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# Kurile island-arc volcanism: structural and petrological aspects

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ABSTRACT

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This study discusses the structural and spatial characteristics of all known Kurile island-arc Quaternary volcanoes, which include 105 that are subaerial and 96 submarine. Volcanic activity in the island arc is distributed in two zones parallel to the Kurile-Kamchatka deep-sea trench. The depth to the seismo-focal zone in the frontal zone is 110-140 km and in the rear zone 160-190 km. These frontal and rear volcanic zones show distinct variations in geochemical, petrologic, and mineralogic characteristics.

Concentrations of K, Rb, Ba, Sr, F, Be, La, Ce, Nb, Zr, U, Th, Ni, and Cr in similar volcanic rocks of the rear zone are typically more than twice as high as those in rocks of the frontal zone, whereas concentrations of Fe and V are half as high in the rear-zone lavas as in those of the frontal zone. Variations in concentration along the strike of the arc are less pronounced. The average $^{87}Sr/^{86}Sr$ ratios for the frontal and rear zones are: Northern Kuriles 0.70322 and 0.70304, Middle Kuriles 0.70302 and 0.70295, and Southern Kuriles 0.70347 and 0.70306, respectively.

$^{143}Nd/^{144}Nd$ values in lavas from the frontal and rear zones are 9-10 and 7-8, respectively. $^{10}Be$ abundances in the Kurile island arc lavas range from $2.2 \cdot 10^6$ at/g to $7.9 \cdot 10^6$ at/g. No differences in $^{10}Be$ abundances corresponding to the frontal and rear-arc zones have been found.

Acid and intermediate lavas from the volcanic front are characterized by a two-pyroxene phenocryst association, while similar lavas from the rear arc have amphibole- and biotite-bearing associations. Mineral compositions (plagioclase, pyroxene, amphibole, olivine) in the two zones also show distinct differences. Plagioclase in the rear-arc lavas is less calcic, with higher K, Sr, Ba and lower Fe than in the frontal lavas. Ferromagnesian minerals in the rear-arc lavas contain less Fe and more Mg than in frontal lavas. These data are used to develop a model for magma generation related to two levels of volatile separation from the subducting lithospheric plate.

## Introduction

The geological and geophysical characteristics of submarine and subaerial volcanoes in the Kurile island arc have been studied in detail during six cruises of the R/V *"Vulkanolog"* and field studies on several of the islands (Fig. 1).

The work included morphostructural studies, seismic reflection and magnetic surveys, dredge sampling and analysis of volcanic rocks, water samples, and sediments from submarine volcanoes. Analyses of samples from subaerial volcanoes were included. The work included about 1100 bulk-rock major-element analyses, over 1000 determinations of trace elements (Rb, Li, Ba, Sr, V, Cr, Ni, Co, Cu, Zn), 650 determinations of Be, Ba and F, 150 determinations of U, Th, Nb, Te, Zr, and Hf, and more than 130 rare-earth element analyses. We have also completed 2000 electron-microprobe analyses, 220 Sr-isotopic and 26 Nd-isotopic measurements, and several $^{10}Be$ determinations.

Detailed analyses of volcanic rocks from the Kurile islands have been reported in Avdeiko et al. (1985, 1986) Antonov et al. (1987), Volynets et al. (1988) Volynets et al. (1990a), etc. Models for magma genesis in the arc have been developed by Popolitov and Volynets (1981), Avdeiko et al. (1986), and Avdeiko (1989). The extensive geochemical and petrologic work discussed here has allowed us to develop a more accurate model for magma genesis in the subaerial and submarine portions of the Kurile arc.

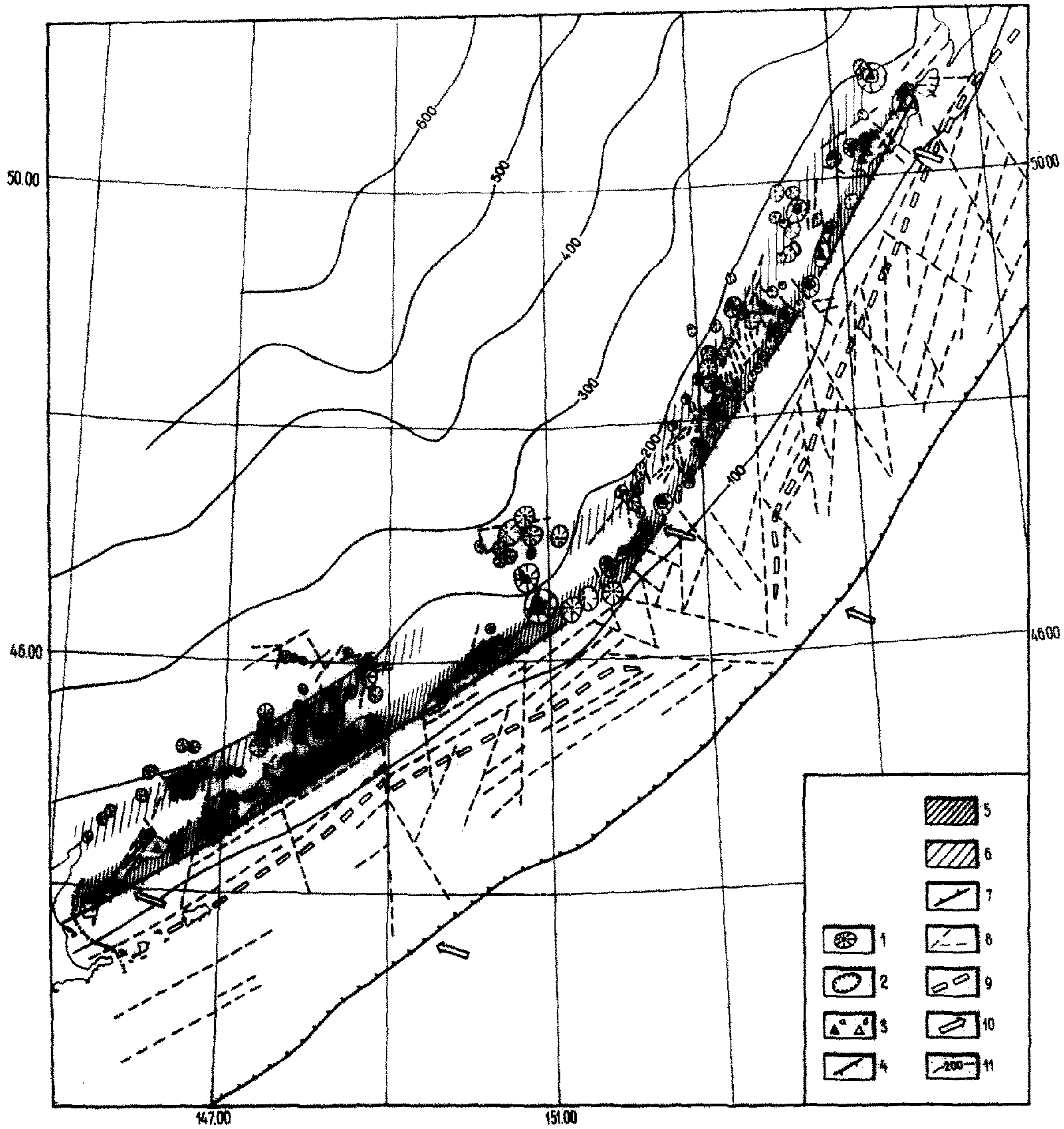

Fig. 1. Structural position of the Kurile island-arc volcanoes. *1* = submarine volcanoes; *2* = submarine calderas; *3* = active (a) and extinct (b) subaerial volcanoes; *4* = volcanic front; *5* = frontal volcanic zone; *6* = rear-arc volcanic zone; *7* = deep-sea trench axis; *8* = fractures revealed by seismic reflection data during Legs of R/V "*Vulkanolog*"; *9* = axis of frontal (non-volcanic) arc; *10* = direction of the Pacific plate motion; *11* = isodepths (km) down to the seismofocal plane.

## Structural and spatial characteristics of volcanoes

Figure 1 shows the distribution of 96 submarine and 105 subaerial volcanoes, 42 of the latter are active. The estimates of activity are based upon Gorshkov (1958). The majority of volcanoes are of Quaternary although older edifices also exist. Nearly all of them form chains which are oriented at a sharp angle to the general strike of the arc. The positions of these across-strike chains of volcanoes may be controlled by faults or fractures in the arc crust. These may most likely be fractures, as no distinct objects are identified at the ends of the chains (Sergeev, 1976).

The existence of fractures within the Kurile arc has been confirmed by seismological data (Simbireva et al., 1976). A similar system of fractures (without volcanoes) has been identified by seismic profiling in the region between the deep-sea trench and the volcanic front (Fig. 1).

These fractures appear to be magma-supplying. Individual volcanoes located at distances of 3–7 km from each other and belonging to the same chain possibly have common shallow magma chambers. In Fig. 2 these volcanoes form the first peak. The second peak can reflect more deeply rooted relations between volcanoes located on one and the same fracture. The distances between volcanoes, located on different fractures (i.e, belonging to different chains) vary greatly, the maximum being 56–79 km.

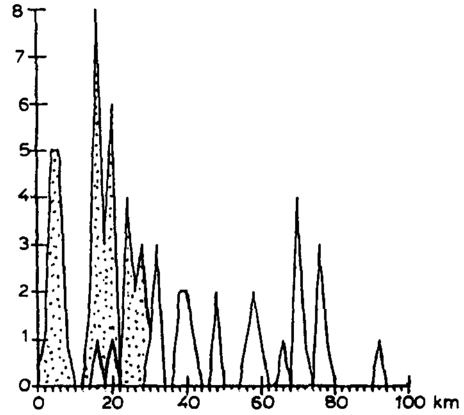

Fig. 2. Space histogram between neighbouring volcanoes. Shaded areas show the distance between closest volcanoes within one volcanic chain (on one fracture).

TABLE 1

Some features of the Kurile island arc

| Parameters | North Kuriles | Middle Kuriles | South Kuriles |
|---|---|---|---|
| $L_1$ (km) | 200 | 160 | 220 |
| $L_2$ (km) | 210 | 180 | 270 |
| $H_1$ (km) | 120–140 | 120 | 110–120 |
| $H_2$ (km) | 170–190 | | 160 |
| $\alpha$ (°) | 75–85 | 51–74 | 45–50 |
| $\beta$ (°) | 48–55 | 50 | 38–46 |
| $D$ (km) | 85 | 105 | 115 |
| $d_1$ (km) | 15 | 15–20 | 20 |
| $d_2$ (km) | 25 | | 30–35 |
| $d_3$ (km) | 20 | | 20–25 |
| $\sigma_F$ | 5.1 | | 5.0 |
| $\sigma_I$ | 1.3 | | 0.9 |
| $\sigma_R$ | 2.6 | | 1.9 |
| $\sigma_W$ | 0.9 | | 0.5 |
| $V$ | 9 | 9.5 | 10 |
| $M$ (km) | 25–36 | 27–30 | 34–44 |

* $L_1$ is the shortest distance from the trench to the volcanic front, $L_2$ is the same along the line of the Pacific plate movement; $H_1$ and $H_2$ = depth to the seismofocal zone beneath the volcanic front and beneath the second (rear-arc) volcanic zone, respectively (Abdurakhmanov et al., 1981); $\alpha$ = angle between the direction of subduction and the volcanic front; $\beta$ = slope of subduction plane; $D$ = general width of the volcanic arc; $d_1$ and $d_3$ = width of the main (frontal) and second (rear-arc) volcanic zones, respectively, $d_2$ is the width of the zone of decreased activity between the frontal and rear-arc zones; $\sigma_F$, $\sigma_I$, $\sigma_R$, $\sigma_W$ = density of volcanoes in the volcanic zones, see Fig. 3; $V$ = subduction rate (Sergeev and Krasny, 1987); $M$ = thickness of the crust (Zlobin, 1987).

One significant parameter of island-arc systems is the height of the active volcanoes above the Benioff zone. The volcanic front in the Kuriles consists of two nearly straight sections linked by a sharp bend (22–23°) in the region of the Boussole Strait (see Fig. 1). It is useful to distinguish the region around the change in strike as the Middle Kuriles. The main parameters of the Kurile island-arc structure are given in Table 1. The direction of the Pacific plate motion (Minster and Jordan, 1978) within the North Kuriles is almost perpendicular to the line of the volcanic front.

We can treat this as a normal subduction of the Pacific plate under Eurasia, whereas in the South Kuriles an oblique subduction is observed. The volcanic front belt follows the bends of isodepths

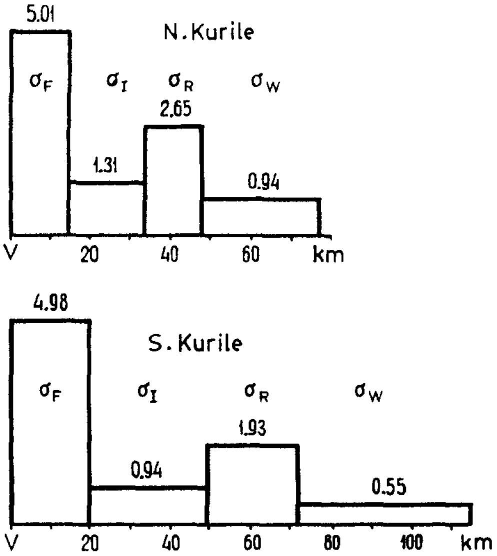

Fig. 3. Histogram of volcanic density per unit area ($\sigma$) across Kurile island arc relative to the distance from volcanic front ($V$). Figures designate volcanic density per 1000 km$^2$.

down to the seismo-focal zone (according to Tarakanov, 1987). This change in orientation of the seismic zone is not manifested in the geometry of the trench.

The distribution of volcanoes in the South and North Kuriles shows distinct regularities across strike. Histograms constructed separately for the South and North Kuriles, which show the number of volcanoes per unit area (areal density of volcanos) vs. the distance from the volcanic front, have a bimodal distribution (Fig. 3). The main peak indicates the frontal zone, whose width varies from 15 to 20 km. More than 55% of all submarine and subaerial volcanoes are concentrated here. The second peak characterizes the zone of increased volcanic activity of a rear-arc zone which extends parallel to the strike of the main arc, 40–60 km from the volcanic front in the north and 55–75 km from it in the south. 20–25% of the volcanoes are located in this rear-arc zone. Subaerial volcanoes comprise the majority (87%) of the frontal-arc edifices, while submarine volcanoes are in the majority (81%) in the rear-arc area.

From the volcanic front towards the Sea of Okhotsk, we can observe the following volcanic zones: (1) a main frontal arc with 5.0–5.1 volcanoes per 1000 km$^2$; (2) a zone of decreased volcanic activity with 0.9–1.3 volcanoes per 1000 km$^2$; (3) a second peak of volcanic activity (termed here the rear-arc zone), with 1.5 to 2.1 volcanoes per 1000 km$^2$; and (4) another zone of waning activity with 0.4 to 0.9 volcanoes per 1000 km$^2$.

The spacing between the frontal and rear-arc volcanic zones varies inversely with the slope of the Benioff zone; in the north the Benioff zone is steeper and the width of volcanic zones is 85 km, while in the south, where the slab has a shallower dip, it is 115 km wide. However, the difference in depth to the Benioff zone beneath the frontal and rear-arc volcanic zones is quite constant at about 50 km; the absolute depths to the Benioff zone are somewhat greater in the North Kuriles (Table 1).

The existence of two distinct peaks in volcanic activity across the Kurile Arc suggests that there are two regions of magma generation related to two different depth regions along the subducted slab (Avdeiko, 1989).

## Petrology and geochemistry of volcanic rocks

The transverse petrochemical zonation in the Kurile island arc is well-known (Gorshkov, 1976; Markhinin and Stratula, 1971; Piskunov, 1975; Piskunov, 1987). In recent years, across-arc variations in a number of rare and trace elements, isotopic ratios, and mineral compositions have been revealed (Abdurakhmanov et al., 1986; Avdeiko et al., 1985; 1986; Antonov et al., 1987; Volynets et al., 1988; Yermakov et al., 1987). Considering the volcanic rocks from both subaerial and submarine volcanoes, it can be seen that the concentrations of K, Rb, Ba, Sr, F, Be, La, Ce, Nb, Zr, U, Th, Mg, Ni, and Cr increase from the volcanic front to the rear-arc, whereas the concentrations of Fe and V, as well as values of $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd, decrease.

The differences between the frontal and rear-arc lavas are clearly shown in Table 2 and Fig. 4. Representative analyses are shown normalized to values for undepleted mantle (Wood, 1979). The hydromagmatophile elements have distinctly higher concentrations in the rear-arc lavas. However, it should be emphasized that the volcanics there have all the characteristics of arc eruptives. The normalized plots (Fig. 4) show the high left-to-right slope, the Nb-minimum, and Sr-maximum

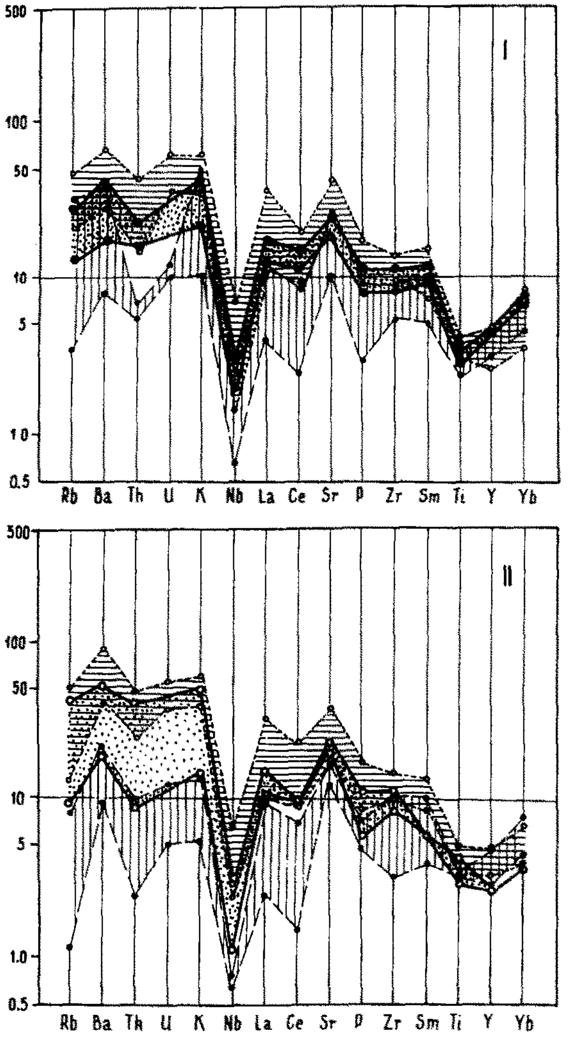

Fig. 4. Normalized distribution of hygromagmatophile rare elements as related to undepleted mantle in the Kurile island-arc volcanic basalts. (I) North Kuriles, (II) South Kuriles. *1* = frontal zone; *2* = intermediate zone; *3* = rear-arc zone and zone of waning volcanic activity. Shaded areas indicate areas between minimum and maximum element concentrations of corresponding zones.

characteristic of most island-arc samples. The Kurile rear-arc volcanism is neither morphologically nor chemically similar to back-arc spreading volcanism observed in places like the Mariana Trough, Lau Basin or Scotia Sea (Tarney et al., 1981).

Lavas from the zone between the frontal and the rear arcs include examples of both compositional extremes. This suggests that, if there are two zones of magma generation, there may also be a zone of mixing between them.

The differences between the frontal and rear-arc zones are clearly shown in rare-earth and isotopic data. Frontal-arc lavas have flat patterns (low La/Yb, Fig. 5) while rear-arc lavas are typically enriched in light rare earths. Both across-arc and along-arc variations in average and minimum values of $^{87}Sr/^{86}Sr$ occur (Fig. 6). Rear-arc lavas generally have lower ratios than those of the frontal arc. In both rear-arc and frontal-arc zones, the minimum of $^{87}Sr/^{86}Sr$ tends to increase from the Middle Kuriles to the north and south. Rear-arc lavas fall largely within the mantle array in a $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ plot (Fig. 7), while frontal-arc lavas tend to have higher values of both $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$. Except for the Brouton transversal zone (Middle Kuriles), there is no significant difference in the groups.

Increased (as compared to MORB) concentrations of $^{10}Be$ in island-arc lavas may indicate the participation of pelagic sediments of the subducting plate in the process of island-arc magma genesis. Determinations of $^{10}Be$ abundances in some Kurile volcanic rocks were carried out at the Carnegie Institution, U.S.A. It has been stated that concentrations of $^{10}Be$ in the lavas from historic eruptions of Kurile volcanoes range with $2.2–7.9 \cdot 10^6$ at/g (Morris et al., 1989; Tsvetkov et al., 1989). No differences have been found in $^{10}Be$ abundances between the frontal and rear zones. Calculations using the formula suggested by F. Tera and coauthors (Tera et al., 1986) show that the maximum proportion of the pelagic sedimentary component in the Kurile lavas does not exceed 4% and averages about 2% (Fig. 8) It should be emphasized that recent experimental work (Tatsumi and Isoyama, 1988) has shown the high mobility of Be in a fluid phase. Transfer of $^{10}Be$ may be feasible by a fluid flow which occurs in the process of dehydration of the oceanic plate in the subduction zone (Tatsumi and Isoyama, 1988).

Distinct differences also occur in mineral associations and mineral compositions in the frontal- and rear-zone suites (Volynets et al., 1990a). Intermediate and acid lavas from the volcanic front are characterized by two-pyroxene phenocryst associations; similar lavas from the rear-arc

TABLE 2

Average composition of Quaternary lavas of the Kurile Island Arc volcanoes

| | Basalts | | | Basaltic andesites | | | Andesites | | | Acid rocks | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F | I | R | F | I | R | F | I | R | F | I | R |
| *Northern Kuriles* | | | | | | | | | | | | |
| $SiO_2$ (wt.%) | 51.24 | 50.87 | 50.31 | 50.94 | 54.99 | 55.11 | 59.64 | 58.41 | 59.23 | 66.13 | – | – |
| $TiO_2$ | 0.84 | 0.86 | 0.88 | 0.78 | 0.72 | 0.67 | 0.73 | 0.72 | 0.54 | 0.71 | – | – |
| $Al_2O_3$ | 18.57 | 18.37 | 18.14 | 18.09 | 18.15 | 18.18 | 17.02 | 17.05 | 17.67 | 15.03 | – | – |
| $Fe_2O_3$ | 4.23 | 3.64 | 4.38 | 3.33 | 3.54 | 3.50 | 3.39 | 3.51 | 2.95 | 2.32 | – | – |
| FeO | 5.99 | 5.50 | 5.07 | 5.50 | 4.43 | 3.61 | 4.12 | 4.35 | 2.97 | 3.30 | – | – |
| MnO | 0.21 | 0.17 | 0.19 | 0.19 | 0.17 | 0.20 | 0.18 | 0.18 | 0.18 | 0.17 | – | – |
| MgO | 4.58 | 5.03 | 5.24 | 3.67 | 4.06 | 4.27 | 2.60 | 3.19 | 2.76 | 1.34 | – | – |
| CaO | 10.25 | 10.15 | 10.30 | 8.63 | 8.54 | 8.14 | 6.90 | 7.07 | 6.61 | 4.37 | – | – |
| $Na_2O$ | 2.61 | 2.82 | 2.93 | 3.04 | 3.16 | 3.14 | 3.54 | 3.31 | 3.57 | 4.30 | – | – |
| $K_2O$ | 0.62 | 1.20 | 1.62 | 0.80 | 1.40 | 1.80 | 0.93 | 1.50 | 2.17 | 1.23 | – | – |
| $P_2O_5$ | 0.14 | 0.26 | 0.24 | 0.15 | 0.19 | 0.28 | 0.17 | 0.19 | 0.24 | 0.17 | – | – |
| LOI | 0.50 | 0.73 | 0.63 | 0.65 | 0.40 | 0.94 | 0.58 | 0.43 | 0.95 | 0.74 | | |
| Rb (ppm) | 10.6 | 20.8 | 29.8 | 12.3 | 28.7 | 40.5 | 13.3 | 30 | 54.7 | 16.7 | – | – |
| Li | 5.2 | 6.9 | 5.9 | 6.0 | 7.8 | 7.9 | 8.0 | 8.8 | 9.7 | 9.8 | – | – |
| Ba | 155 | 277 | 390 | 210 | 314 | 544 | 237 | 320 | 617 | 317 | – | – |
| Sr | 376 | 578 | 733 | 390 | 502 | 653 | 352 | 458 | 615 | 280 | – | – |
| V | 391 | 384 | 424 | 287 | 263 | 306 | 180 | 214 | 187 | 74 | – | – |
| Cr | 41 | 89 | 64 | 32.1 | 74 | 64 | 20.6 | 27 | 32 | 15.7 | – | – |
| Co | 31 | 31 | 30 | 25 | 25.7 | 23 | 19 | 23 | 15 | 9.4 | – | – |
| Ni | 20 | 61.5 | 45 | 18 | 39.8 | 47 | 10 | 17 | 23 | 7.3 | – | – |
| Cu | 86 | 80 | 88.5 | 72 | 64 | 47 | 40 | 41 | 29 | 21.2 | – | – |
| Zn | 103 | 91 | 97.5 | 97 | 92 | 92 | 92 | 99 | 81 | 98 | – | – |
| Pb | 3.3 | 3.75 | 3.9 | 4.2 | 4.5 | 4.3 | 4.6 | 4.6 | 5.2 | 7.1 | – | – |
| Sn | 1.65 | 1.85 | 1.5 | 1.7 | 1.8 | 1.45 | 1.4 | 1.6 | 1.5 | 1.4 | – | – |
| W | 0.40 | 0.39 | 0.40 | 0.44 | 0.52 | 0.50 | 0.47 | 0.58 | 0.63 | 0.54 | – | – |
| Mo | 1.1 | 1.0 | 1.3 | 1.4 | 1.5 | 3.0 | 1.6 | 2.0 | 1.95 | 4.0 | – | – |
| Be | 0.49 | 0.73 | 0.77 | 0.49 | 0.73 | 0.81 | 0.54 | 0.80 | 0.85 | 0.54 | – | – |
| B | 41 | 31 | 31 | 46 | 30 | 33 | 45 | 32 | 32 | 60 | – | – |
| F | 269 | 387 | 426 | 319 | 406 | 324 | 342 | 331 | 316 | 368 | – | – |
| U | 0.34 | 1.27 | 1.17 | 0.42 | 1.11 | 1.47 | 0.57 | 1.30 | 2.03 | 0.66 | – | – |
| Th | 0.82 | 2.60 | 2.36 | 0.88 | 2.61 | 3.82 | 1.27 | 3.08 | 4.88 | 1.28 | – | – |
| Nb | 1.5 | 2.1 | 2.7 | 1.7 | 2.8 | 2.0 | 1.7 | 2.2 | 3.0 | 1.8 | – | – |
| Ta | – | 0.1 | – | – | – | 0.3 | – | 0.1 | 0.2 | 0.4 | – | – |
| Zr | 65.5 | 99 | 118 | 89 | 131 | 152 | 148 | 185 | 182 | 128 | – | – |
| Hf | 1.8 | 2.65 | 2.7 | 1.8 | 2.75 | 2.4 | 2.2 | 2.6 | 2.8 | 2.55 | – | – |
| *n* | 16 | 4 | 10 | 21 | 7 | 14 | 19 | 7 | 13 | 6 | – | – |
| *Middle Kuriles* | | | | | | | | | | | | |
| $SiO_2$ (wt.%) | 51.93 | 51.94 | 50.31 | 56.16 | 54.96 | 54.94 | 58.98 | 58.95 | 60.52 | 68.39 | 67.27 | 71.29 |
| $TiO_2$ | 0.60 | 0.73 | 0.91 | 0.85 | 0.80 | 0.73 | 0.74 | 0.82 | 0.56 | 0.33 | 0.63 | 0.26 |
| $Al_2O_3$ | 18.81 | 18.74 | 17.50 | 17.60 | 17.44 | 17.36 | 16.98 | 16.35 | 17.04 | 14.98 | 14.77 | 13.95 |
| $Fe_2O_3$ | 2.41 | 2.81 | 2.86 | 2.61 | 2.89 | 2.93 | 3.84 | 2.77 | 2.77 | 1.77 | 1.55 | 1.09 |
| FeO | 6.41 | 6.63 | 5.47 | 5.57 | 6.32 | 4.53 | 3.07 | 5.60 | 2.97 | 1.04 | 4.09 | 1.23 |
| MnO | 0.18 | 0.18 | 0.16 | 0.18 | 0.18 | 0.19 | 0.18 | 0.16 | 0.16 | 0.11 | 0.14 | 0.10 |
| MgO | 5.19 | 5.19 | 7.78 | 3.64 | 4.29 | 4.97 | 3.34 | 3.35 | 2.88 | 1.21 | 1.07 | 0.65 |
| CaO | 10.15 | 10.36 | 9.90 | 8.12 | 8.81 | 8.26 | 6.93 | 7.35 | 6.23 | 2.77 | 3.68 | 2.03 |
| $Na_2O$ | 2.73 | 2.47 | 2.80 | 3.32 | 2.88 | 3.13 | 3.47 | 3.07 | 3.47 | 4.06 | 4.07 | 4.00 |

TABLE 2 (continued)

| | Basalts | | | Basaltic andesites | | | Andesites | | | Acid rocks | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F | I | R | F | I | R | F | I | R | F | I | R |
| *Middle Kuriles* | | | | | | | | | | | | |
| $K_2O$ (wt.%) | 0.74 | 0.55 | 1.28 | 1.05 | 0.94 | 1.63 | 1.56 | 1.23 | 2.07 | 2.41 | 1.90 | 3.17 |
| $P_2O_5$ | 0.15 | 0.11 | 0.25 | 0.16 | 0.19 | 0.24 | 0.17 | 0.16 | 0.21 | 0.09 | 0.12 | 0.09 |
| LOI | 0.53 | 0.15 | 0.51 | 0.36 | 0.51 | 0.81 | 0.29 | 0.23 | 1.08 | 2.47 | 0.48 | 2.01 |
| Rb (ppm) | 13.3 | 8.2 | 23 | 15.5 | 16.2 | 30.4 | 23.6 | 21.6 | 41.8 | 55 | 25.5 | 69.7 |
| Li | 5.3 | 5.8 | 6.3 | 5.5 | 7.2 | 7.7 | 6.5 | 9.5 | 10.6 | 4 | 11.8 | 11.2 |
| Ba | 153 | 165 | 302 | 300 | 212 | 419 | 344 | 304 | 532 | 490 | 365 | 832 |
| Sr | 368 | 398 | 661 | 421 | 364 | 569 | 427 | 317 | 587 | 370 | 268 | 291 |
| V | 330 | 388 | 320 | 232 | 432 | 271 | 233 | 301 | 206 | 70 | 43 | 45 |
| Cr | 92 | 59.5 | 258 | 33 | 41 | 129 | 13 | 24 | 55 | bl | 16 | 10.2 |
| Co | 33 | 35 | 35 | 29 | 29 | 27 | 27 | 23 | 15 | 13 | 18 | 6.2 |
| Ni | 33 | 29 | 121 | 14.4 | 25 | 63 | 8.5 | 14.6 | 30 | – | 16 | 10.7 |
| Cu | 72 | 88 | 47 | 39.5 | 95 | 44 | 37 | 47 | 33 | 8 | 36 | 6.1 |
| Zn | 119 | 118 | 93 | 122 | 115 | 94 | 95 | 110 | 91 | 58 | 109 | 55 |
| Pb | 3.15 | 3.2 | 3.65 | 6.35 | 7.4 | 5.8 | 4.65 | 6.4 | 6.3 | – | 9.3 | 6.9 |
| Sn | 1.5 | 1.5 | 1.85 | 1.7 | 1.8 | 1.8 | 1.6 | 2.1 | 1.7 | – | 2.2 | 1.7 |
| W | 0.35 | 0.24 | 0.45 | 0.45 | 0.41 | 0.34 | 0.45 | 0.48 | 0.71 | 0.48 | 0.57 | 0.98 |
| Mo | 1.0 | 1.1 | 2.95 | 1.0 | 1.6 | 2.6 | 1.0 | 1.9 | 2.3 | – | 4.0 | 1.9 |
| Be | 0.43 | 0.53 | 0.81 | 0.52 | 0.55 | 0.82 | 0.40 | 0.57 | 0.85 | – | 0.52 | 0.72 |
| B | 44 | 36 | 27 | 38 | 45 | 29 | 45 | 70 | 38 | – | 58.5 | 28 |
| F | 197 | 278 | 370 | 393 | 302 | 373 | 130 | 456 | 446 | – | 512 | 254 |
| U | 0.53 | 0.42 | 0.90 | 1.05 | 0.70 | 1.27 | 1.1 | 1.17 | 1.42 | – | 2.0 | 2.95 |
| Th | 1.43 | 0.88 | 2.13 | 2.25 | 1.39 | 2.99 | 2.9 | 2.48 | 3.68 | – | 3.2 | 7.38 |
| Nb | 2.1 | – | 3.75 | 2.1 | – | 3.15 | 1.3 | – | 3.4 | – | 3.0 | 3.7 |
| Ta | – | – | 0.30 | – | – | – | – | – | – | – | – | 0.25 |
| Zr | 130 | – | 181 | 165 | – | 140 | 130 | – | 175 | – | 180 | 190 |
| Hf | 2.6 | – | 3.0 | 2.0 | – | 3.1 | 3.4 | – | 3.1 | – | 6.0 | 3.2 |
| *n* | 4 | 3 | 3 | 3 | 6 | 4 | 2 | 5 | 3 | 1 | 2 | 2 |
| *Southern Kuriles* | | | | | | | | | | | | |
| $SiO_2$ (wt.%) | 50.79 | 51.50 | 51.49 | 54.52 | 54.37 | 54.82 | 60.07 | 58.50 | 60.83 | 67.29 | – | 64.61 |
| $TiO_2$ | 0.82 | 0.91 | 0.94 | 0.88 | 0.89 | 0.76 | 0.72 | 0.68 | 0.52 | 0.64 | – | 0.35 |
| $Al_2O_3$ | 19.15 | 18.29 | 18.19 | 17.96 | 17.46 | 17.45 | 16.60 | 17.41 | 16.91 | 14.56 | – | 14.93 |
| $Fe_2O_3$ | 3.27 | 3.34 | 2.91 | 3.22 | 3.03 | 3.03 | 3.13 | 2.36 | 2.51 | 2.57 | – | 2.14 |
| FeO | 7.10 | 6.20 | 5.54 | 6.18 | 5.93 | 4.88 | 4.51 | 4.66 | 3.27 | 2.93 | – | 1.89 |
| MnO | 0.19 | 0.18 | 0.16 | 0.18 | 0.19 | 0.18 | 0.16 | 0.15 | 0.17 | 0.12 | – | 0.16 |
| MgO | 4.69 | 5.21 | 5.07 | 3.97 | 4.37 | 4.10 | 2.94 | 3.13 | 2.18 | 1.31 | – | 1.38 |
| CaO | 10.65 | 9.56 | 9.85 | 8.78 | 8.34 | 8.29 | 7.01 | 6.56 | 5.89 | 4.27 | – | 4.12 |
| $Na_2O$ | 2.26 | 2.78 | 2.80 | 2.76 | 3.10 | 3.09 | 3.19 | 3.32 | 3.52 | 3.90 | – | 3.99 |
| $K_2O$ | 0.39 | 1.17 | 1.39 | 0.57 | 1.37 | 1.70 | 0.83 | 1.75 | 2.31 | 1.06 | – | 2.67 |
| $P_2O_5$ | 0.13 | 0.27 | 0.26 | 0.13 | 0.22 | 0.23 | 0.11 | 0.21 | 0.20 | 0.10 | – | 0.17 |
| LOI | 0.50 | 0.48 | 1.01 | 0.87 | 0.69 | 1.11 | 0.63 | 1.14 | 1.37 | 1.27 | – | 3.56 |
| Rb (ppm) | 5.7 | 28.4 | 27.8 | 8.5 | 31.5 | 40.1 | 11.8 | 38.5 | 51.4 | 18.6 | – | 69.8 |
| Li | 5.0 | 5.6 | 3.8 | 5.7 | 6.9 | 5.9 | 7.8 | 8.0 | 6.7 | 6.1 | – | 8.0 |
| Ba | 133 | 286 | 365 | 172 | 316 | 475 | 240 | 465 | 675 | 289 | – | 1013 |
| Sr | 303 | 479 | 608 | 290 | 441 | 530 | 287 | 416 | 452 | 180 | – | 393 |
| V | 511 | 351 | 361 | 375 | 222 | 293 | 230 | 195 | 164 | 77 | – | 79 |
| Cr | 86 | 119 | 117 | 53 | 57 | 80 | 24 | 72.5 | 21 | 13.7 | – | 18 |
| Co | 32 | 35 | 29 | 29 | 27.5 | 27 | 20 | 23.5 | 17 | 11.5 | – | 12 |

TABLE 2 (continued)

| | Basalts | | | Basaltic andesites | | | Andesites | | | Acid rocks | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F | I | R | F | I | R | F | I | R | F | I | R |
| *Southern Kuriles* | | | | | | | | | | | | |
| Ni | 27 | 47 | 45 | 16 | 29.5 | 21 | 12.1 | 19 | 14 | 6.0 | – | 7.3 |
| Cu | 68 | 53 | 62 | 54 | 38 | 43 | 34 | 34 | 20 | 21 | – | 11 |
| Zn | 108 | 123 | 104 | 106 | 104 | 98 | 99 | 96 | 89 | 87 | – | 70 |
| Pb | 5.7 | 2.2 | 3.2 | 3.15 | 3.9 | 4.9 | 5 | 7.45 | 4.85 | 7.15 | – | 11.05 |
| Sn | 1.8 | 1.4 | 1.3 | 1.4 | 1.6 | 1.1 | 1.5 | 2.6 | 1.2 | 1.7 | – | 1.25 |
| W | 0.20 | 0.30 | 0.43 | 0.26 | 0.61 | 0.44 | 2.52 | 0.78 | 0.94 | 0.60 | – | 1.08 |
| Mo | 2.7 | 1.7 | 3.1 | 1.15 | 1.9 | 2.95 | 5.3 | 3.5 | 4.7 | 2.3 | – | 5.3 |
| Be | 0.39 | 0.88 | 0.93 | 0.43 | 0.91 | 1.01 | 0.43 | 1.17 | 1.04 | 0.39 | – | 1.4 |
| B | 17.5 | 38 | 66 | 22.5 | 57 | 50 | 39 | 83.5 | 71 | 51 | – | 104 |
| F | 325 | 320 | 461 | 314 | 428 | 476 | 300 | 395 | 367 | 400 | – | 327 |
| U | 0.23 | 1.0 | 1.30 | 0.47 | 1.30 | 1.6 | 0.50 | 1.66 | 2.31 | 0.82 | – | 2.73 |
| Th | 0.52 | 2.49 | 3.02 | 1.06 | 3.65 | 4.46 | 0.93 | 5.14 | 0.59 | 1.65 | – | 7.28 |
| Nb | 0.5 | 1.4 | 2.55 | 1.5 | 2.3 | 2.5 | 1.2 | 2.8 | 3.7 | 1.5 | – | 3.7 |
| Ta | – | – | – | – | 0.3 | – | – | 0.4 | 0.5 | – | – | 0.25 |
| Zr | 72.5 | 106 | 150 | 82.5 | 133 | 148 | 129 | 188 | 161 | 176 | – | 135 |
| Hf | 1.55 | 2.1 | 2.1 | 2.65 | 2.9 | 2.2 | 2.8 | 4.1 | 2.3 | 3.7 | – | 2.3 |
| *n* | 5 | 3 | 8 | 6 | 4 | 9 | 8 | 5 | 9 | 5 | – | 2 |

* Note: F = Frontal zone, I = Intermediate zone, R = Rear zone.

have amphibole- and biotite-bearing associations. Amphibole and mica were found here even in some basalts and basaltic andesites. Typical rocks of the frontal zone are magnophyric basalts with megacrysts of plagioclase ≥ 10 mm across. These varieties are not characteristic of the rear-arc basalts. Olivine and quartz phenocrysts are common in rear-arc andesites while in the frontal zone

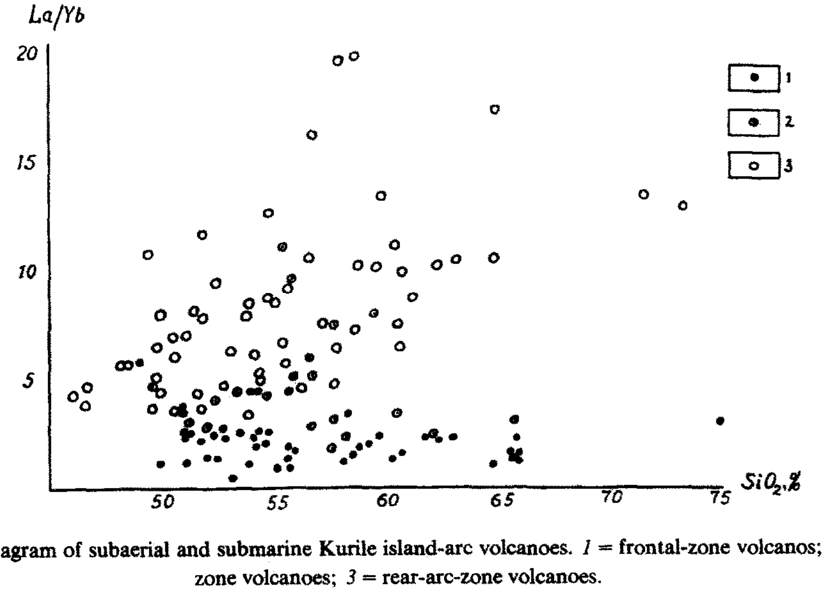

Fig. 5. La/Yb–$SiO_2$ diagram of subaerial and submarine Kurile island-arc volcanoes. *1* = frontal-zone volcanos; *2* = intermediate = zone volcanoes; *3* = rear-arc-zone volcanoes.

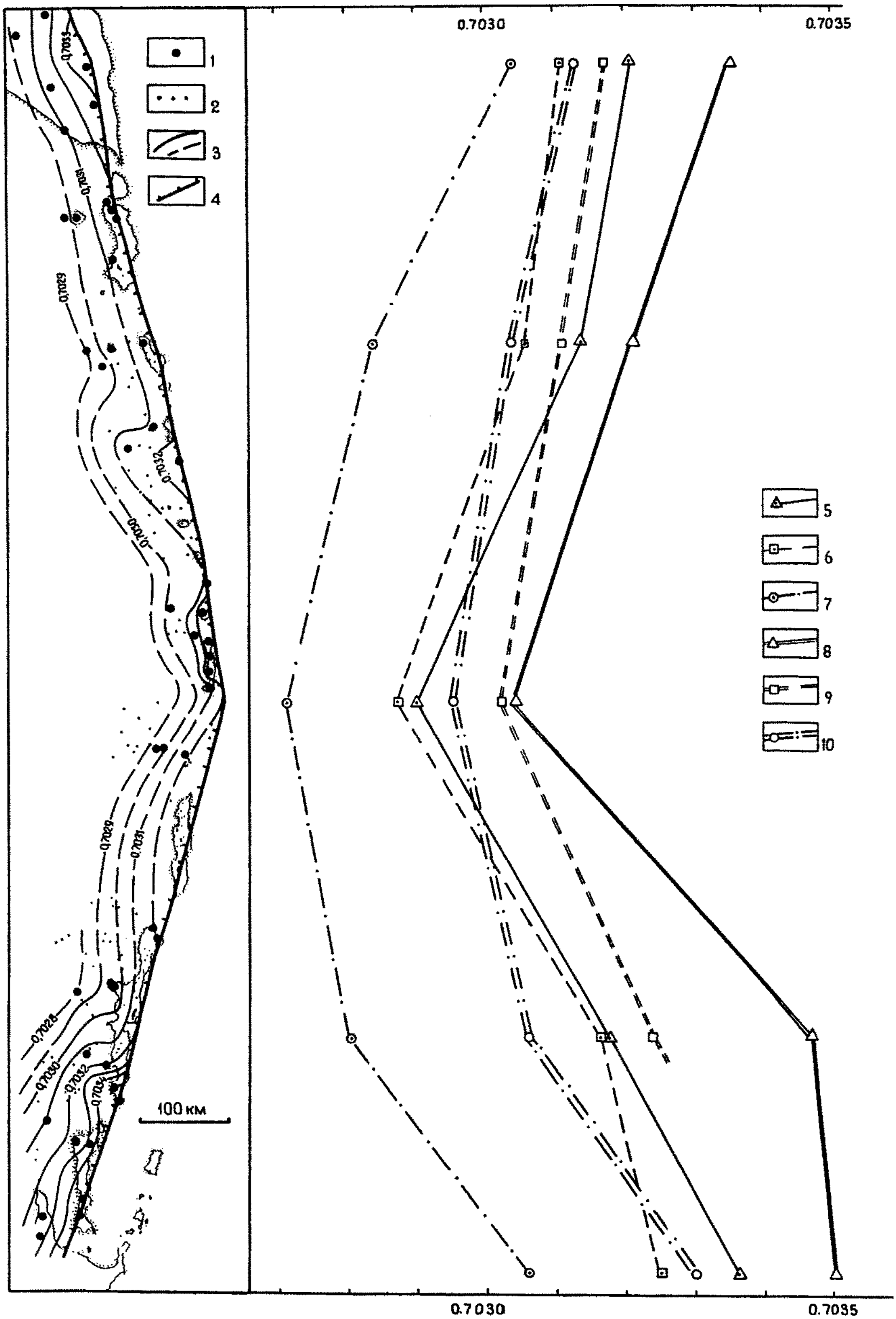

Fig. 6. Distribution of $^{87}Sr/^{86}Sr$ in Quaternary lavas of the Kurile island arc. *Map*: *1* = volcanoes with determined $^{87}Sr/^{86}Sr$ values in lavas; *2* = other submarine and subaerial volcanoes; *3* = isolines of average values of $^{87}Sr/^{86}Sr$; *4* = volcanic front. *Graph*: *5–7* = minimum values of $^{87}Sr/^{86}Sr$ in lavas of the frontal (*5*), intermediate (*6*) and rear-arc (*7*) zones; 8–10 = average $^{87}Sr/^{86}Sr$ values in lavas of the frontal (*8*), intermediate (*9*), and rear-arc (*10*) zones.

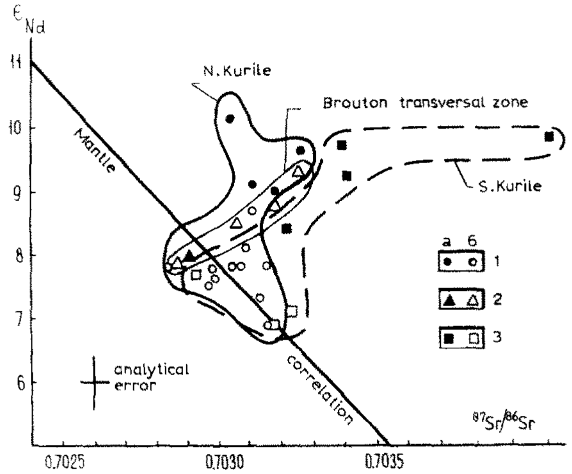

Fig. 7. Sr and Nd isotopic characteristics in Quaternary lavas of the Kurile island arc. *1–3* = segments of the arc: *1*—North Kuriles, *2*—Brouton transversal zone, *3*—South Kuriles; *a*—lavas of the frontal, *b*—rear-arc and intermediate zones.

they are less frequent. Rear-arc basalts typically contain such typomorphic accessory minerals as spinel and zircon, which are not observed in the

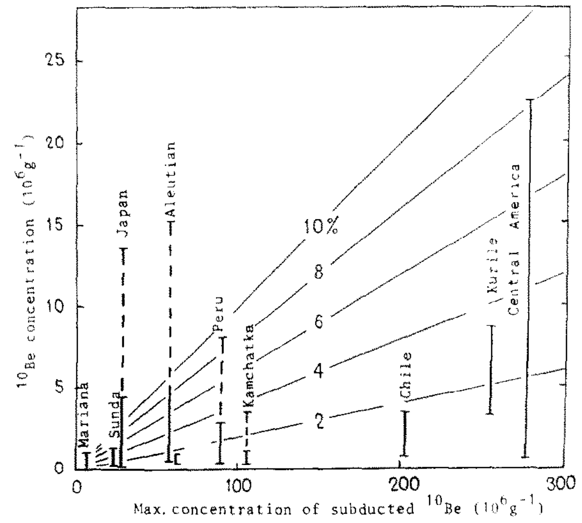

Fig. 8. A diagram to determine the proportion of sedimentary components in lavas of volcanoes in island arcs (after Tera et al. (1986) with additions by the authors. Calculations have been carried out proceeding from the assumption that 100% of subducted sediments participate in magma genesis. Dashed lines show deviations in $^{10}$Be contents.

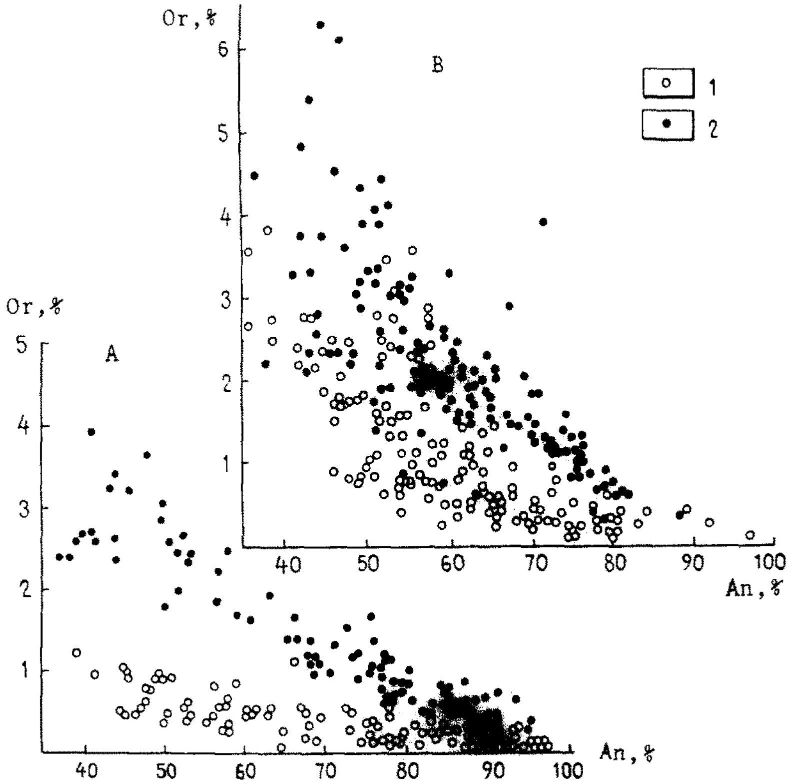

Fig. 9. The content of Or-molecules in the plagioclase of the Kurile island arc lavas. *1* = frontal lavas; *2* = rear-arc lavas. (A) Phenocrysts; (B) microlites and phenocryst rims.

frontal-arc rocks. In addition, apatites are more frequent in rear-arc rocks as compared to the frontal rocks. Plagioclase phenocrysts in the rear-arc lavas are less calcic, with higher Ba, Sr, and K, and with less Fe than plagioclase in frontal-arc lavas. The content of Or-molecules in plagioclase

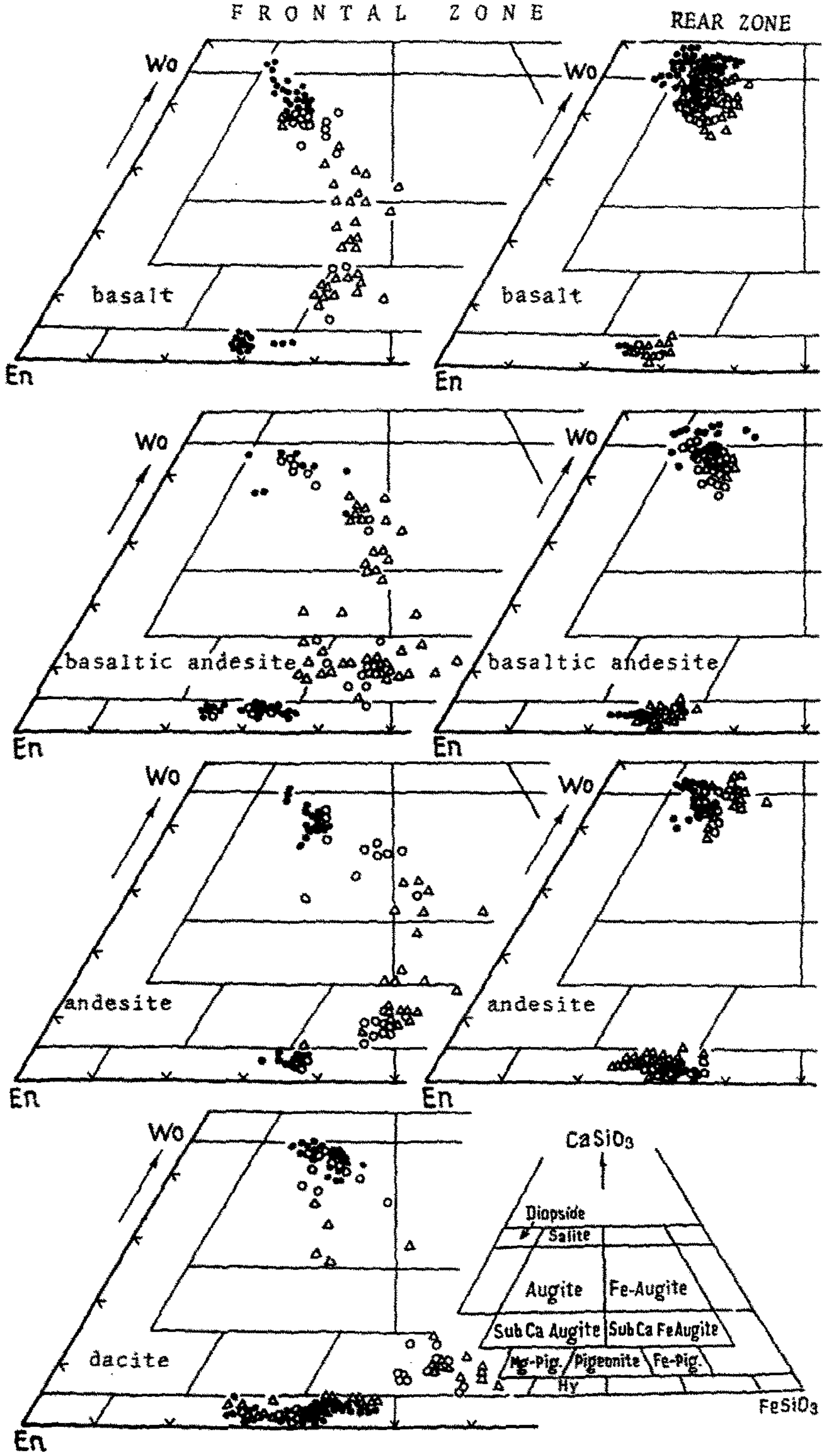

Fig. 10. Composition of pyroxenes in basalts, basaltic andesites, andesites and acid rocks of the Kurile island arc. Dots for phenocryst cores, circles for phenocryst rims, triangles for microlites.

phenocrysts and microlites from the rear-arc lavas is generally more than twice as high as in similar rocks from the frontal zone (see Fig. 9).

There are some differences in the composition of olivines, pyroxenes and other minerals.

Olivines from the rear-arc lavas are more magnesian than those from the frontal zone. If the Mg contents in olivines from the two zones are the same, the rear-arc olivines typically have higher concentrations of Mn and Ca than those from the frontal zone. Clinopyroxenes of the rear-arc lavas are more calcic, less ferruginous and contain more Ti, Al and Cr (in basalts) than those of the frontal-arc lavas. Clinopyroxene phenocryst cores in the rear-arc volcanics are typically diopsides and salites, while in the frontal-arc lavas they are commonly augites. Orthopyroxene phenocrysts of the rear-arc lavas are generally less ferruginous than in frontal-arc lavas, though both samples contain bronzites and hypersthenes (Fig. 10). The evolutionary trend in pyroxenes in basalts and basaltic andesites in the frontal zone is tholeiitic, while in the rear-arc a calc-alkalic trend is observed.

The described differences in associations and compositions of minerals from the frontal and rear-arc zones are related to different compositions of melts, as well as to various thermodynamic conditions of crystallization. The occurrence of hydrous mafic mineral assemblages in rear-arc lavas and the dominance of two-pyroxene assemblages in the frontal arc suggest a higher $H_2O$ activity in the rear-arc region. Lavas in the rear-arc have higher $PO_2$, as estimated from magnetite–ilmenite geothermometry (Volynets et al., 1990a).

Differences in the character of magmas from the two zones are also reflected in the compositions of lithic inclusions studied recently (Volynets et al., 1990b). Ultrabasic xenoliths are nearly absent in frontal-arc lavas but are rather common in the rear arc. For example, in Chirinkotan volcano in the rear-arc, inclusions of gabbro, metamorphic rocks and ultrabasic rocks occur in the ratios 10 : 1 : 1. Granitic inclusions, on the contrary, were found mostly in frontal-arc lavas. The frontal-arc inclusions, as a rule, have only anhydrous mineral assemblages, while those of the rear-arcs include amphibole- and biotite-bearing associations. Gabbroid and metamorphic rock inclusions of the frontal and rear-arc zones of the Kurile arc differ also in chemical and rare-element compositions. The rear-arc inclusions are enriched in $TiO_2$, alkalies, Rb, Ba, Sr, Ni, Cr and Zn and depleted in Co, V, Pb, and Sn.

## A model for magma formation

The described petrochemical, geochemical, isotopic, and mineralogic characteristics of the volcanic rocks from frontal arc and the rear-arc, as well as the data on the volcanic inclusions, are consistent with a hypothesis of two zones of magma generation at depth, as was originally suggested on the basis of the distribution of submarine and subaerial volcanoes across the Kurile arc (Avdeiko, 1989). Judging from the above-mentioned data, magma generation takes place within the mantle wedge above the seismo-focal plane under the influence of volatiles which separate from the subducted slab of the Pacific plate. The role of volatiles in magma formation under the Kurile–Kamchatka island-arc system was first explained by Popolitov and Volynets (1981). The model suggested here and shown in Fig. 11 is just a development of that idea. The model involves two zones of magma generation which result from two different levels of volatile separation from the subducted plate. The first water to come off the subducted plate will be hygroscopic-which is contained in the intergranular space in sediments and in the porosity of the volcanic rocks. Most of this water will come out at about 105 ° C, i.e., at a depth of 30–50 km (see Fig. 11). These fluids are unlikely to be directly involved in magma generation. Part of this fluid will be bound in hydrous phases in the mantle wedge and part will form hydrous phases (chlorite, amphibole, serpentine, epidote) within the subducted plate.

The next level of volatile separation is obviously caused by dehydration of hydrous minerals, mostly zeolites and argillaceous minerals. Argillites form much of the non-calcareous portion of deep-water sediments, while zeolites are the products of the low-temperature secondary alteration of volcanic rocks. Dehydration of zeolites at atmospheric pressure occurs in a few stages within the temperature range of 200–700 °C; full dehydration occasionally occurs at 1000 °C. The major of argillaceous minerals dehydrate within the same temperature range. It is natural that at high pressure the temperature limits of stability of zeolites, argillaceous and other hydrous minerals would be different as compared to those obtained through experiments at atmospheric pressure. None the less, a wide temperature range for dehydration of zeolites, smectites, epidotes and other hydrous minerals allows us to suggest that at least some of them dehydrate under the volcanic front, providing volatiles that reduce melting temperatures within the mantle wedge.

In the boundary layer between the subducting oceanic plate and the mantle wedge, there is a temperature inversion (see Fig. 11) which impedes

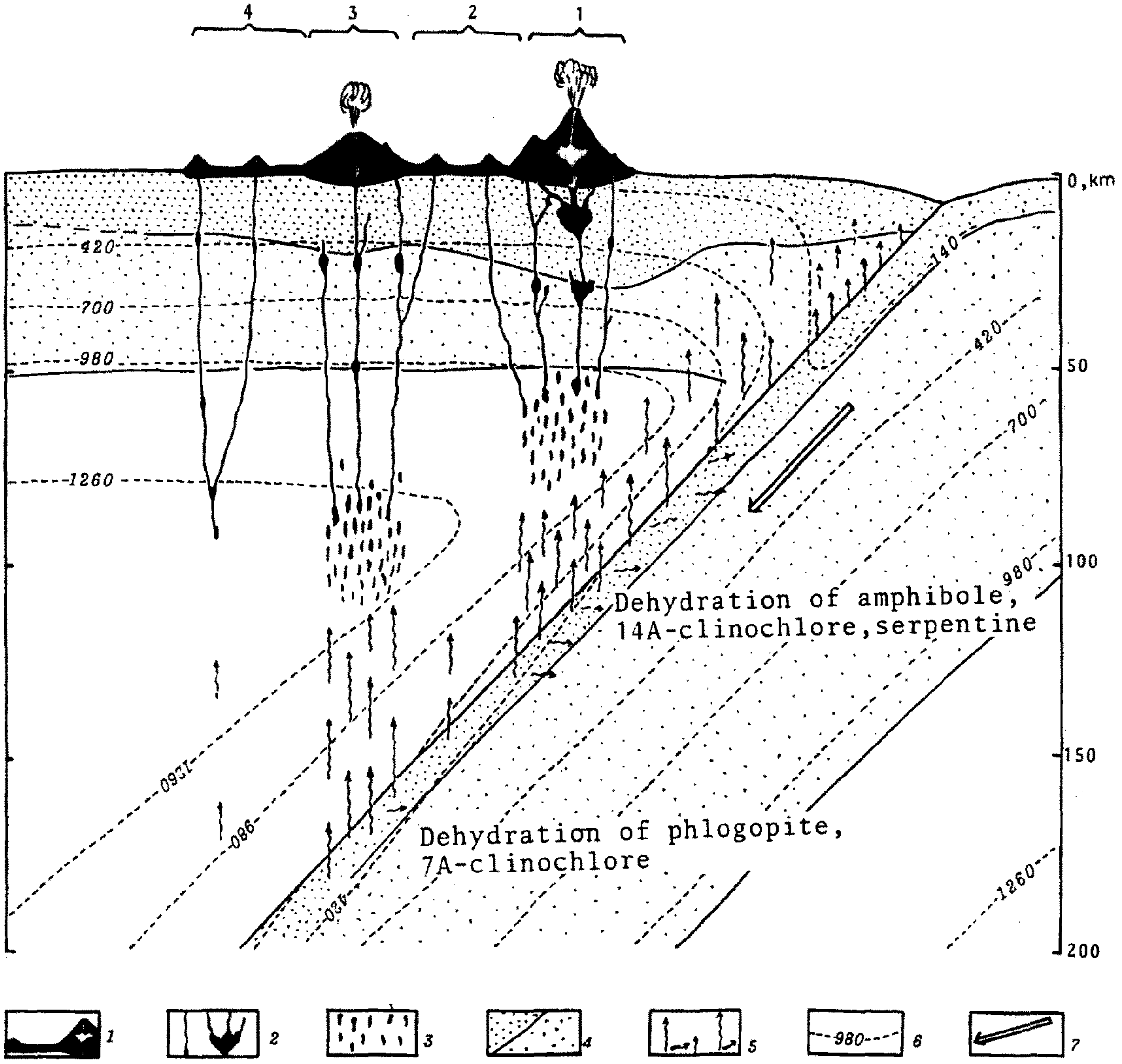

Fig. 11. A model for magma formation under the Kurile island arc. *Figure braces*: *1* = volcanic front, *2* = intermediate zone, *3* = rear-arc zone, and *4* = zone with waning activity. *Key*: *1* = volcanic zones, *2* = supplying channels and intermediate magma chambers, *3* = magma generation sources, *4* = lithosphere with the lower crustal boundary under the South Kuriles, *5* = direction of volatile migration separating from subducting lithosphere, *6* = geoisotherms, *7* = direction of the Pacific plate subduction.

the migration of fluid into the wedge. This fluid may, in fact, initially migrate into the subducting slab to react with colder oceanic crust and mantle. Judging from calculations of dehydration reactions in the system $K_2O$–$Na_2O$–MgO–FeO–$Al_2O_3$–$SiO_2$–$H_2O$ during sinking of the lithospheric plate (Delany and Helgeson, 1978) and taking into account the temperature model by Honda and Uyeda (1983), as applied to the Kurile subduction zone, we suggest that both the proposed levels of volatile separation results from dehydration of various modifications of chlorite, as well as hydromicas and serpentine. Dehydration of amphiboles may serve as the additional source of water at the front. $CO_2$, H and other volatiles are liberated through decay of sedimentary carbonates and other minerals.

There may be other mechanisms which enhance the development of two levels of volatile separation. Tatsumi (1986) suggests that amphibole dehydration takes place beneath the volcanic front of an arc, while phlogopite, carried in a secondary convection cell in the mantle wedge, dehydrates beneath the rear-arc. Amphibole dehydration does indeed occur at about 100 km, which corresponds to the depth beneath the frontal-arc zone. Phlogopite dehydration, however, should occur around 190 km, which is much deeper than the depth beneath the rear-arc volcanic zone.

A more quantitative discussion of the role of volatiles in arc petrogenesis, particularly as regards their composition and depth of release, requires much more experimental and analytical information.

In this study we only wish to emphasize that the dual zones of magma generation in the Kurile arc may be the result of two depths of volatile separation from the subducted plate. The depths of this separation may vary depending on temperature and pressure gradients and the dip of the slab, and hence the depths of magma generation may vary. In fact, the depth to the Benioff zone below the volcanic front is 10–20 km greater in the North Kuriles, where the slab dips more steeply, than in the South Kuriles. The depths beneath the rear-arc zone are also about 10–30 km greater in the north (Table 1). This might result from the lesser slopes and oblique subduction in the South Kuriles producing a different temperature gradient along the top of the lithospheric plate and bottom of the mantle wedge.

In the proposed model, the difference in composition of lava from the volcanic front and rear-arc is the consequence of a number of facts, the most important of which are quantity and composition of fluids participating in melting, the composition of melting material and the degree of partial melting. It is difficult here, as in all arcs, to unambiguously identify the relative contribution of each to magma genesis.

We infer that the quantity of fluid separating from the subducting lithosphere is greater beneath the volcanic front, and the composition of that fluid will be closer to that of seawater. This would account for the differences in Sr and Nd isotopic ratios between the two parts of the arc. Judging from the increased Rb-concentrations and higher Rb/Sr in the rear-arc lavas, one would expect a positive correlation between $^{87}Sr/^{86}Sr$ and depth to the Benioff zone. However, the opposite is observed (Volynets et al., 1988). This indicates that the Rb enrichments must be quite recent and probably related to the release of fluids immediately prior to magma genesis.

The chemical composition of the fluids released from the slab must be determined by their volume, the composition of the slab and mantle which the fluids encounter, and the length of time over which the interaction occurs. Such fluids will generally carry incompatible elements, primarily those with large ionic radii (Tatsumi et al., 1986). As can be seen from Fig. 11, the distance to the fusion zone covered by the fluid in the rear arc is larger and, consequently, the abundance of incompatible rare elements in the participating melting fluid is higher than in the volcanic front. In addition, the fluid from the rear-arc zone interacts with the crust and mantle at a higher $T$ and $P$, which may result in it having higher concentrations of incompatible elements. The ionic control on fluid composition is reflected in the higher ratios of large-radius to smaller-radius elements (i.e., Rb/Sr, Rb/K, La/Yb).

The greater abundances of K and lithophile elements including light rare-earth elements, in the rear-arc lavas might result from lesser degrees of partial melting of a similar mantle source. However, the rear-arc lavas have higher concentrations of refractory elements (Ni and Cr), lower FeO/MgO at the same $Al_2O_3$ and CaO, and similar abundances of high-field-strength cations (Nb, Zr, and Ti) when compared to the frontal-arc lavas. This evidence suggests that the differences between the frontal and rear-arc lavas are not the result of crystal fractionation.

Our chemical and volcanological data do not agree with the proposal by Melekestsev (1980) that the intensity of volcanic activity is higher in the rear-arc than in the volcanic front. This differs from the Japan arc, where volcanic activity is higher in the frontal arc (Kushiro, 1983).

According to the proposed model (see Fig. 11), the magma generation chambers under the rear arc are located somewhat deeper than those under the volcanic front. The data on mineralogic composition of lavas and inclusions testify to higher water contents in the melts of the rear-arc as compared to those from the frontal volcanic zone. This requires that melting beneath the rear-arc occurred at higher fluid pressure, and so perhaps increased the degree of partial melting. This would account for the higher Ni and Cr in the rear-arc lavas; if this is the case, the degree of melting is higher, not lower, in the rear-arc volcanic zone.

Though we have attributed the compositional variations in these lavas largely to the effect of fluids and degree of melting, it is possible that source heterogeneity contributes to the differences (Avdeiko et al., 1986).

Some of the factors which contribute to variations in lava chemistry, such as thickness and composition of the crust, are apparently of subordinate importance in the Kuriles in producing the primary compositional differences. These crustal-level effects have been discussed in detail elsewhere (Avdeiko et al., 1985; Avdeiko et al., 1986; Volynets et al., 1988).

The proposed model explains the discussed structural-spatial distribution of the volcanoes, as well as the data on petrochemical, geochemical, mineralogical and isotopic zoning and zonal distribution of inclusions in lavas. We have, however, no satisfactory explanation for the fact that the frontal volcanics, whose source is postulated to have higher fluid contents, lower water contents and more anhydrous mineral assemblages, compared to the rear-arc zone.

The fact is that the parent magmas of the island-arc basalts form an increased water pressure and loss of water in the near-surface magma chambers can possibly explain this. The near-surface magma chambers are more characteristic of the volcanic front (Kushiro, 1983), hence the probability of magma losing water in this zone is higher. It is also possible that differences in mineral associations between the two zones can result not from the quantitative but from the qualitative differences in the fluid-phase compositions.

In conclusion, we need to emphasize that the principal systematic differences in the composition of volcanic rocks from the volcanic front and rear-arc (Kuno, 1959; Gill, 1981; Kushiro, 1983; Piskunov, 1987) and the bimodal distribution of arc volcanic centers in the Kuriles, Japan and other island arcs suggest that a double zone of magma generation may be a common feature of island arcs. Such a hypothesis should be taken into account when considering models for the petrogenesis of island-arc volcanic rock series.

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