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ORIGIN OF LATERAL VARIATIONS IN $^{87}Sr/^{86}Sr$ RATIOS OF QUATERNARY VOLCANIC ROCKS FROM THE KURILE ARC IN HOKKAIDO, JAPAN

by

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(with 6 text-figures and 1 table)

Abstract

$^{87}Sr/^{86}Sr$ ratios were examined for volcanic rocks from Quaternary volcanoes in the Kurile arc in Hokkaido, Japan. The results show that the ratios decrease immediately away from the volcanic front, then increase in the middle part of the arc, but decrease again toward the back-arc side. The complex lateral variations of the ratios can be ascribed to breakdown of different minerals in the mantle wedge, i.e. amphibole decomposes beneath the volcanic front, whereas phlogopite breaks down beneath the middle part of the arc. Geochemical characters of the rocks from Rishiri volcano, located furthest away from the volcanic front are quite different from those commonly observed in the trench-arc systems. The characters are similar to those of lavas from Deception island, located in Bransfield Strait formed by back-arc spreading. This suggests that the Rishiri volcanism is independent of the arc magmatism.

Introduction

In Hokkaido, 45 Quaternary volcanoes (or volcano groups) are distributed along two arcs, the Kurile arc and the Northeast Japan (North Honshu) arc (Text-fig. 1). The pacific plate is considered to subduct beneath the North American plate to form both trench-arc systems (Kobayashi, 1983; Nakamura, 1983). The junction of the two arcs is located in the Sapporo-Tomakomai lowland which separates the island into east-central and southwestern parts (Katsui et al., 1978).

Lateral variation of magma chemistry related to subduction has been observed in many arc systems (e.g. Dickinson, 1968). Volcanic rocks from the Northeast Japan and Kurile arcs show increasing K, Ba, Th, F, H_2O, K/Hf, and LREE/HREE ratios toward the back-arc side (Sugimura, 1960; Kuno, 1966; Masuda et al., 1975; Ui and Aramaki, 1978; Katsui et al., 1978; Masuda, 1979; Sakuyama, 1979; Fujimaki and Kurasawa, 1980; Ishikawa et al., 1980; Fujitani and Masuda, 1981; Aramaki and Ui, 1983; Tatsumi and Nakano, 1984). Their $^{87}Sr/^{86}Sr$ ratios decrease toward the back-arc side, while the $^{143}Nd/^{144}Nd$ ratios increase (Hedge and Knight, 1969; Nohda and Wasserburg, 1981; Notsu, 1983; Notsu et al., 1983). The above lateral variations are considered to be a result of two factors: i) a decrease in partial melting of the mantle toward the back-arc side, and ii) interaction between mantle wedge and subducting

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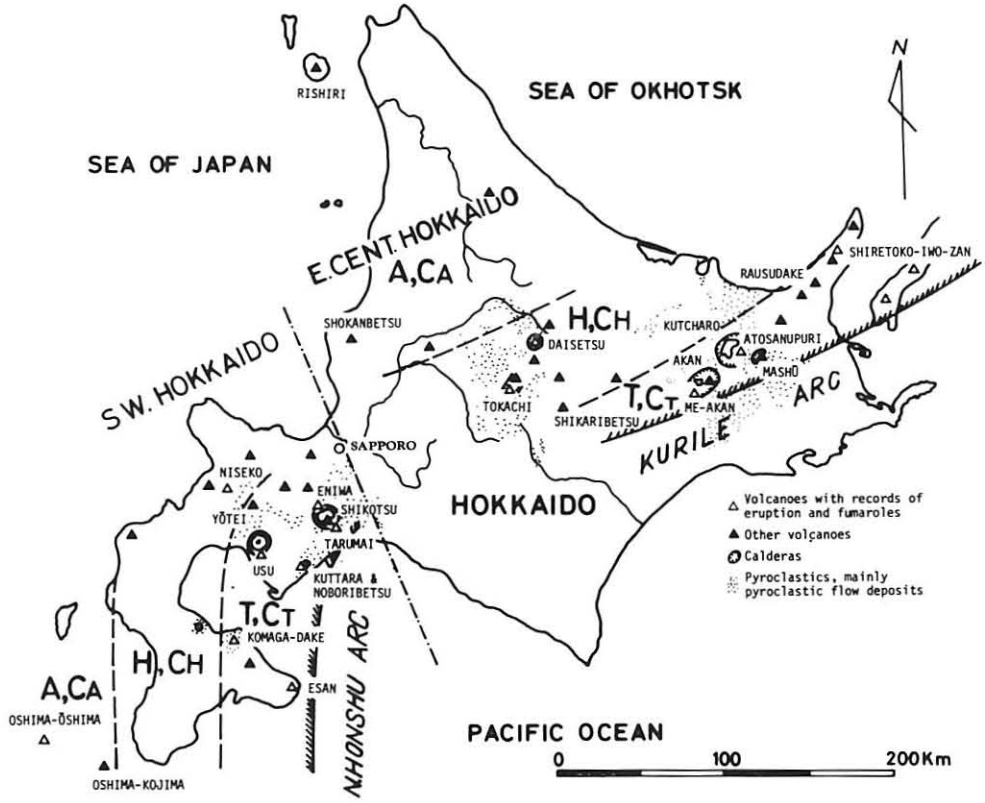


Text-fig. 1 Distribution of Quaternary volcanoes in Hokkaido (after Katsui et al., 1978). Petrographic provinces are shown by the symbols of rock series as follows: T (tholeiite basalt) & C_T (calc-alkali rock associated with T), H (high-alumina basalt) & C_H (calc-alkali rock associated with H), and A (alkali basalt) & C_A (calc-alkali rock associated with A).

plate (Fujitani and Masuda, 1981; Notsu, 1983; Tatsumi and Nakano, 1984; Nakamara et al., 1985). Recently Tatsumi and Nakano (1984), and Tatsumi (1986) emphasized that amphibole and phlogopite which are formed from a combination of slab and oceanic sediment play an important role in supply of water to the mantle wedge.

Along-arc petrochemical variations in some arcs, which are correlated with crustal thickness have been observed (Gill, 1981). The longitudinal zoning in the Kurile arc is uncertain (Gorshkov, 1969; Zhuravlev et al., 1985; Bailey et al., 1987), while abundant occurrence of felsic rocks is noticed in central Hokkaido where the crust is thick compared with the major part of the Kurile arc (Utsu et al., 1972).

This paper deals with lateral variations in $^{87}Sr/^{86}Sr$ ratios of Quaternary volcanic rocks from the Kurile arc in Hokkido and discusses the interaction between the slab and the mantle wedge.

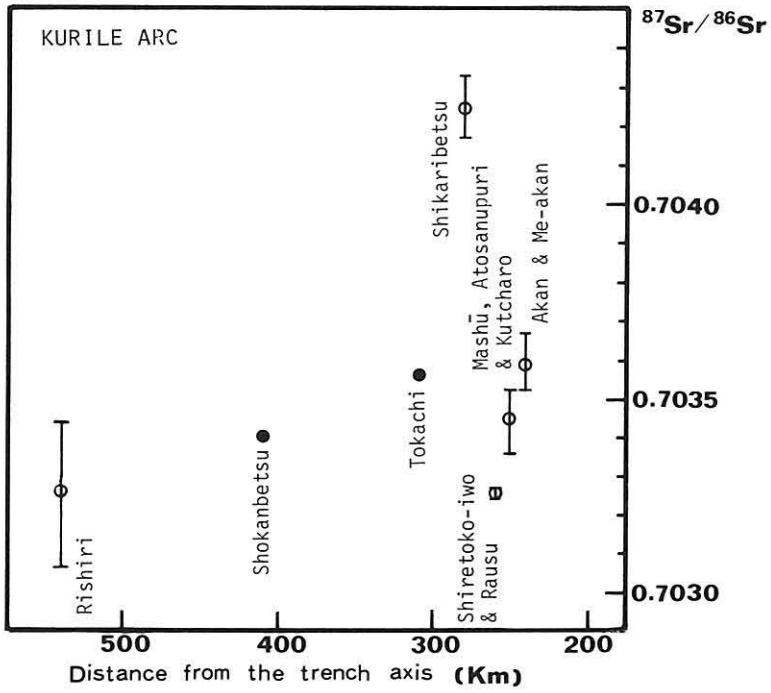
Samples and analytical method

The samples were collected from 11 volcanoes or volcano groups of the Kurile arc in Hokkaido (Text-fig. 1). Major and trace element abundances in the volcanic rocks have already been determined by Masuda et al. (1975) and Katsui et al. (1978). Sr isotope ratios of the same samples are newly obtained in this paper.

Strontium isotopic compositions were measured at the Geological Survey of Japan on a VG Isomass 54E-double collector mass spectrometer with on-line computer facilities using a single tantalum filament. All measurements have been normalized to $^{86}Sr/^{88}Sr = 0.1194$ as $(^{87}Sr/^{86}Sr)_n$. Average $^{87}Sr/^{86}Sr$ ratios of 0.708054 ± 8 (σ_m) and 0.710278 ± 9 (σ_m) were obtained for the Eimer and Amend $SrCO_3$ and NBS 987 $SrCO_3$ standards, respectively.

Results

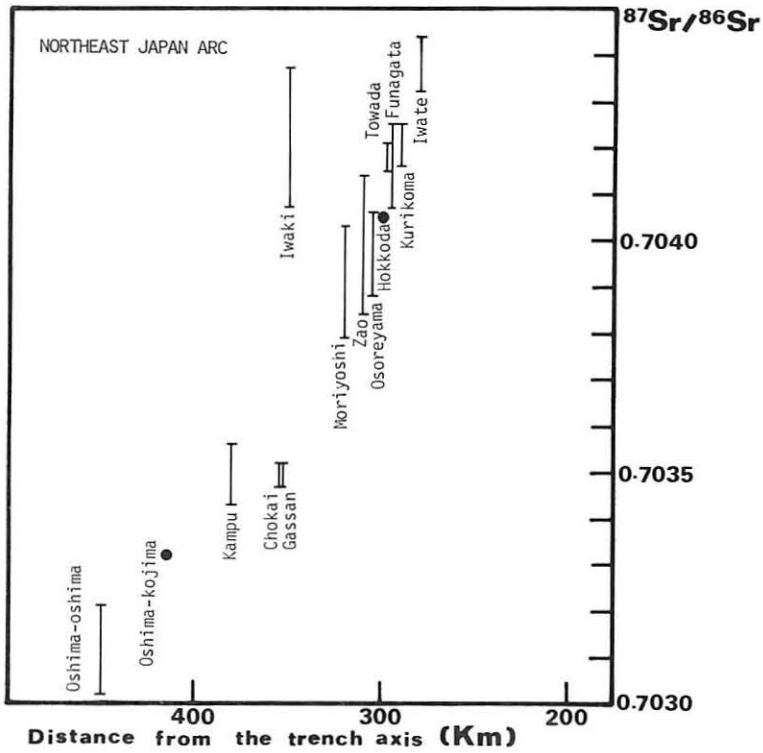
The analytical data of the samples are listed in Table 1 together with SiO_2 contents. $^{87}Sr/^{86}Sr$ ratios of igneous rocks are susceptible to crustal contamination and magma mixing. Generally speaking, the ratios increase with promotion of contamination. Ikeda et al. (1985) pointed out that calc-alkali andesites from the Daisetsu-Tokachi volcanic chain in central Hokkaido have mixing relationships between the



Text-fig. 2 Variations in $^{87}Sr/^{86}Sr$ ratios of Quaternary volcanic rocks across the Kurile arc. Open circles: mean values.

high-alumina basalt and rhyolite or dacite magmas. Furthermore, Ikeda (1984) showed that Pliocene — early Pleistocene pyroclastic flow deposits in central Hokkaido are derived from a magma produced by partial melting of lower crust. These rocks from central Hokkaido have been eliminated from consideration in order to make clear the lateral variation in $^{87}Sr/^{86}Sr$ ratios of the mantle-derived magmas.

Text-fig. 2 shows the lateral varition in $^{87}Sr/^{86}Sr$ ratios of Quaternary volcanic rocks from the Kurile arc with distance from the trench axis. As shown in Text-fig. 2, the $^{87}Sr/^{86}Sr$ ratios decrease toward the back-arc near the volcanic front (from Akan to Shiretoko-iwozan), then increase in the middle part of the arc (from Shikaribetsu to Shokanbetsu), but decrease again in the back-arc (Rishiri). The Shikaribetsu andesites have anomolously high Sr isotope ratios, which might be interpreted as due to crustal contamination or magma mixing, though it is uncertain because of insufficient data. Without the Shikaribetsu rocks, the variation pattern would not be essentially changed (Text-fig. 2). It is noticed that $^{87}Sr/^{86}Sr$ ratios of the rocks from Rishiri volcano have the lowest values in the Kurile arc. A similar pattern of $^{87}Sr/^{86}Sr$ ratio variation away from the trench axis has been observed across the Northeast Japan arc (Text-fig. 3, data from Notsu, 1983 and Kurasawa, unpublished data).

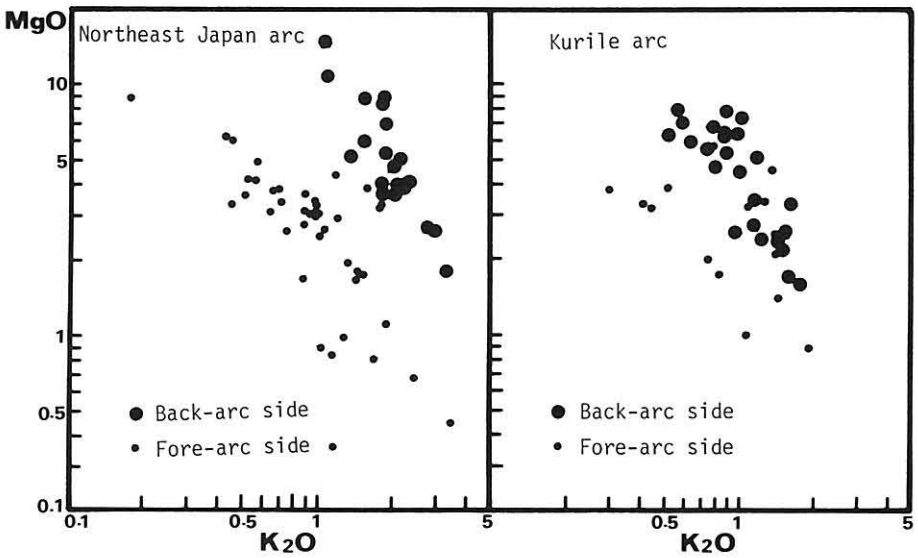


Text-fig. 3 Variations in $^{87}Sr/^{86}Sr$ ratios of Quaternary volcanic rocks across the Northeast Japan arc (data from Notsu, 1983; H. Kurasawa, unpublished data, Oshima-Ōshima, $^{87}Sr/^{86}Sr$ = 0.70302 — 0.70321, Oshima-Kojima, $^{87}Sr/^{86}Sr$ = 0.70332).

Discussion

Increasing K, Ba, Th, U, and F abundances of arc magmas from the volcanic front to back-arc side have been interpreted as due to a decease in the degree of partial melting of mantle material toward the back-arc side, since these elements have a tendency to concentrate into the liquid phase during smaller partial melting processes. However, basaltic rocks from the back-arc side of both the Kurile and Northeast Japan arcs in Hokkaido are higher in MgO contents than those from the fore-arc side at the same K_2O content (Text-fig. 4). This is inconsistent with the degree of partial melting model. Accordingly, the complex lateral variations in $^{87}Sr/^{86}Sr$ ratios of the rocks from the Kurile arc also cannot be interpreted simply by the degree of partial melting.

Decreasing $^{87}Sr/^{86}Sr$ ratios of the volcanic rocks from the fore-arc to back-arc side in the Northeast Japan, Izu-Ogasawara, and Kurile islands arcs have already been shown by Hedge and Knight (1969), Katsui et al. (1978), Nohda and Wasserburg (1981), Notsu (1983), Notsu et al. (1983), and Zhuravlev et al. (1985). Notsu (1983) pointed out that the systematic variation of the Sr isotope ratios is ascribed to oceanic sediment accompanied with the subduction slab. This model may be reasonable since the contribution of the subducting slab component becomes smaller away from the volcanic front (Notsu, 1983; Notsu et al. 1983). Zhuravlev et al. (1985) considered that the isotopic zoning ($^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$) across the arc in the Kurile islands is mainly related to heterogeneity in the source mantle although a slight contamination of the magmas by crustal material or sea water would occur beneath near the volcanic

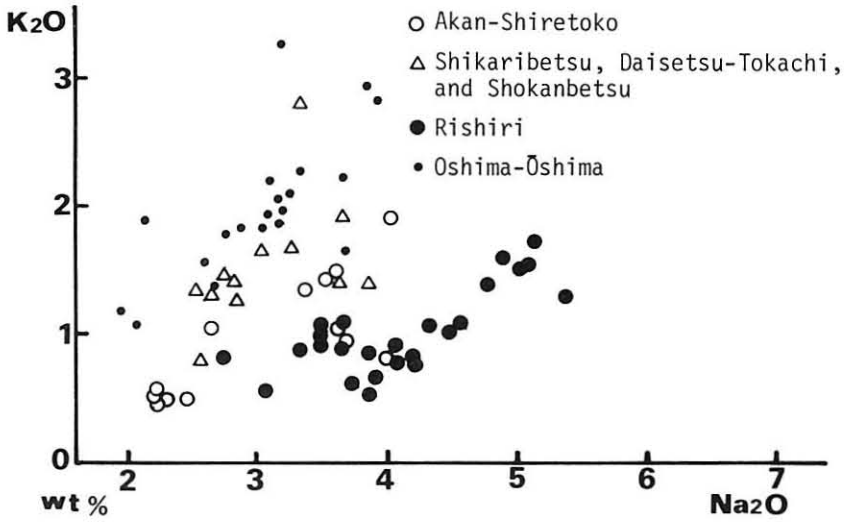


Text-fig. 4 MgO vs. K_2O log-log diagram for Quaternary volcanic rocks from the Northeast Japan and Kurile arcs in Hokkaido (data from Katsui, 1953; Matsui et al., 1967; Katsui et al., 1978; Yamamoto, 1984).

front. However, these models alone cannot explain in the complex lateral variation of $^{87}Sr/^{86}Sr$ ratios in the Kurile arc in Hokkaido.

It is a widely accepted view that fluid phase from downgoing lithosphere has a significant effect on arc magmatism (Wyllie, 1973; Fyfe and McBirney, 1975; Delany and Helgeson, 1978). This fluid phase is released through dehydration of hydrous minerals in descending slab. On the basis of available data of trace elements and isotopic ratios of Japanese Quaternary volcanic rocks, Nakamura et al. (1985) suggest that the extent of contamination of magma by the fluid phase decreases with distance from the trench. According to Tatsumi and Nakano (1984) and Tatsumi (1986), serpentine, talc, clinocholore, clay mineral, and amphibole which are formed by alteration of peridotitic minerals at the top of slab, break down beneath the fore-arc side of the volcanic front, and they cannot be directly related to the production of arc magmas. Amphibole and phlogopite which are produced in a mantle wedge by the combination of the convection in the mantle wedge and a fluid phase derived from subducting oceanic crust would decompose at around 35 kb and 40—50 kb, respectively (Tatsumi, 1986).

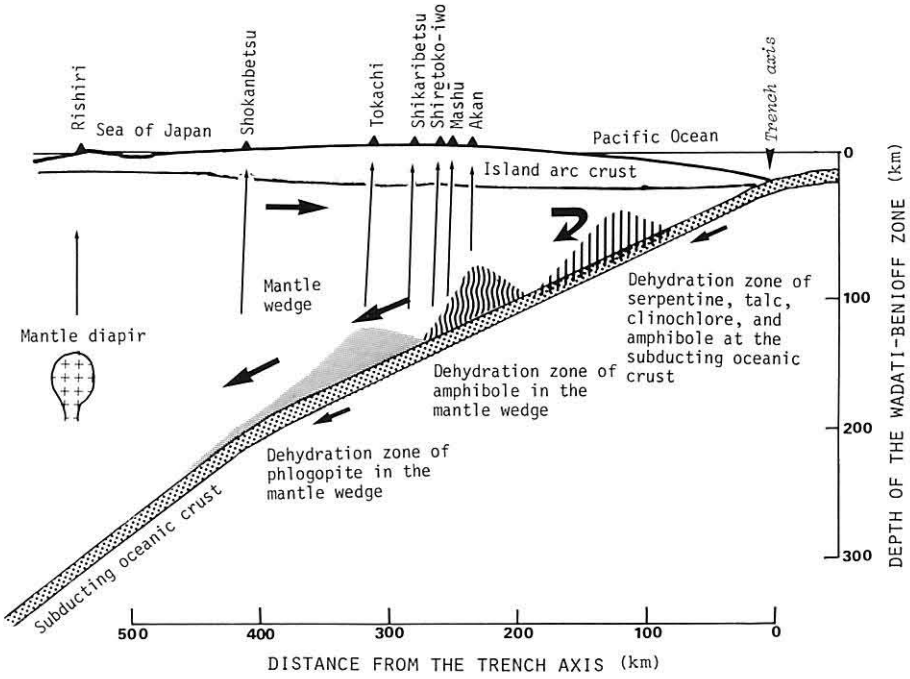
These mineral dehydrations may offer the most reasonable explanation for the variations in $^{87}Sr/^{86}Sr$ ratios of the rocks from the Kurile arc. The region near the volcanic front where volcanoes of Akan, Mashū, Shiretoko-Iwozan and Rausu are located, is possibly above the dehydration zone of amphibole in the mantle wedge. The dehydration must have proceeded from Akan to Shiretoko-Iwozan and Rausu volcanoes, because the $^{87}Sr/^{86}Sr$ ratios decrease. The middle part of the arc where Shikaribetsu and Tokachi volcano groups are located, may correspond to the phlogopite dehydration zone in the mantle wedge inferred from an increase in $^{87}Sr/^{86}Sr$



Text-fig. 5 K_2O vs. Na_2O diagram for Quaternary volcanic rocks from Hokkaido (data from Katsui, 1953; Matsui et al., 1967; Katsui et al., 1978; Yamamoto, 1984).

ratios of the rocks from these volcanoes.

$^{87}Sr/^{86}Sr$ ratios of basalt and andesite from Rishiri volcano which is located far from the volcanic front, are markedly low compared with those from the fore-arc side. Judging from the stability limit of phlogopite (40—70 kb, Kushiro et al., 1967; Tatsumi and Nakano, 1984), the fluid phase may have little effect on the composition of the rocks from Rishiri volcano which is situated above the Wadati-Benioff zone at a depth of 300 km (Notsu and Kobayashi, 1985). The Rishiri rocks are also characterized by high Na_2O/K_2O ratios (3.0—6.4, Katsui, 1953 and Matsui et al., 1967), which are markedly higher than those of rocks of the fore-arc side of the Kurile arc and Oshima-Ōshima and Ichinomegata rocks (1.0—2.0, Katsui et al., 1979 and Yamamoto, 1984) on the back-arc side of the Northeast Japan arc (Text-fig. 5). Such chemical properties of the Rishiri rocks are quite different from those commonly observed by Dickinson (1968) and Ui and Aramaki (1978) in other tranch-arc systems. Aramaki and Ui (1983) noted rare occurrence of rocks similar to those of Rishiri near the junction between two arcs in Japan. The alkali basalts from Rishiri are low in LREE/HREE ratios (Ce_N/Yb_N = 2.7—3.9) as compared with other alkali basalts from the back-arc volcanic centers, e.g. Oshima-Ōshima in Northeast Japan (Ce_N/Yb_N = 2.8—4.6) and Oki-Dogo and Hamada in Southwest Japan (Ce_N/Yb_N = 6.9—22) (Philpotts et al., 1971; Nagasawa, 1973; Kurasawa and Fujimaki, 1977; Katsui et al., 1978).



Text-fig. 6 Cartoon to illustrate arc magmatism and subducting oceanic crust across the Kurile arc. Arrows in the mantle wedge indicate the convective current.

Geochemical characters of the Rishiri rocks (Ce_N/Yb_N = 2.7—3.9, high Na_2O/K_2O = 3.0 — 6.4, and low $^{87}Sr/^{86}Sr$ = 0.70306 — 0.70345) are similar to those of the rocks of Deception island (Ce_N/Yb_N = 1.9 — 2.9, high Na_2O/K_2O = 4.4 — 14.5, and low $^{87}Sr/^{86}Sr$ = 0.70336 — 0.70347) which is located in Bransfield Strait representing an initial stage of back-arc spreading (Weaver et al., 1979). In the light of the geochemical characters mentioned above it seems probable that the Rishiri rocks are not related to the arc magmatism which involves interaction between mantle wedge and subducting lithosphere. The authors suggest that the mantle diapir yielded the Rishiri rocks has come from a mantle at a greater depth, such as source material of T- or P-type MORB.

As already discussed above, various models on the origin of arc magmas have been proposed to compromise the lateral variations in composition of volcanic rocks. As revealed in Hokkaido, the fine variations in the compositional features of arc volcanics such as $^{87}Sr/^{86}Sr$ ratios, are essential and give important constraints on the models of arc magma generation.

On the basis of the above discussion, the relationships between arc magmatism and hydrated subducting slab across the Kurile arc can be schematically illustrated in Text-fig. 6.

Table 1 SiO_2 contents and $^{87}Sr/^{86}Sr$ ratios of Quaternary volcanic rocks from the Kurile arc in Hokkaido (sample numbers refer to Katsui et al., 1978)

Volcano	No.	SiO_2 (wt %)	$^{87}Sr/^{86}Sr \pm 1\sigma$
Akan	K-10	52.43	0.703527 ± 16
	K-11	65.87	0.703568 ± 15
Me-akan	K-28	50.62	0.703676 ± 21
	K-12	57.54	0.703581 ± 17
Kutcharo	K-3	54.14	0.703481 ± 16
	K-4	71.25	0.703357 ± 21
Atosanupuri	K-5	64.26	0.703362 ± 23
Mashū	K-6	55.08	0.703469 ± 23
	K-7	52.78	0.703468 ± 17
	K-8	65.73	0.703468 ± 21
	K-9	72.96	0.703527 ± 22
Shiretoko-iwo	K-1	60.69	0.703248 ± 21
Rausu	K-2	61.76	0.703275 ± 28
Shikaribetsu	K-13	59.16	0.704174 ± 21
	K-14	61.26	0.704332 ± 17
Tokachi	K-21	46.79	0.703560 ± 15
Shokanbetsu	K-24	55.41	0.703405 ± 14
Rishiri	K-26	50.69	0.703295 ± 14
	K-27	50.78	0.703063 ± 14
	K-25	63.48	0.703454 ± 14

K-10 Augite-bearing olivine basaltic andesite, a somma lava of Akan volcano. Loc., Senpoku-toge.
K-11 Augite hypersthene andesitic welded tuff, a pyroclastic flow deposit of Akan volcano. Loc., north of the Akan caldera.

K-28 Hypersthene-bearing augite olivine andesite, Nishiyama lava of Me-akan volcano. Loc., western flank of Me-akan-dake.

K-12 Augite hypersthene andesite, a lava of Ponmachineshiri, one of the strato-cones of Me-akan-dake volcano. Loc., Northwest of the summit of Ponmachineshiri.

K-3 Augite hypersthene basalt, a somma lava of Kutcharo volcano. Loc., south of Kamisattsuru.

K-4 Augite-bearing hypersthene dacitic welded tuff, a welded part of the first pumice-flow deposit of Kutcharo volcano. Loc., a quarry of Furume, south of Bihoro.

K-5 Aphyric andesite, a somma lava of Atosanupuri volcano. Loc., eastern part of Atosanupuri caldera-wall.

K-6 Augite-bearing hypersthene andesite, a somma lava of Mashū volcano. Loc., foot of the western part of Mashū caldera.

K-7 Hypersthene andesite, a somma lava of Mashū volcano. Loc., foot of the western part of Mashū caldera.

K-8 Augite hypersthene andesite, pumice from the Ma-f pumice-flow deposit. Loc., Nijibetsu, east of Mashū caldera.

K-9 Augite hypersthene dacite, Kamuishu dome lava of Mashū caldera. Loc., Kamuishu island.

K-1 Augite hypersthene andesite, Naka-daka lava of Shiretoko-iwo-zan volcano. Loc., smmit of Naka-dake.

K-2 Augite hypersthene andesite, a dome lava of Rausudake volcano. Loc., summit of Rausu-dake.

K-13 Hypersthene andesite, Yambetsu-gawa lava, an older lava of Shikaribetsu volcano. Loc., north of Lake Shikaribetsu.

K-14 Hornblende hypersthene augite andesite, Tembo-zan dome lava, Shikaribetsu volcano.

K-21 Augite olivine basalt, a lava of Furano-dake, one of the strato-cones of Tokachi-dake volcano. Loc., summit of Furano-dake.

K-24 Hornblende- and quartz-bearing olivine augite hypersthene andesite, a lava of Shokanbetsu volcano. Loc., summit of Shokanbetsu-dake.

K-26 Olivine augite basalt, a lava of the 2nd ejecta of Rishiri volcano. Loc., eastern side of the top of Rishiri.

K-27 Olivine augite basalt, Motodomari lava of the Rishiri volcano. Loc., northern coast of Rishiri island.

K-25 Augite hypersthene andesite, a lava of the 1st ejecta of Rishiri colcano. Loc., eastern ridge of Rishiri.

Conclusions

$^{87}Sr/^{86}Sr$ ratios in volcanic rocks from the Kurile arc in Hokkaido, decrease toward the back-arc near the volcanic front, then increase at the middle part of the arc, and finally decrease again at the back-arc side. The stability limit of serpentine, talc, clinocholore, amphibole, and phlogopite, suggests that the above complex lateral variations in composition may be ascribed to difference of dehydration minerals in the mantle wedge. Beneath the volcanic front, amphibole breaks down in the mantle wedge, whereas beneath the middle part of the arc, phlogopite in the wedge decomposes.

$^{87}Sr/^{86}Sr$ ratios in the rocks from Rishiri volcano which is located far from the volcanic front on the back-arc side are markedly low compared with those from the fore-arc side. The Rishiri rocks are also characterized by high Na_2O/K_2O and low Ce_N/Yb_N compared with the rocks from the back-arc side of the Northeast Japan and Southwest Japan. The geochemical properties of the Rishiri rocks differ from those commonly observed in the back-arc of other trench-arc systems, but are similar to those of rocks related to back-arc spreading, such as those of Deception island. These geochemical characters of the Rishiri rocks suggest that the volcanism is not related to

the Kurile arc magmatism. The primitive Rishiri rocks may have been derived from a greater depth and originated from a mantle similar to the source material of T- or P-type MORB.

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