust of this region may have relatively high $^{87}Sr/^{86}Sr$ ratios in places, for example, Southwest Japan. Thus high $^{87}Sr/^{86}Sr$ ratios may not necessarily indicate unmodified $^{87}Sr/^{86}Sr$ ratios of the source region of magma generation, where the crust with high $^{87}Sr/^{86}Sr$ ratios is assumed to exist in the deeper level.

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