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GEOCHEMISTRY

Magmatic Sources of Quaternary Lavas in the Kuril Island Arc: New Data on Sr and Nd Isotopy

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Subduction zones of oceanic plates are among the most complicated tectonomagmatic systems in our planet. The relative contribution of the three major geochemical reservoirs into magma genesis (suprasubduction mantle wedge, crust, and oceanic lithosphere) is substantially governed by the geodynamic parameters of the subduction process, including the vector of the convergence of interacting plates, the inclination of the subducting plate, and the activity of back-arc processes and transform faults. Therefore, resolution of issues related to the origin and evolution of primary melts in island arcs requires a complex approach, which includes the study of lateral isotope-geochemical variations in the composition of igneous rocks [10, 11, 13–15]. The present communication discusses the longitudinal and transverse zonality of Quaternary volcanic rocks in the Kuril island arc based on high-precision trace element and isotope analyses carried out at Shimane University, Matsue, Japan. Figure 1 shows the sampling sites. The Kuril island-arc system is represented by the Kuril–Kamchatka deep-water trench, the Great Kuril volcanic range, and the Kuril deep-water basin located in the back-arc zone. The deep-water trench is filled with oceanic sediments composed of a mechanical mixture of continental material (17–80 vol %), organogenic quartz (9 vol %, on average), volcanic ash (*n* vol %), and traces of carbonate material [11]. The Kuril transarc basin was initiated in the Early Oligocene–Middle Miocene (32–27 Ma ago) [8]. However, the process of its extension may also have continued into the Late Miocene and magmatic processes are active up to the present time [8].

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The Great Kuril Range is conventionally divided into the southern, central, and northern sectors (Fig. 1). According to [1], the crust is thinner in the central Kuril sector (8–10 km) and thicker (up to 20–35 km) in the northern and southern sectors. However, according to [2], the crustal thickness is virtually similar in the southern (28–33 km), central (25–30 km), and northern (32–36 km) sectors.

Data on the trace element (particularly, isotopic) composition of Quaternary volcanic rocks in the Kuril island arc are scanty. After the pioneering works of Zhuravlev et al. [3], new data on the Nd isotopy were only reported from separate volcanoes of Iturup Island [9] and the adjacent area of the Kuril deep-water basin [8]. Data on the trace element composition are also scanty [5, 7, 11]. Concepts of magma genesis in this region differ appreciably because of its insufficient study. According to the authors of [11], who scrutinized this issue on the basis of modern analytical data, $\delta^{11}B$ shows a linear correlation with $^{87}Sr/^{86}Sr$ and Nb/B. These authors argue that the transverse geochemical zonality noted in this region is related to the mixing of two isotopically homogeneous components (subduction fluid and mantle wedge). The values of the Nb/B ratio in two samples of the back-arc volcanic rocks (central and southern sectors) are relatively high. Therefore, we can assume the possibility of partial contribution of a fresh mantle material into magma genesis.

The important role of the fluid phase in the origin of igneous rocks of the frontal zone has also been noted by other researchers [1, 3, 4, 9]. At the same time, some researchers [4, 9] assumed a progressive compositional evolution of magma sources toward the back-arc zone of the island arc.

According to [11], the weak longitudinal geochemical zonality of volcanic rocks of the Kuril island arc is related to an insignificant compositional difference between the northern and southern sectors. The authors of [4] emphasized that high-K alkaline lavas are confined to the junction of differently oriented flanks of the island arc in the northern (Paramushir Island) and central (Simushir Island) sectors.

Our original results significantly supplement the available geochemical information. In the $^{143}Nd/^{144}Nd$–$^{87}Sr/^{86}Sr$ plot, data points of basalts and andesites of modern volcanoes in the Kuril island arc make up a cluster (Fig. 2). Volcanic rocks of the back-arc zone are sufficiently homogeneous in the isotopic composition. Together with rocks of submarine volcanoes of the Kuril deep-water basin, the volcanic rocks are located in the Indian MORB field, except for two samples with isotopic characteristics similar to those of lavas of the frontal zone. Sample KY-08 was taken at the base of Bogdan Khmel'nitskii Volcano (Iturup Volcano), while sample KY-34/72 was taken near the summit of Alaid Volcano (Alaid Island). The second sample characterizes the margin zone of a modern (still hot) lava flow.

Basalts and andesites of the frontal zone occur in the Kamchatka lava field and differ from the back-arc variety in the persistent higher contents of radiogenic Sr and often Nd (Fig. 2). The $^{87}Sr/^{86}Sr$ values (0.703145–0.703297) virtually do not change along the strike of the island arc. They are similar to the values (0.70326–0.7033) calculated for the subduction fluid of the Kuril island-arc system [11], except for two analyses of basalts from the central zone (KY-10/84 and KY-11/84) with a higher content of radiogenic Sr (table, Fig. 2).

In contrast to $^{87}Sr/^{86}Sr$, the $^{143}Nd/^{144}Nd$ ratio significantly varies in rocks of the volcanic front (table, Fig. 2). Lower values are typical of lavas from large and small islands of the southern (Kunashir, Iturup, and Chernye Brat'ya) and northern (Paramushir and Atlasovo) zones, whereas higher values are recorded in rocks from Simushir Island and small islands of the central zone. In [3], only two samples (Kunashir 40/8-88 and Iturup 107/81) deviate from the trend described above.

The distribution patterns of Sr and Nd isotopes in Quaternary volcanic rocks of the Kuril island arc are very similar to those in northeastern Japan [15]. In both cases, lavas of the back-arc zone are sufficiently homogeneous and isotopically similar to asthenospheric basalts in marine back-arc basins. Lavas of the volcanic front are enriched in radiogenic Sr. The content of radiogenic Nd in them varies considerably along the arc strike. Based on results of geochemical modeling, the authors of [15] concluded that frontal and back-arc lavas of the Japanese volcanic arc have compositionally similar mantle sources. According to these authors, the transverse geochemical zonality in the region is related to differences in depth, melting degree, and contributions of subduction fluid and crustal contamination. →

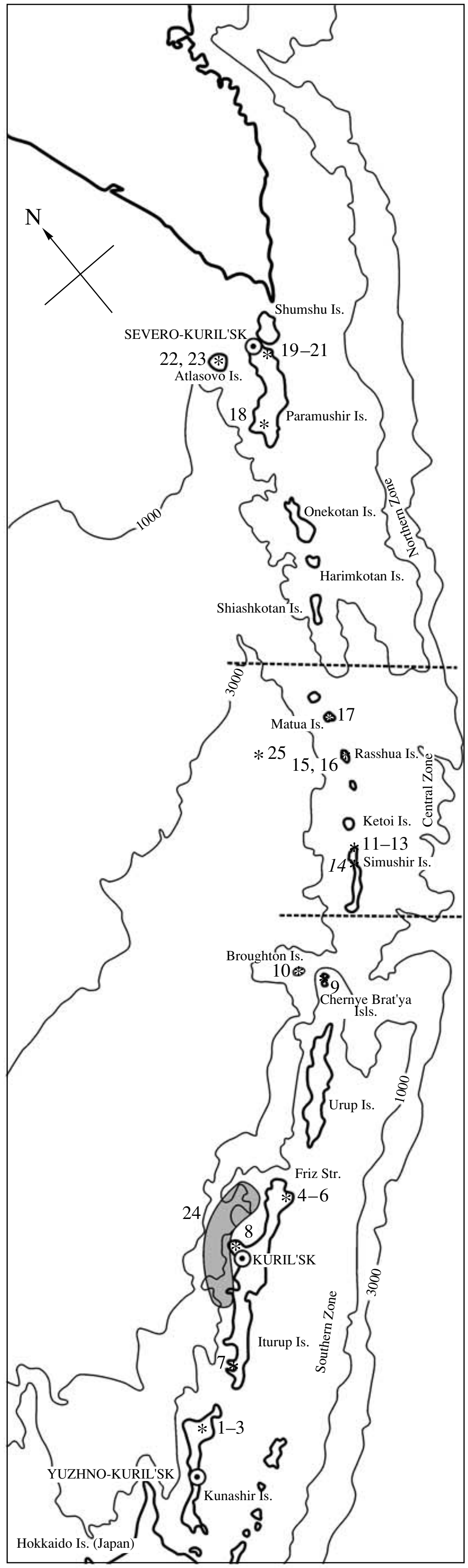

Fig. 1. Map of the Great Kuril Range. Sampled volcanoes: (1–3) Tyatya; (4–6) Men'shoi Brat and Kudryavyi; (7) L'vinaya Past; (8) Bogdan Khmel'nitskii; (9) Brat Chirpoev; (10) Broughton; (11–13) Uratman; (14) Prevo; (15, 16) Rasshua; (17) Sarychev; (18) Chikurachki; (19–21) Ebeko; (22, 23) Alaid; (24) field of small volcanoes in the back-arc zone of Iturup Island [9]; (25) Geofizik submarine volcano [8].

Contents of major (wt %) and trace elements (ppm) and radiogenic isotopes in representative samples of volcanic rocks from the Great Kuril Range

Component	KY-108/73	KY-P1-2002	KY-sr-4	KY-sr-2	KY-08	KY-233/84	KY-20/76	KY-229/83
	1	2	3	4	5	6	7	8
	Kunashir		Iturup, frontal zone		Iturup, back-arc zone	Brat Chirpoev Is.	Broughton Is.	Simushir Is.
SiO_2	52.87	51.93	52.15	55.49	51.79	52.62	54.04	52.12
TiO_2	1.18	1.10	0.73	0.82	0.92	0.72	0.72	0.83
Al_2O_3	16.18	16.38	16.46	16.73	20.53	18.50	17.14	18.33
Fe_2O_3	12.60	12.88	10.48	10.17	9.04	9.69	6.53	10.33
MnO	0.21	0.18	0.18	0.25	0.20	0.17	0.14	0.16
MgO	4.52	5.21	7.80	4.18	3.42	4.97	7.13	5.45
CaO	9.26	9.30	9.46	8.97	9.68	9.96	9.22	9.35
Na_2O	2.90	2.80	2.28	2.53	3.25	2.92	2.64	2.85
K_2O	0.67	0.60	0.48	0.63	0.61	0.63	1.89	0.48
P_2O_5	0.19	0.23	0.18	0.19	0.26	0.13	0.28	0.16
Total	100.58	100.61	100.2	99.96	99.7	100.31	99.73	100.06
Rb	12.42	11.80	7.06	10.12	8.31	9.32	29.15	8.60
Ba	253.10	196.20	147.70	209.90	94.20	189.90	214.50	120.20
Pb	6.39	6.52	5.69	5.85	5.91	4.92	28.37	5.17
Zr	90.85	87.07	47.44	50.41	47.74	74.65	84.79	47.65
Hf	2.55	2.29	1.46	2.06	1.85	1.54	2.56	1.51
La	6.11	5.56	3.16	3.54	4.47	5.64	13.23	3.39
Ce	16.59	15.33	7.33	9.61	10.56	13.06	33.94	8.85
Pr	2.42	2.33	1.24	1.40	1.99	1.82	3.53	1.33
Nd	12.72	11.68	5.81	7.08	9.54	9.81	16.22	6.70
Sm	3.83	3.59	1.97	2.14	3.05	2.62	3.69	2.16
Eu	1.19	1.14	0.74	0.82	1.15	0.92	1.38	0.79
Gd	3.39	4.60	1.66	2.01	2.51	2.25	3.61	2.71
Tb	0.91	0.77	0.51	0.59	0.76	0.61	0.75	0.48
Dy	5.46	5.15	3.27	3.77	4.41	3.54	4.13	3.23
Ho	1.15	1.09	0.69	0.81	0.92	0.69	0.69	0.71
Er	3.35	2.94	2.00	2.28	2.53	2.04	2.17	1.98
Tm	0.47	0.45	0.30	0.38	0.38	0.31	0.31	0.32
Yb	3.22	3.04	2.03	2.44	2.62	2.14	2.02	2.11
Lu	0.50	0.45	0.31	0.37	0.40	0.31	0.32	0.33
Nb	1.12	1.16	0.48	0.57	0.84	1.08	3.13	0.89
Y	27.19	29.37	18.44	21.25	20.81	18.00	17.91	20.45
Ta	0.08	0.08	0.04	0.05	0.06	0.08	0.20	0.08
Th	1.02	1.02	0.53	0.78	0.68	0.96	3.23	0.64
Cs	1.17	1.18	0.65	0.94	0.68	0.53	1.25	0.48
U	0.39	0.37	0.23	0.30	0.25	0.35	1.06	0.27
Be	0.47	0.50	0.24	0.28	0.44	0.43	0.76	0.40
$^{87}Sr/^{86}Sr$	0.703273	0.703177	0.703236	0.703269	0.703352	0.703155	0.702993	0.703213
$^{143}Nd/^{144}Nd$	0.513041	0.513095	0.513062	0.513021	0.513060	0.513017	0.513058	0.513158

Table. (Contd.)

Component	KY-56/84	KY-11/84	KY-36/76	KY-1301	KY-46/72	KY-34/72	KY-161/72
	9	10	11	12	13	14	15
	Simushir Is.	Rasshua Is.	Matua Is.	Paramushir Is.		Atlasovo Is.	
SiO_2	52.24	51.50	55.31	52.40	52.98	49.01	48.91
TiO_2	0.72	0.60	0.84	0.72	0.74	0.92	0.80
Al_2O_3	18.75	16.60	18.08	20.75	16.30	19.68	20.77
Fe_2O_3	9.32	10.66	9.09	8.67	10.12	10.72	8.85
MnO	0.19	0.21	0.16	0.17	0.17	0.17	0.17
MgO	5.30	6.17	3.41	3.90	7.50	3.78	4.91
CaO	9.62	9.28	8.45	9.46	8.10	10.78	10.54
Na_2O	2.60	2.55	3.15	2.84	2.65	2.85	2.83
K_2O	0.30	0.77	0.96	1.03	1.40	1.61	1.65
P_2O_5	0.15	0.13	0.25	0.08	0.27	0.35	0.36
Total	99.19	98.47	99.7	100.02	100.23	99.87	99.79
Rb	18.94	12.35	14.13	14.45	30.62	32.82	43.70
Ba	68.89	140.70	183.30	227.90	323.30	158.90	
Pb	2.56	6.61	7.25	8.96	6.22	4.19	4.69
Zr	47.84	53.36	53.24	52.78	68.25	63.95	115.10
Hf	1.49	1.58	2.00	1.72	2.30	1.89	2.02
La	3.11	3.23	7.80	6.47	9.51	11.28	12.94
Ce	8.82	8.64	18.54	16.64	22.06	24.96	33.47
Pr	1.45	1.33	2.73	2.32	3.14	3.53	3.83
Nd	7.91	6.93	13.26	10.68	14.01	15.31	19.26
Sm	2.50	2.22	3.54	2.99	3.50	3.88	4.30
Eu	0.95	0.78	1.19	1.07	1.08	1.29	1.38
Gd	3.25	2.94	3.86	2.98	3.32	3.82	4.26
Tb	0.57	0.52	0.62	0.60	0.59	0.59	0.61
Dy	3.84	3.51	3.99	3.75	3.61	3.49	3.87
Ho	0.82	0.76	0.83	0.76	0.73	0.72	0.75
Er	2.29	2.13	2.36	2.21	2.11	1.94	2.11
Tm	0.35	0.34	0.37	0.34	0.31	0.31	0.32
Yb	2.34	2.23	2.52	2.25	2.20	1.95	2.12
Lu	0.37	0.35	0.39	0.35	0.33	0.31	0.31
Nb	0.77	0.65	1.36	1.19	1.66	3.66	3.35
Y	22.23	19.98	21.06	20.54	18.67	18.74	21.50
Ta	0.06	0.06	0.08	0.08	0.35	0.22	0.20
Th	0.38	0.70	1.40	1.30	2.76	2.14	2.29
Cs	12.32	0.14	0.91	0.70	1.56	1.14	1.17
U	0.17	0.32	0.49	0.46	1.01	0.78	0.90
Be	0.35	0.34	0.55	0.48	0.64	0.86	0.84
$^{87}Sr/^{86}Sr$	0.703003	0.703617	0.703141	0.703225	0.703245	0.703186	0.703044
$^{143}Nd/^{144}Nd$	0.513063	0.513179	0.513129	0.513100	0.513106	0.513106	0.513027

Note: Volcanoes: (1, 2) Tyatya; (3, 4) Men'shoi Brat; (5) Bogdan Khmel'nitskii; (6) Brat Chirpoev; (7) Broughton, (8) Uratman, (9) Prevo, (10) Rasshua, (11) Sarychev, (12) Chikurachki, (13) Ebeko, (14, 15) Alaid. Analyses were carried out at Shimane University, Matsue, Japan by the following methods: X-ray fluorescence analysis (major elements), ICP-MS analysis (trace elements, Termo ELEMENTAL VG PQ 3), TIMS analysis (radiogenic isotopes, Finnigan MAT 262).

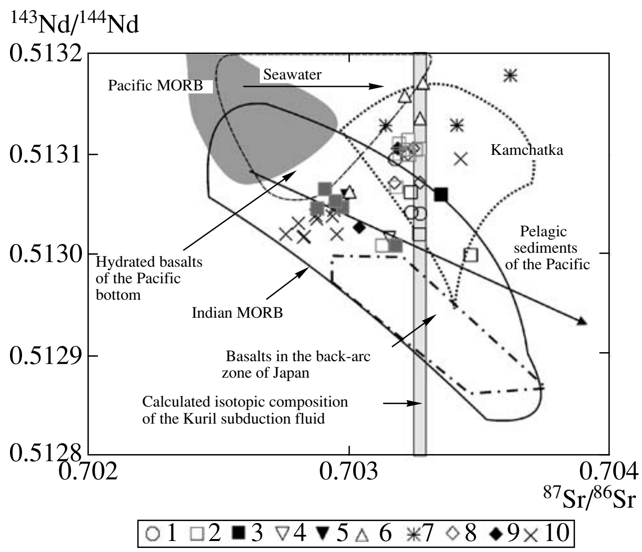

Fig. 2. Sr and Nd isotope ratios in Quaternary lavas in the (*1–5*) southern, (*6, 7*) central, and (*8, 9*) northern sectors of the Great Kuril Range. Legend for Figs. 2–4. (*1*) Kunashir Is.; (*2, 3*) Iturup Is., frontal and back-arc zones, respectively; (*4*) Brat Chirpoev Is.; (*5*) Broughton Is.; (*6*) Simushir Is.; (*7*) Matua and Rasshua Isls.; (*8*) Paramushir Is.; (*9*) Atlasovo Is.; (*10*) submarine volcanoes of the Kuril deep-water basin. Gray symbols are adopted from [5, 8, 9]. The calculated isotopic composition of the Kuril subduction fluid is taken from [11].

Compositional variations of lavas along the volcanic front are attributed to different compositions of the crustal contaminant. Geochemical indicators revealed in our work also testify to a relatively high degree of melting of the mantle source beneath the frontal zone of the Kuril island arc [5]. High and persistent $^{87}Sr/^{86}Sr$ values in lavas of the volcanic front, particularly variations in ratios of elements with similar bulk coefficients of the mineral–melt system but different degrees of mobility in the aqueous fluid, such as Ba/Nb (Fig. 3), indicate a significant role of the fluid phase in their origin.

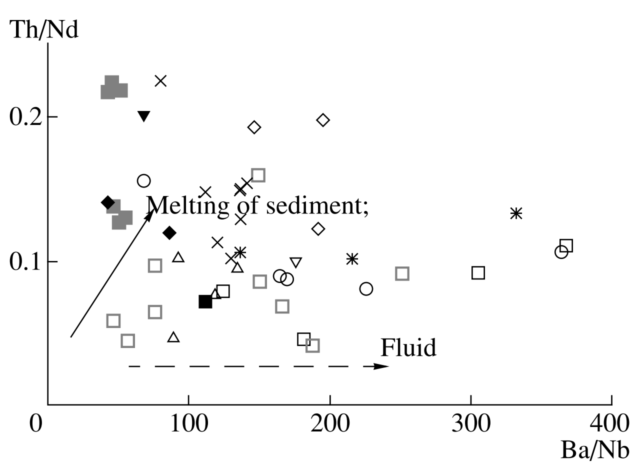

Fig. 3. Th/Nd–Ba/Nb diagram for Quaternary lavas of the Kuril island arc.

However, obvious geological and geochemical signs of crustal contamination are absent (Fig. 4). The lack of correlation of the $^{143}Nd/^{144}Nd$ ratio with the Th content and the Th/Nd ratio (Figs. 2, 3) contradicts the conclusion [11] about the crucial role of subduction-related sediments in the development of longitudinal zonality in the Kuril island-arc system. For example, values of the Th/Nd ratio in lavas of the central sector are similar or even slightly higher than those in the southern sector, whereas isotopic properties suggest a more depleted source for the central sector. Thus, variations in the Nd isotopic composition observed within the frontal zone of the Kuril island arc can only be explained by heterogeneity of the mantle source that was more depleted beneath the central sector of the volcanic arc. This conclusion is consistent with geological data. Crustal xenoliths (granite gneisses and plagioclase–hypersthene schists), which are typical of igneous rocks in the southern and northern sectors [1, 6], have not been found at the volcanic front.

Taking into consideration the relatively small size of the transverse section of islands, the absence of longitudinal geochemical zonality in volcanic rocks of the back-arc zone of the Great Kuril Range suggests that their origin was substantially influenced by magmatic processes related to the formation of a marginal sea, primarily the opening of the Kuril deep-water basin. An analogous scenario is recorded, for example, within the Izu–Bonin arc, where the longitudinal isotopic zonality is attributed to the mixing of two mantle sources (plates of the Philippine Sea in the back-arc zone and the Pacific plate in the frontal zone [12]). The isotopic compositions of back-arc basalts in the Quaternary volcanic belt in northeastern Japan are similar to the MORB composition in the Sea of Japan, Philippine Sea, and Indian Ocean [15].

The relatively high Th/Nd values in rocks of the back-arc zone (Fig. 3) testify to the higher contribution of the subduction-related sedimentary material into magma genesis. This is a rather typical phenomenon in

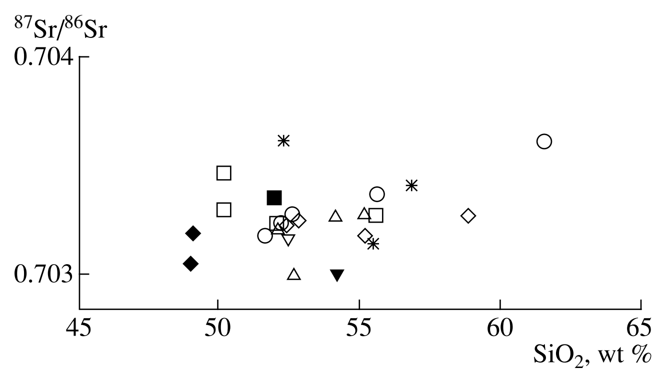

Fig. 4. SiO_2–$^{87}Sr/^{86}Sr$ relationship in the analyzed samples.

many island-arc systems, such as Japan [15] and Kamchatka [10].

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