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Geochemical Types, Petrology, and Genesis of Late Cenozoic Volcanic Rocks from the Kurile-Kamchatka Island-Arc System[1]

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Abstract

The Kurile-Kamchatka Late Cenozoic volcanic rocks can be categorized as magmatic series of island-arc and within-plate geochemical types, respectively. These types clearly can be identified on geochemical discriminant diagrams. Across-arc geochemical, mineralogical, and Sr-Nd-isotope zoning is characteristic of island-arc volcanics, but is not found for within-plate volcanics. Such zoning probably is the result of modification of fluid-phase composition, which originates in the underlying subducting plate (as a result of dehydration of water-bearing secondary minerals) and rises into the zone of island-arc magma generation in the mantle wedge. Along-arc Sr, Be, H, and 0 isotopic zoning is noted for island-arc volcanics. Probably it is associated with various levels of island-arc magma contamination. $_{10}$Be data for modern island-arc lavas attest to the fact that young pelagic sediments from the subducting plate participate in island-arc magma genesis.

Within-plate lavas are found in the region north of Avacha Bay. They may precede island-arc volcanics (East Kamchatka), coexist with them during the latestage of volcanic activity (Central Range), or be completely unrelated to island-arc volcanics in the far rear arc (West Kamchatka). The appearance of within-plate lavas probably is connected with deep faults that accompanied the formation of the northern Kurile-Kamchatka trench and the associated new subduction zone in this part of the island-arc system, an event caused by the accretion of the Kronotskiy terrane to eastern Kamchatka in Middle Miocene time.

Geologic-Geophysical Features of the Kurile-Kamchatka Island-Arc System

THE KURILE-KAMCHATKA island-arc system is one of the largest arc systems in the NW margin of the Pacific Ocean, extending more than 12000 km from Hokkaido in the SW to the Kamchatka Inlet in the NE. The system began to be. formed in the Late Oligocene or Early Miocene, but acquired its present configuration only in the Late Miocene-Early Pliocene, when a new northern branch of the Kurile-Kamchatka trench was formed from the latitude of Avacha Bay to the Cape Kamchatka Peninsula (Legler. 1977). The along-arc structure is non-uniform, corresponding to the divergent evolution of individual arc segments. Unlike the Kurile segment of the arc-system, where a single volcanic belt exists, in the Kamchatka segment several volcanic belts exist: Southern, Eastern, Central Depression, Central Range, and Western (Fig. 1). The Southern belt is separated from Eastern by the Malki-Petropavlovskiy transverse fault zone. Some authors suggest that these belt. together with the Central Depression, are united into a single structure (the Eastern volcanic belt), with respect to which the volcanic belt of the Central Range occupies a rear or leeward position (e.g., Vlasov, 1964). Other investigators assume that the Southern belt represents the northern termination of the Kurile segment, and the belt in NE Hokkaido its southern termination (Shantser and Shapiro. 1984).

The Kurile back-arc basin is situated in the rear zone of the Kurile segment of the arc system. It is wide in the south and narrow in the north. Some scientists believe that Kurile basin structures continue northward into Kamchatka as the Golygina Trough and Central Depression. extending to Litke Strait in the north. These structures sometimes are considered as a continental back-arc rift (Yermakov, 1987).

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Fig. 1. Volcanoes and volcanic zones of the Kurile-Kamchatka island-arc system (according to C P. Avdeyko and I. V. Melekestsev). Volcanic zones of Kamchatka: SK = Southern Kamchatka: EK = Eastern Kamchatka: CKD = Central Kamchatka Depression: CR = Central Range: WK = Western Kamchatka. Black stars = large stratovolcanoes: dark concentric rings cut by radial lines = large shield volcanoes; dots = small volcanic centers (cinder and lava cones of regional zones and lateral eruptions); black rings with cogs = calderas: circles with stars = submarine volcanoes; boxes with inscription Fe-Mn and index-lines = locations of Fe-Mn crusts and concretions on submarine volcanoes; thin straight line with cogs = volcanic front; thick straight line with cogs = axis of deep-water trench; curved lines with figures = isodepths to Benioff zone; double arrows = vector of Pacific plate; figures near single arrows indicate the distance to deep-water trench axis from volcanic front.

In Late Pliocene-Quaternary time, volcanoes in the Kamchatka segment of the island-arc svstem formed solely in, subaerial conditions. In the Kurile segment, volcanoes (dominant in the frontal zone) coexist with submarine volcanoes (dominant in the rear-arc zone). The latter are located on the eastern slope and. sometimes, even at the base of the Kurile trough.

The Pliocene-Quaternary volcanic belts of the Kuriles, South Kamchatka, and Central Range inherited the position of the Oligocene-Miocene belts. The volcanic belts of Eastern Kamchatka and Central Depression are superimposed on nonvolcanic structures and started to form only since the Late Miocene-Early Pliocene after a new subduction zone had been formed in this part of the island-arc system. Previously the trench was situated nearly 200 km to the west (Legler, 1977). The "jumping" of the trench may be caused by the collision of the Kronotskiy terrane and Eastern Kamchatka in the Middle Miocene (Kononov, 1989). Subsequently, in the Early Pliocene (Late Miocene?), volcanism within the Central Range apparently lost its connection with the subduction processes, inasmuch as the subduction zone corresponding to this volcanic belt was no longer active at that time (Legler, 1977). However, volcanic activity continued here until the Late Holocene, because the volcanic processes tend to exhibit greater inertia than the tectonic ones. The Western Kamchatka volcanic belt probably developed as a non-island-arc structure from the very onset.

Emplacement of the new branch of the trench and the new subduction zone apparently was accompanied by the generation of deep faults in the nonaccreted block, which promoted the ascent of within-plate magmas from deep-seated mantle sources (Volynets et al.. 1987, 1990a, 1990b). In the Central Range, within-plate volcanics were formed at the late stages of development of the island-arc volcanic belt, and island-arc and within-plate magmas coexisted in the interior of this structure during the Pliocene to Holocene periods..In Eastern Kamchatka, manifestations of within-plate magmas preceded the formation of the Pliocene-Quaternary island-arc volcanic belt, but in Western Kamchatka they are unrelated to island-arc volcanics.

The principal geodynamic parameters of the Kurile-Kamchatka island-arc system change noticeably along the arc. For example, from the Southern Kuriles towards Kamchatka, the convergence angle of the lithospheric plates increases (from 45-50° to 85-90°), the angle of the subducted plate dip also increases (from 36-40° to 45-50°), and the rate of plate convergence decreases (from 10 cm/year to 8.5 cm/year) (Avdeyko et al., 1991; Pushcharovskiy, 1992). The latest geophysical data (Balesta, 1981, p. 134; Sergeyev and Krasnyy, 1987) show that the thickness of the crust corresponds to continental values throughout the Kurile-Kamchatka island-arc system, which does not agree with earlier data (Gorshkov, 1970). However, the crust's minimum thickness (27-30 km) exists in the Central Kuriles, as noted earlier. Crustal thickness increases both southwards to the Southern Kuriles and NE Hokkaido (32-44 km) and northwards to Kamchatka (36-46 km). The thickness of the "granitic" layer is small (5-10 km) and it varies slightly along the arc. Only under volcanic belts of the Central Depression and Central Range does the thickness of the "granitic" layer correspond to continental (15-20 km).

Distribution and Geologic Position of Rock Varieties and Volcanic Series Types

The composition of Late Cenozoic volcanic rocks of the Kurile-Kamchatka island-arc system varies from basalt to rhyolite, but the proportion of rock varieties differs in the Kurile and Kamchatka segments (Volynets et al., 1987; Fedorchenko et al.. 1989). In the Kuriles, rocks of intermediate composition generally predominate: basaltic andesites and andesites (60-70%), basalts (17-20%), and acidic rocks (only 12-16%). In Kamchatka, according to Melekestsev's data (Volvnets et al.. 1987), basalts and basic basaltic andesites dominate (ca. 50%). and there is a higher proportion of acidic rocks than in the Kuriles (ca. 30%). However, some authors (e.g., Yermakov. 1987) consider that the proportion of acidic volcanics in Kamchatka also does not exceed 15 to 18%.

Outbursts of basic and acidic volcanism were episodic, with eruptions *of* profuse acidic lava always preceded by the intensive basaltic volcanism.

The Kurile-Kamchatka island-arc volcanic rocks can be subdivided in terms of their K ,0 content into low-K, middle-K, high-K. and shoshonite-latite scries and in terms of their total alkali content into lavas of normal and alkaline series. The latter include the lavas of shoshonite-latite and. in part, high-K series. Within each series, following Gill (1981), tholeiitic and calc-alkaline varieties can be distinguished in terms of their FeO^*/MgO ratio.

Most lavas in both Kamchatka and the Kuriles belong to the intermediate-K calc-alkaline series. They are found in all zones and volcanic belts (Fig. 2). Lavas of the low-K series occur in the frontal zones of volcanic belts ami are dominant in the Kuriles, frequent in Southern and Eastern Kamchatka, and rare in the Central Depression and Central Range. Lavas of the high-K series are located in the back-arc

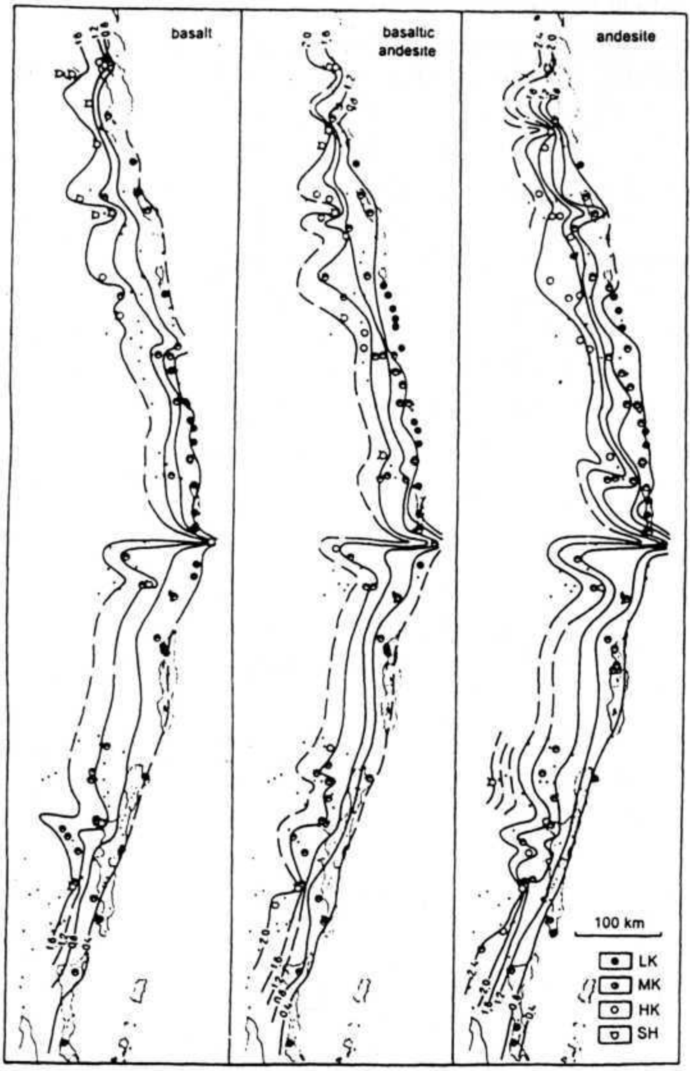


Fig. 2. Distribution of $K_2$0 in the Quaternary volcanics of the Kuriles (after Pushcharovskiy, 1992). Rock series: LK = low-K. MK = intermediate-K, HK = high-K normal alkalinity, SH = subalkaline high-K and shoshonite-latite. Isarithms show $K_2$0 concentration (wt%). Circles indicate subaerial and submarine volcanoes for which analytical data are available and dots indicate other volcanoes.

zones of all volcanic belts, but in the Central Range also are found in the central zone. Finally, lavas of the shoshonite-latite series are rare: they have been found at some volcanoes of the back-arc zones of the Northern Kuriles (among basalts) and Southern Kamchatka, as well as in the rear and central zones of the Central Range. Such a distribution of different rock series is sometimes broken within large transverse fault zones (Fig. 2), where lavas of the high-K series sometimes are found even in the frontal zones of volcanic belts (Volynets, 1987; Pushcharovskiy, 1992). As for the tholeiitic and calc-alkaline series, the former are more typical in the frontal and the latter in the central and rear zones of the volcanic belts (Pushcharovskiy, 1992).

Lavas of volcanic series of the within-plate geochemical type include both subalkaline and alkaline types. They are divided into the follow-

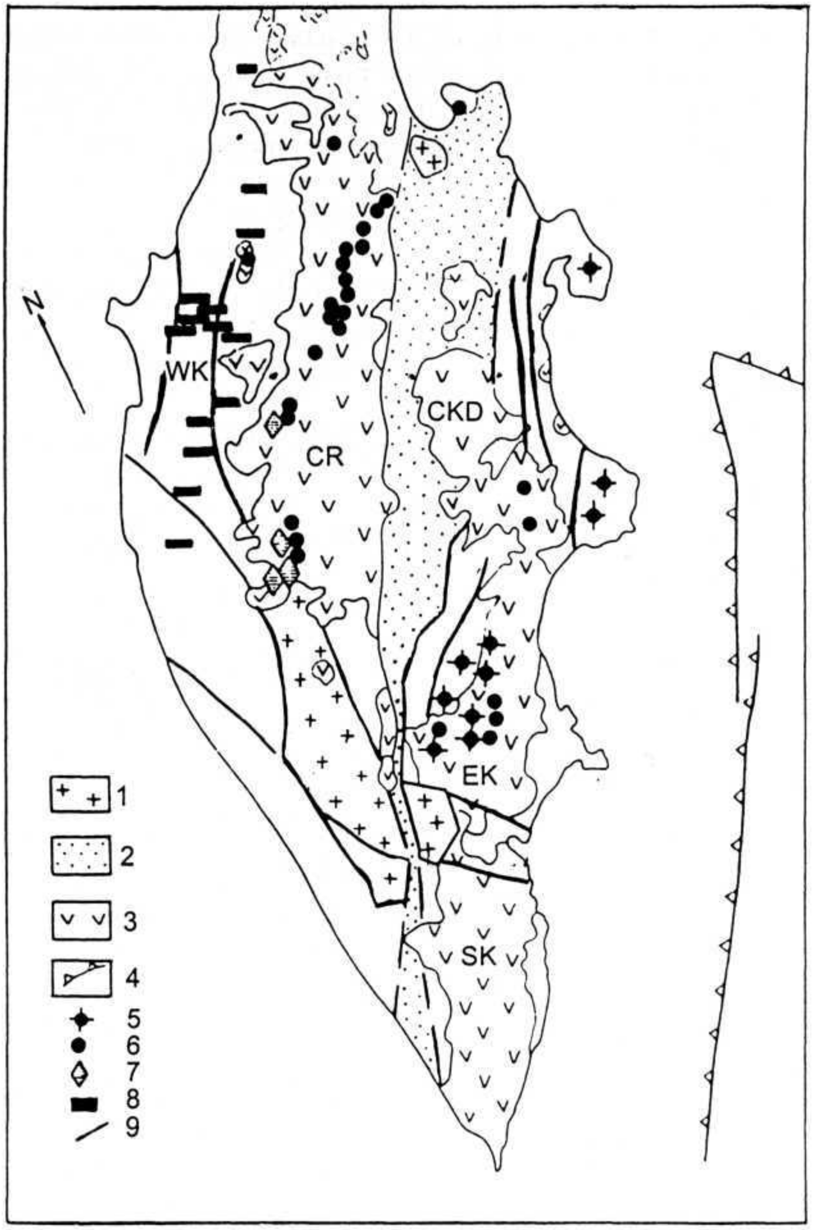


Fig. 3. Distribution of the rocks of the within-plate geochemical type in Kamchatka. Legend: 1 = ancient metamorphic basement; 2 = Central Kamchatka Depression (Central Rift); 3 = Pliocene-Quaternary volcanic belts: SK = Southern Kamchatka. EK = Eastern Kamchatka, CKD = Central Kamchatka Depression, CR = Central Range. WK = Western Kamchatka; 4 = axis of deep-sea trench; 5-8 = locations of the rocks of within-plate geochemical type series: 5 = K-Na alkali basalts, 6 = K-Na alkali olivine basalt, 7 = K-Na transitional basalt-comendite, 8 = magnesian K alkali basalt; 9 = major faults.

ing series: K-Na alkali basalt (Late Miocene, Eastern Kamchatka); K-Na alkali olivine basalt (Pliocene, Eastern Kamchatka and Late Pleistocene-Holocene, Central Range); K-Na transitional basalt-comendite (Pliocene-Early Pleistocene, Central Range); magnesian K-alkali basalt and associated shoshonite-latite (Late Miocene-Pliocene, Western Kamchatka).

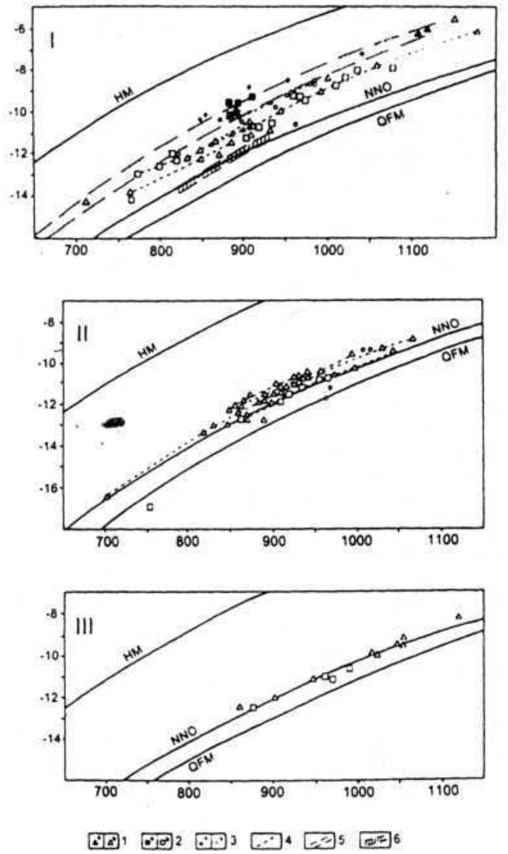


FIG. 4. Magnetite-ilmenite temperature-oxygen fugacity diagram for volcanics of Kurile-Kamchatka island-arc system. Temperatures (°C) displayed along horizontal axes and log fO_2 displayed on vertical axes. Calculation method from Powell and Powell (1977), maximum T data used. Legend: I—III = rock series: I = island-arc. II—III = within-piate geochemical type (II = K-Na, III = K); 1-3 = rock types: 1 = basalt, 2 = basaltic andesite and andesite, 3 = dacite and rhyolite (a = with hornblende + biotitc associations of phenocrysts, b= with pyroxene + olivine associations of phenocrysts); 4 = dashed lines connect data for different magnetite-ilmenite intergrowths from one sample: 5-6 = fields of lavas from USA and Alaska with hornblende and biotite paragenesis (5) and pyroxene paragenesis (6), after Ewart (1983).

Manifestations of volcanics of the within-plate geochemical type on Kamchatka during the Late Cenozoic are not controlled by the Central Depression or Central Rift (Yermakov, 1987). They also do not depend on outcrops of old metamorphic basement blocks (Fig. 3). Within-plate K-Na subalkaline and alkaline basaltic series form cinder-cone zones within special linear structures that obliquely cut the modern island-arc volcanic belts. Lavas of basalt-comendite series are located within the large volcanotectonic depression in the rear zone of the Central Range volcanic belt. The rocks of K-basalt and accompanying shoshonite-latite series occur along the boundary of the ancient continental Okhotsk plate, which is arbitrarily drawn by some investigators (e.g., Khanchuk, 1983).

Mineral Composition of Volcanic Rocks

The phenocryst association types and mineral compositions in lavas correspond to different geochemical series, SiO_2 contents, Mg numbers, and also volatile contents (first of all H_2O) and oxygen fugacity. Phenocryst crystallization in calc-alkaline amphibole-containing island-arc volcanics from Kamchatka and the Kuriles occurs at essentially higher $f(O_2)$ than that in tholeiitic pyroxene lavas: 2-3 log $f(O_2)$ higher than the NNO buffer for the former and 0.5-2.0 log$f(0_2)$ higher than the NNO for the latter, as determined by magnetite-ilmenite geobarometry-geothermometry. Crystallization of the melts that produce lavas of the within-plate geochemical type occurs at lower $f(O_2)$ values (near NNO buffer) than the melts that produce lavas of the island-arc geochemical type (Fig. 4).

Pyroxenes from the island-arc tholeiitic series evolve in a tholeiitic trend accompanied by the formation of pigeonites and subcalcium augites in the groundmass of the rocks. However, these minerals are very rare in calc-alkaline lavas and were found only in some low-K and intermediate-K basalts (Fig. 5). The evolution of clinopyroxenes from within-plate basalts proceeds in the direction of titaniferous salites and fassaites (Fig. 6), and that of clinopyroxenes from differentiated basalt-comendite series toward ferroaugites, sodium ferrohedenbergites, aegirine-hedenbergites, and aegirines.

The clinopyroxenes from within-plate basalts are more titaniferous than clinopyroxenes from the island-arc series (Fig. 7). The same relationship is characteristic also of amphiboles and micas (Fig. 8).

Crystallization of most phenocrysts in lavas takes place at shallow depths, probably within

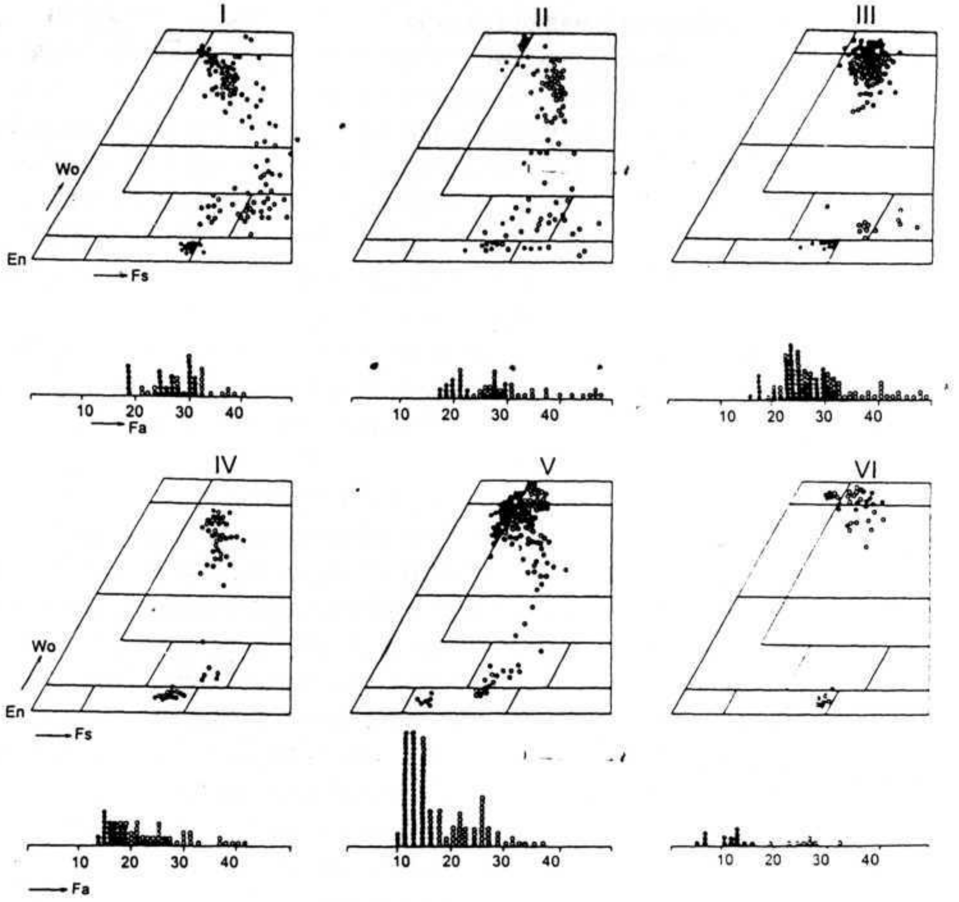


FIG. 5. Composition of pyroxene and olivines in the island-arc basalts from the Kurile-Kamchatka region. Legend: I—III = tholeiitic: I = low-K, II = intermediate-K, III = high-K and shoshonite-latite: IY-VIII = calc-alkaline: IV = intermediate-K, intermediate-Mg, V = intermediate-K, high-Mg; VI = hish-K. intermediate-Mg.

magma chambers of subvolcanic intrusions in shallow magma chambers and in volcanic channels, sometimes during the eruptions. This conclusion is based on comparisons of the composition, morphology, and structural stage of plagioclases from the different depth facies and also from investigations of the content and composition of plagioclases from lavas of Kamchatka and Kurile modern eruptions.

Most phenocrysts in lavas crystallized from the melts corresponding to these lavas by chemistry, and these phenocrysts are not relict or xenogenic. This inference is supported by the distinct correlation between the chemical composition of rock-forming minerals (phenocrysts and microlites) and that of host rocks, by successive change of mineral composition each geochemical rock series from basic to acidic lavas, and by the presence of essential variations in phenocryst contents (sometimes 10-20 times) in lavas of some eruptions without visible modification in lava bulk chemistry.

However, there are disequilibrium phenocryst assemblages in many Kurile-Kamchatka calc-alkaline lavas, mainly those that are intermediate in SiO_2 content. These lavas contain plagioclase with anorthite and andesine cores and labrador-bitownite rims, as well as chromium diopside and augite together with magnesian and ferrous olivines. and, finally, quartz and magnesian olivine. The occurrence of such assemblages may be interpreted as resulting

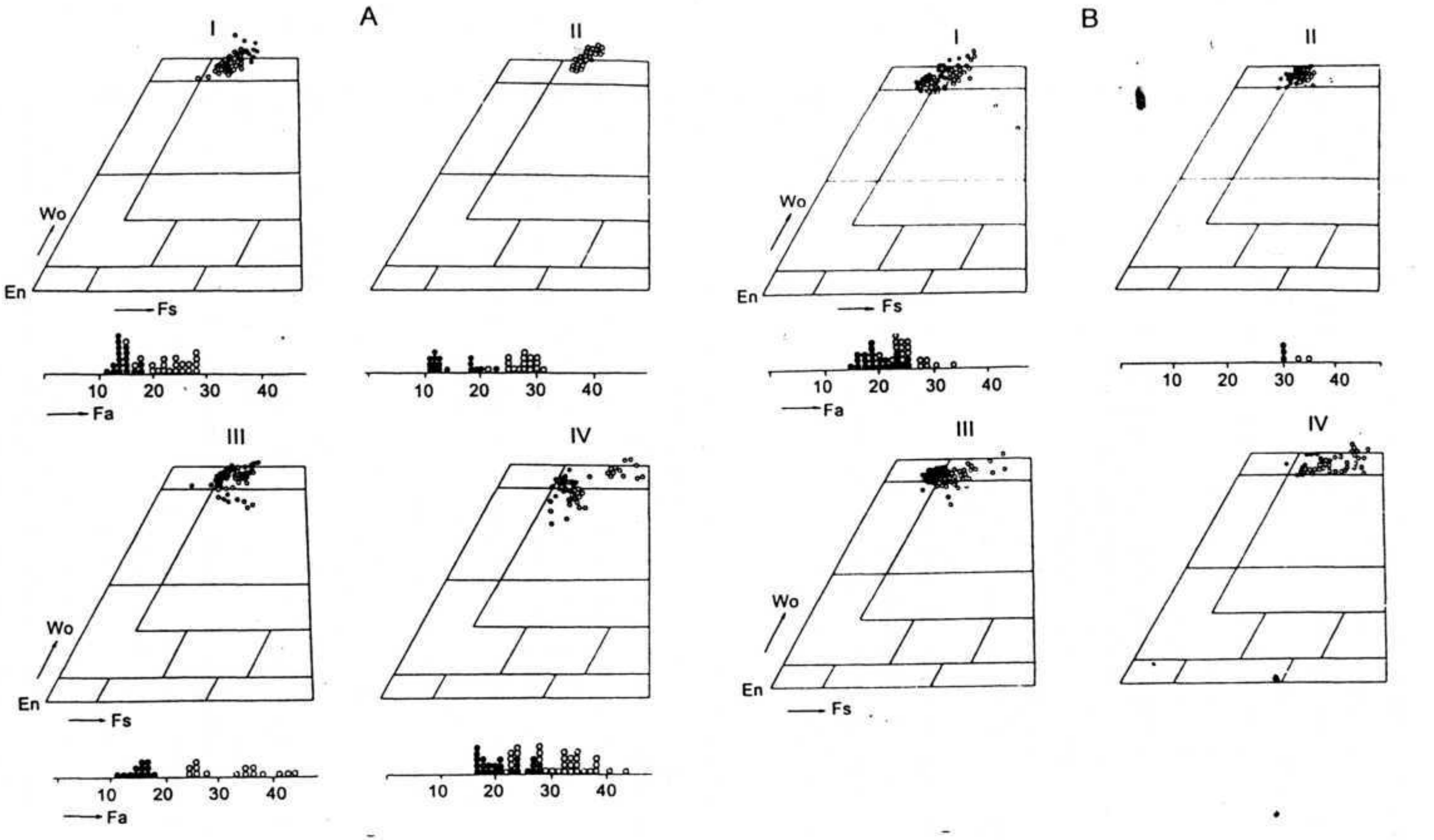


Fig. 6. Composition of pyroxenes and olivines in the Kamchatka basalts of within-plate geochemical type, Legend: A = lavas of K-Na alkali basalt series from East Kamchatka (I, II) and K-Na alkali olivine basalt series from the Central Range (III-IV): I, III = high-Mg, II, IV = intermediate-MG; B = lavas of K alkali basalt from West Kamchatka: I = absarokites, II = mica shonkinites, III = phlogopite trachybasalts, IV = biotile syenites. Solid circles = phenocryst cores; open circles = phenocryst rims and microlites.

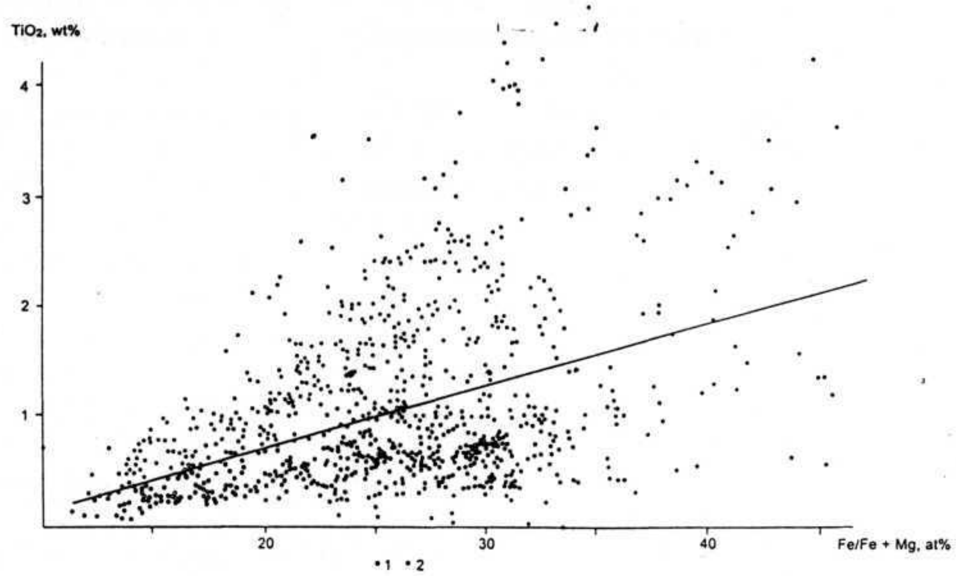
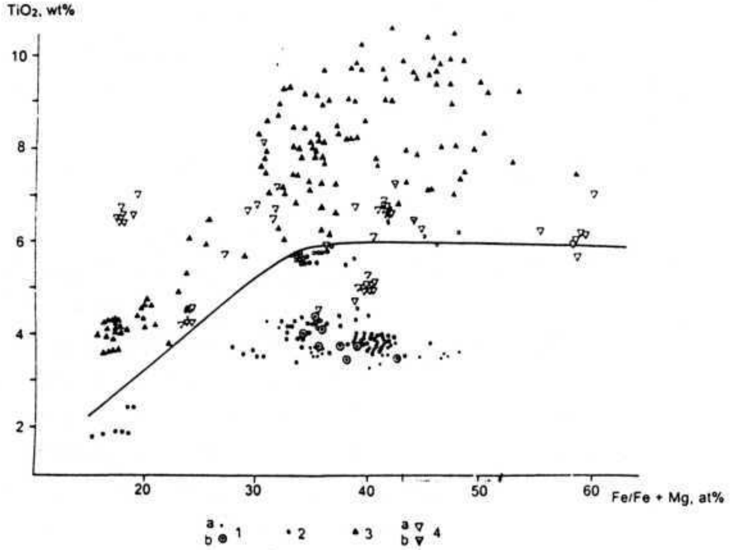


FIG. 7. TiO_2 content in clinopyroxenes of basalts of island-arc (1) and within-plate (2) geochemical types from Kamchatka.



Fig;. 8. TiO_2 content in micas of volcanic rocks from the Kurile-Kamchatka island-arc system. Legend: 1-2 = volcanic series of island-arc geochemical type: 1 = middle-K, 2 = high-K and shoshonite-latite; 3-4 = volcanic series of within-plate geochemical type: 3 = K alkali basalt. 4 = K-Na alkali olivine basalt and basalt-comendite; a = microprobe data; b = wet (chemistry data.

from magma mixing. The magma mixing idea is confirmed by glasses of different compositions found in such lavas, as well as lavas and pumices with bands of variable composition in association with rocks characterized by disequilibrium mineral assemblages.

TABLE 1. Whole-Rock Major and Trace Element Contents in the High-Al Basalts of the [redacted] Island-Arc Geochemical Type from the Kurile-Kamchatka System (representative analyses)

Samples:[a] Components[b]	1	2	3	4	5	6	7	8	9
SiO_2	50.39	48.32	51.38	50.92	51.38	51.72	50.98	51.86	51.07
TiO_2	0.84	0.85	0.80	0.95	0.94	0.99	1.15	0.67	1.32
Al_2O_3	18.44	19.55	18.59	17.60	16.29	18.36	18.52	20.44	18.54
Fe_2O_3	3.18	3.06	3.00	2.87	2.95	2.91	3.65	4.09	4.15
FeO	7.70	7.56	5.63	6.20	6.41	6.82	5.86	2.50	4.66
MnO	0.19	0.16	0.17	0.16	0.18	0.20	0.20	0.12	0.17
MgO	6.07	7.01	4.71	6.86	7.78	4.32	5.04	2.66	3.46
CaO	10.05	11.26	9.85	10.45	9.25	9.24	8.98	8.34	8.18
Na_2O	2.11	1.90	2.98	2.95	2.85	3.26	3.13	3.28	3.14
K_2O	0.22	0.32	1.36	0.73	1.20	1.93	1.95	3.30	2.90
P_2O_5	0.06	0.12	0.20	0.26	0.22	0.32	0.40	0.58	0.62
L.O.I.	0.46	0.09	1.02	0.76	0.22	0.28	0.00	0.82	0.57
H_2O	-	-	-	-	-	-	0.48	0.94	1.15
Total	100.51	100.32	99.68	100.71	99.66	100.34	100.34	99.62	99.93
K_{Mg}[c]	0.51	0.55	0.50	0.58	0.60	0.45	0.50	0.43	0.42
Cs	-	0.13	-	0.30	0.36	-	0.72	1.0	0.53
Rb	2.2	2.0	20	18	13	41.4	42	52.5	68.1
Sr	283	258	614	422	541	676	810	1020	569
Ba	92	102	282	300	445	396	714	1610	466
La	<1	1.8	11	7.9	10.7	13	13.0	17.5	12.8
Ce	<2	4.9	26	18.9	24.0	26	26.0	32.5	32.6
Nd	4	3.8	16	12.4	13.0	24	16.6	17.4	21.2
Sm	-	1.42	-	3.65	3.05	-	4.25	4.76	5.93
Eu	-	0.50	-	1.25	0.95	-	1.40	1.55	1.98
Gd	-	2.1	-	3.9	3.4	-	4.6	-	-
Tb	-	0.37	-	0.66	0.55	-	0.70	0.70	1.09
Yb	-	1.65	-	2.22	2.05	-	2.31	1.79	2.97
Lu	-	0.22	-	0.31	0.27	-	0.34	0.25	0.43
Y	16.8	-	22	17	18	23	-	18.8	32.0
Th	<1	0.10	-	1.1	1.1	1	1.8	3.17	2.05
U	-	0.07	-	0.43	0.50	-	1.3	2.09	1.89
Zr	31	-	52	116	137	86	-	115	176
Hf	-	0.7	-	2.1	2.8	-	3.0	2.52	4.07
Nb	1.0	-	4.9	3.0	7.0	5.0	-	2.8	5.7
Ta	-	0.026	-	0.15	0.29	-	0.30	0.18	0.35
Sc	41	37.5	27	41	31.5	28	17	17	19
V	361	350	343	350	180	348	250	235	271
Cr	37	70	250	295	346	13	22	15	20
Co	33	36.8	26	39.0	36.0	27	19.3	19	25
Ni	18	45	21	68	103	8	13	12	13

[a] Samples 1, 3, and 6 from Kuriles, others from Kamchatka. Legend: 1 = sample V17-669, Ol-Opx-Cpx-Pl basalt, Medvezh'ye caldera, Zevok bay, Iturup island; 2 = sample 5939, Ol-Pl basalt, Ilinsky volcano, Southern Kamchatka; 3 = sample V40-20/2, Amph-containing Ol-Opx-Cpx-Pl basalt, submarine slope of island-volcano Chirinkotan; 4 = sample 5864, Ol-Pl basalt, cinder cone Ucho, Southern Kamchatka; 5 = sample 6446/1, Ol-Pl basalt, cinder cone in Ichinskaya zone of cinder cones, Central Range; 6 = sample 6002/1, Phl and Amph-containing Ol-Cpx-Pl basalt, Alaid volcano, Atlasova Island, 1972 eruption; 7 = sample 6746, Ol-Cpx-Pl basalt, Kekuknayskiy volcano, Central Range; 8 = sample 7319, plagiophiric basalt, Tekletunup volcano, Central Range; 9 = sample 6955, Ol-Cpx-Pl basalt, Bolshaya Ketepana volcano, Central Range.

Geochemical rock series: 1 and 2 = low-K; 3, 4, and 5 = intermediate-K; 6 and 7 = high-K; 8 and 9 = shoshonite-latite.

[b] Here and in Tables 2 and 3 REE, Cs, Th, U, Hf, Ta, partly Sc, Ba, Sr, Cr, Co, and Ni contents determined by INAA technique; Rb, V, Y, Zr, Nb, partly Ba, Sr, Sc, Cr, Co, Ni, La, Ce and Nd by X-ray fluorescence. Major element analyses performed at the Institute of Volcanology, Russian Academy of Sciences, by wet chemistry, at the Institute of Geochemistry, Russian Academy of Sciences, and at Copenhagen University by X-ray fluorescence.

[c] K_{Mg} = Mg/Mg +Fe, at.%

Analyses of trace elements in the samples 1, 3, 6, 8, and 9 were performed at Copenhagen University by Dr. J. C. Bailey; others were performed at the Institute of Geology and Geophysics, Russian Academy of Sciences, V. S. Parkhomenko, analyst.

TABLE 2. Whole-Rock Major and Trace Element Contents in the Magnesian Basalts of the [redacted] Island-Arc Geochemical Type from the Kurile-Kamchatka System (representative analyses)

Samples:[a] Components	1	2	3	4	5	6	7	8	9
SiO_2	50.38	51.90	49.42	47.12	51.64	49.52	50.76	50.16	48.52
TiO_2	0.48	0.54	0.72	0.87	0.90	0.89	0.67	0.67	0.96
Al_2O_3	16.24	10.57	14.79	15.69	12.36	13.96	10.61	12.27	14.73
Fe_2O_3	2.63	1.75	2.96	2.93	4.32	4.00	1.97	3.12	3.14
FeO	6.38	6.65	5.84	6.89	4.90	5.20	6.39	5.52	5.80
MnO	0.17	0.13	0.18	0.16	0.16	0.18	0.23	0.13	0.16
MgO	10.50	14.11	10.16	11.32	11.20	12.05	18.68	15.02	10.41
CaO	11.63	11.60	12.69	11.12	8.74	9.26	6.50	8.46	10.12
Na_2O	1.56	1.82	2.15	2.18	2.76	2.85	2.13	2.31	2.55
K_2O	0.35	0.37	0.68	0.98	1.42	1.04	0.92	1.68	2.02
P_2O_5	0.07	0.09	0.14	0.22	0.23	0.20	0.24	0.56	0.30
L.O.I.	0.19	-	0.22	0.12	0.33	0.16	0.73	0.64	0.23
H_2O	0.00	0.75	-	0.28	0.24	0.24	0.27	-	0.56
Total	100.58	100.28	99.95	99.88	99.20	99.55	100.10	100.54	99.50
K_{Mg}	0.68	0.75	0.68	0.68	0.69	0.71	0.80	0.79	0.68
Cs	0.35	0.21	0.41	0.20	0.56	0.12	0.37	1.00	
Rb	5	4	9	15	-	11	15	41	44
Sp	320	220	380	198	707	488	-	462	750
Ba	69	132	192	162	816	362	353	509	311
La	3.14	2.93	6.23	8.87	9.77	6.2	5.02	8.96	31.0
Ce	7.7	6.9	14.7	20.4	24.3	14.8	12.7	22.3	66.1
Nd	-	4.8	9.0	12.0	15.60	9.5	-	15.0	44.0
Sm	1.45	1.60	2.43	3.37	4.10	2.74	2.34	4.20	10.4
Eu	0.53	0.54	0.80	1.04	1.14	0.90	0.73	1.23	2.82
Gd	-	-	-	-	-	2.8	-	-	7.2
Tb	0.27	0.31	0.48	0.53	0.52	0.52	0.37	0.60	0.91
Yb	1.20	1.10	1.49	1.76	1.50	1.61	1.11	1.70	1.48
Lu	0.184	0.157	0.230	0.265	0.223	0.21	0.176	0.245	0.18
Y	-	14	-	19	-	17	-	20	20
Th	0.40	0.45	1.08	1.36	0.84	0.41	0.46	0.89	2.0
U	0.10	-	0.40	0.40	0.52	0.37	0.50	0.60	0.85
Zr	-	47	-	56	-	112	-	86	138
Hf	0.87	1.03	1.45	1.88	2.11	2.1	1.64	2.57	3.4
Nb	-	-	-	2.5	-	-	-	2.3	3.6
Ta	-	-	0.10	0.14	0.08	0.07	0.09	0.08	0.07
Sc	39.9	44.3	46.1	39.6	29.9	36.0	24.2	33	35
V	360	200	230	324	-	225	-	248	330
Cr	360	1023	407	1092	1068	826	1878	884	541
Co	46.9	48.3	39.2	46.1	30.0	47.6	59.9	46.8	40.7
Ni	100	330	150	203	213	235	-	230	175

[a] Samples 1, 3, and 4 from Kuriles, others from Kamchatka. Legend: 1 = sample V15-90/5, Ol-Cpx-Pl basalt, submarine slope island-volcano Brat Chirpoyev; 2 = sample 5891, Ol-Cpx basalt ("avachit"), Avachinskiy volcano; 3 = sample V25-36/1, Ol-Opx-Cpx basalt, submarine volcano 3.19 (North Kuriles); 4 = sample V40-8/2, Ol-Cpx basalt, submarine slope of island-volcano Broutona; 5 = sample 1002/2, Ol-Cpx basalt, Zarechnyy volcano; 6 = sample 5606, Ol-Cpx basalt, Kharchinskiy volcano; 7 = sample 1023, Ol basalt, the same locality; 8 = sample 1188/1, Phl-Amph-Cpx-Ol basalt, Shiveluch volcano; 9 = sample 7373, Ol-Cpx basalt, Chin cinder cone, northern part of Central Range.

Geochemical series: 1 and 2 = low-K; 3-7 = intermediate-K; 8 = high-K; 9 = absarokite-shoshonite-latite.

Rare elements data for analyses 1-4, 7, and 8 performed in New Mexico Institute of Mining and Technology, by Dr. P. Kyle; analysis 5 in Cornell University, by G. M. Yogodzinskiy; analyses 6 and 9 in the Institute of Geology and Geophysics, Russia Academy of Sciences, V. S. Parkhomenko, analyst.

Bulk Chemistry and Trace Element Composition of Volcanic Rocks

Most island-arc volcanic rocks of Kamchatka and the Kuriles belong to the high-Al type and have low Mg, Ni, and Cr concentrations and Ni/Co and Cr/V ratios (Table 1). However, there are magnesian basalts in each geochemical rock series with magnesian numbers (K_{Mg} = Mg/Mg + Fe, at%) of 0.65-0.75, and high Ni and Cr contents (Table 2). Magnesian varieties also are found among andesites (Volynets et al., 1987, 1990a). Usually magnesian basalts of the Kurile, Kamchatka, and other island-arc systems have low or moderate Al_2O_3 concentrations (e.g., Gorton, 1977; Nye and Reid, 1986; Volynets et al., 1987, 1990a; Kay and Kay, 1994); however, sometimes high-Al magnesian basalts occur (Bartels et al., 1991). Basalts of the K and K-Na alkali basalt series of the within-plate geochemical type belong generally to the high-Mg type (K_{Mg} > 0.65), whereas basalts of the K-Na alkali olivine basalt and basalt-comendite series belong to high-Al type (Table 3).

The identification of high-Mg lavas is quite important, since only magmatic melts with $K_{Mg,}$ = 0.65-0.75 may be in equilibrium with mantle peridotite. High-Mg lavas probably are closer in composition to primary mantle melts than high-Al lavas, which in most cases are differentiated varieties. This hypothesis agrees well with data indicating that in each rock series the magnesian basalts are poorer in incompatible trace elements than in the high-Al basalts (see Tables 1 and 2) and with the fact that groundmass composition of many magnesian basalts is close to bulk composition of common high-Al basalts. This also is corroborated by the results of calculations based on REE contents for the Central Kamchatka Depression lavas, showing that high-Al basalts may be the products of high-Mg basalt fractionation (Volynets et al., 1990a). However, experiments by Bartels et al. (1991) have shown that high-Al magnesian basalts also may be one of the primary magma types produced by the partial melting of the plagioclase-spinel lherzolite. Mg-basalts are present in each geochemical rock series having distinctly different incompatible trace element concentrations, and this is a clear indication that primary magmas are different for lavas of each series.

The main geochemical features of island-arc volcanics are distinctly visible when compared to lavas from other geodynamic situations using various geochemical discriminant diagrams, or "spidergrams." One such diagram, proposed by Wood (1980), demonstrates the depletion of island-arc lavas from Kamchatka in Ta compared with Th and Hf (Fig. 9). Note that there are some samples of basalts enriched in Ta among the moderate-Ti, intermediate-K basalts from the Central Range volcartic belt. They are similar to intermediate-K basalts from the Rio Grande Rift, which are transitional from island-arc to within-plate volcanics in terms of geochemistry (Volynets et al., 1990a). Another diagram depicts the distribution of hygromagmatophile rare elements in Kamchatka basalts (Fig. 10). On the whole the view of distribution curves for the basalts from various island-arc geochemical series, including Mg- and Al-types, remains very similar, although the concentrations of most hygromagmatophile rare elements, used in this spidergram, differ greatly. This picture is quite typical of basalts and basaltic andesites from other ocean-continent transition zones (Holm, 1985). Their distribution curves have a visible left-right slope, i.e., one can observe prevailing enrichment of island-arc lavas in Ba, U, and K as compared with La, Ce, F, and Zr, and in the latter as compared with Ti, Y, and Yb. In addition, all the curves show a pronounced Ta and Nb minimum and Sr maximum, and those for the Kurile-Kamchatka and certain other island-arcs show a Th minimum as well.

Note that the degree of element enrichment of island-arc magmas corresponds in general both to coherent crystallochemical properties of the elements (Wood, 1979) and to their mobility in the fluid phase (Tatsumi et al., 1986). The Sr maximum on the distribution curves (and high Al_2O_3 contents in lavas) may indicate that plagioclase (Sr mineral-concentrator) occurs in the source of the island-arc magmas, i.e., the gabbroization processes take place there. This source characteristic is confirmed by the results of studying ultramafic inclusions in island-arc lavas (Yermakov et al., 1987; Volynets et al., 1990c). Ta and Nb minima on the aforementioned curves for island-arc lavas conform well with their inertia in the fluid phase, which enriches the mantle source of island-arc magmas (Tatsumi et al., 1986).

TABLE 3. Whole-Rock Major and Trace Element Content in the Kamchatka Basalts of the Within-Plate Geochemical Type (representative analyses)

Samples:[a]				ЦОБ		БК		ЦБ	
Components	1	2	3	4	5	6	7	8	9
SiO_2	45.54	44.80	44.84	46.90	51.10	48.78	46.11	50.72	52.45
TiO_2	1.66	2.88	2.75	1.67	1.90	1.92	1.40	1.80	2.08
Al_2O_3	15.03	15.87	15.00	15.60	16.55	17.73	11.70	17.70	14.95
Fe_2O_3	2.66	3.57	6.19	2.34	3.43	4.23	3.78	5.10	4.41
FeO	7.69	5.16	2.70	7.61	5.01	5.76	4.75	2.69	2.81
MnO	0.13	0.24	0.17	0.17	0.14	0.14	0.17	0.15	1.25
MgO	10.38	7.77	6.68	10.50	6.49	5.90	12.67	6.70	4.96
CaO	7.88	7.22	6.45	9.59	8.59	8.88	7.40	6.70	5.35
Na_2O	2.88	2.59	4.96	3.00	3.75	3.60	0.97	2.15	2.09
K_2O	1.66	2.70	1.33	1.85	2.14	1.73	3.89	5.89	7.25
P_2O_5	0.43	1.09	1.30	0.48	0.54	0.63	1.10	0.86	0.77
L.O.I.	2.66	3.42	4.91	0.33	0.44	0.00	2.83	-	0.62
H_2O^-	1.22	2.03	2.42	0.07	0.07	0.46	2.70	3.43	1.19
Total	99.82	99.35	99.70	100.11	100.15	99.71	99.47	99.80	99.05
K_{Mg}	0.65	0.62	0.59	0.66	0.59	0.52	0.73	0.62	0.57
Cs	0.43	3.0	-	0.55	0.60	0.25	0.26	0.89	3.4
Rb	16	30	12	30	20	14	58	145	189
Sr	621	1720	510	600	665	740	521	653	1170
Ba	317	1086	793	586	505	485	1345	1643	3080
La	18.2	66.9	109	16.1	21.6	21.0	26.5	54.2	55.5
Ce	34.8	118	234	30.5	43.0	39.9	50.0	107	118
Nd	19.6	46.2	88.2	18.9	31.1	22.0	26.4	41.3	40.7
Sm	4.9	12.5	16.2	4.9	5.8	4.56	5.56	5.60	6.29
Eu	1.65	3.7	4.66	1.7	1.86	1.55	2.39	1.84	1.83
Gd	5.4	9.6	9.6	3.8	5.5	4.6	5.9	4.7	5.4
Tb	0.87	1.3	1.2	0.6	0.87	0.77	0.86	0.74	0.76
Yb	2.0	2.5	2.3	1.71	1.95	2.08	1.60	2.02	2.23
Lu	0.30	0.41	0.35	0.23	0.30	0.26	0.22	0.28	0.34
Y	22.2	23.0	26.1	21.2	21.0	-	24.7	25.1	22.1
Th	2.2	9.5	8.7	1.5	3.0	1.65	4.1	14.4	17.8
U	0.65	2.9	2.9	-	1.25	0.89	2.8	5.6	6.7
Zr	160	473	550	148	202	230	538	481	588
Hf	4.0	11.2	9.6	3.3	4.2	4.5	14.0	11.0	18.0
Nb	17.9	67.0	85.7	9.0	17	20.7	7.9	8.3	11.1
Ta	1.4	5.4	4.65	0.65	1.5	1.13	0.38	0.39	0.66
Sc	35	35.5	18	30	28.5	25.5	28.5	30	22
V	219	187	145	272	150	125	350	250	325
Cr	241	145	188	296	150	26	667	201	125
Co	36.0	35.0	31.0	28.5	34.0	31.6	47.2	25.0	22.3
Ni	160	87	111	160	130	35	430	56	49

[a] 1–3 = Eastern Kamchatka, Valaginsky Ridge, the basin of the Left Zhupanova River, K-Na alkali basalt series N age: 1 = sample 112, Ol-Cpx basalt, 2 = sample 1135, subafiric Ol basalt, 3 = sample 2141, subafiric Ol basalt; 4–6 = Central Range: 4–5 = cinder cones, region of Geologists Valley, K-Na alkali olivine basalt series Q_3^3-Q_4 age: 4 = sample 6805, Ol-Cpx basalt, 5 = sample 6737, Phl-Cpx-Ol-Pl basalt; 6 = Belogolovskiy volcano, K-Na basalt-comendite series N_2^2-Q_1 age, sample 6254, Ol-Pl basalt; 7–9 = Western Kamchatka, basin of Khlebnaya river, K-alkali basalt series N_1^3 age: 7 = sample 6984 mica microshonkinite, 8 = sample 6982, Phl-Cpx-Ol basalt, 9 = sample 6983, Bi syenite.

Analyses of rare elements performed at the Institute of Geology and Geophysics, Russian Academy of Sciences, V. S. Parkhomenko, analyst.

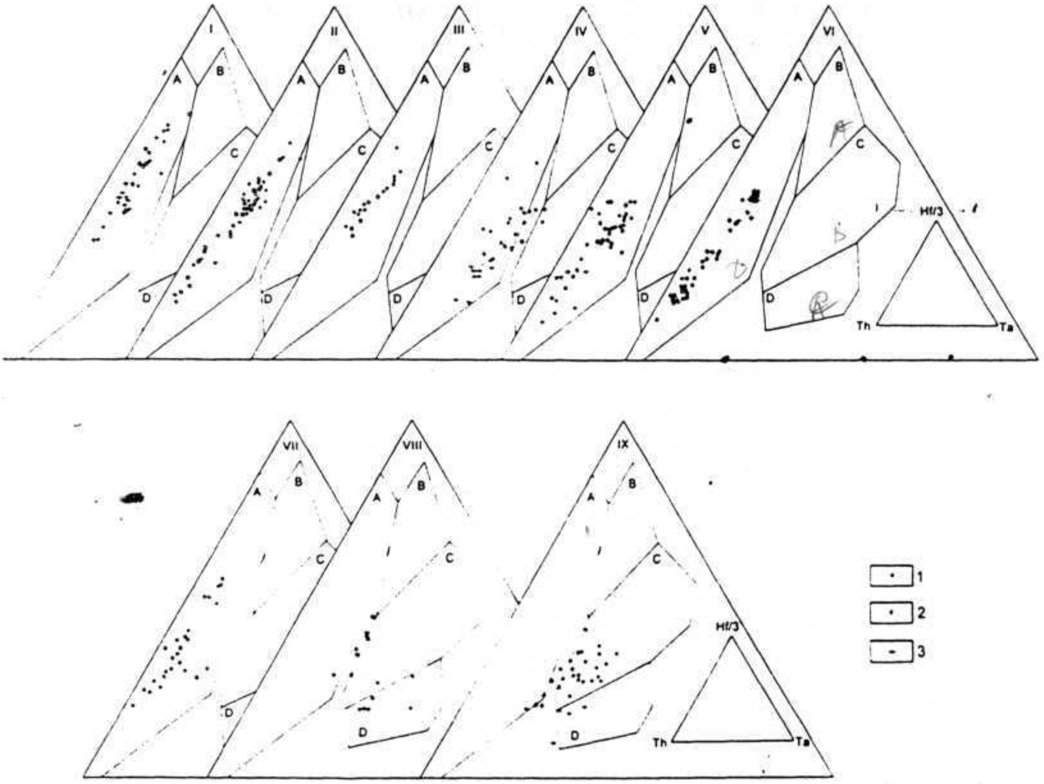


Fig. 9. Th-Hf-Ta systematics of Late Cenozoic volcanic rocks from Kamchatka. Legend: I-IV = rock series of island-arc geochemical type: I = low-K, Southern and Eastern Kamchatka: II—III = intermediate-K, Southern Kamchatka. Eastern Kamchatka, and Central Kamchatka Depression (II = high-Al, III = high-Mg); IV = intermediate-K, Central Range; V - high-K. Southern Kamchatka, Eastern Kamchatka, and Central Kamchatka Depression: VI = shoshonite-latite. Central Range; VII—IX = rock series of within-plate geochemical type: VII = K alkali basalt. Western Kamchatka. VIII = K-Na alkali basalt and K-Na alkali olivine basalts, Eastern Kamchatka, IX = K-Na alkali olivine basalt and K-Na basalt-comendite. Central Range; 1-3 = rock types: 1 = basalt, 2 = basaltic andesite and andesite, 3 = dacite and rhyolite. The fields of rocks are after Wood (1980). A = island arcs and active continental margins; B = mid-oceanic ridges (N-MORB): C = mid-oceanic ridges (E-MORB) and within-plate areas; D = within-plate areas.

Lavas of the within-plate geochemical type are not homogeneous in terms of their geochemical features. The rocks of K-Na subalkaline and alkaline series are quite different from the rocks of K-alkali basalt series. However, both are enriched in Zr, Hf, La, Ce, and Th and the basalts also are enriched in Ti and P and depleted in Ca. Distinctive features of the rocks of the K-Na within-plate series from Kamchatka are high Nb and Ta concentrations, which are 5 to 100 times higher than those in island-arc lavas. Accordingly, they have low La/Ta, La/Nb, Zr/Nb, and Th/Ta ratios and a high Ta/Yb ratio (Figs. 11 and 12), which is typical of within-plate magmatic rocks (e.g., Wood et al., 1980; Gill, 1984). However, variations of Ta and Nb concentration in the lavas of K-Na alkali basalt and K-Na alkali olivine basalt series also are high and they occupy the different fields on the discrimination diagram for Th-Hf-Ta (Fig. 9). Moreover, lavas of K-Na alkali olivine basalt series from Eastern Kamchatka and some intermediate and acidic lavas of the basalt-comendite series from the Central Range fall within the area between fields of within-plate and island-arc magmatic rocks, corresponding to transitional lavas of the Rio Grande Rift.

In the rocks of the K-alkaline basalt series, the Nb and Ta concentrations also are higher than those in island-arc lavas, but only by 2 to

12 times, and the values of the discriminating La/Ta, Zr/Nb, and Th/Ta ratios are not outside the range of those of island-arc magmatic rocks, and on the Th-Hf-Ta diagram (Fig. 9) these rocks also fall within the field of volcanics from ocean-continent transition zones. Only Ta/Yb ratios are on the whole higher in these zones than in the Kamchatka island-arc lavas.

Ta and Nb "island-arc" minima also are found on the spidergrams for K-basalts, but they are absent for the lavas of K-Na alkaline and subalkaline series. At the same time, all within-plate basalts of Kamchatka are distinguished from island-arc basalts by the absence of Sr maxima (Fig. 10). The latter may indicate that plagioclase is lacking in the within-plate magma source.

Within-plate and island-arc volcanics differ also in terms of volatile contents. For example, micas from within-plate lavas have lower Cl concentrations and lower Cl/F ratios than micas from island-arc lavas. Probably fluid from a subducted plate, enriched in sea-water components including Cl, does not take part in within-plate magma generation, unlike the case for the island-arc magmas.

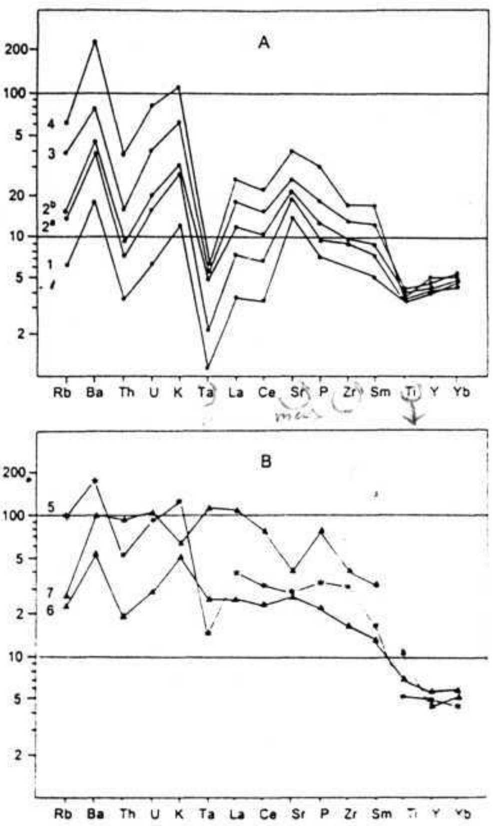


FIG. 10. Spidergrams of hydromamatophile elements in basalts of island-arc (A) and within-plate (B) geochemical types from the Kurile-Kamchatka island-arc system. Normalized to primordial mantle (Wood, 1979). Legend: 1–4 = rock series of island-arc geochemical type: 1 = low-K, 2 = intermediate-K (a = magnesian, b = alumina), 3 = high-K, 4 = shoshonite-latite; 5–7 = rock series of within-plate geochemical type: 5 = K alkali basalt, 6 = K-Na alkali olivine basalt and basalt-comendite, 7 = K-Na alkali basalt.

Isotope Composition of Volcanic Rocks

Nearly 300 published analyses of Sr-isotope composition presently are available for 84 volcanoes of the Kurile-Kamchatka island-arc system (Vinogradov et al., 1986; Bailey et al., 1987; Ikeda et al., 1987; Zhuravlev et al., 1987; Pushcharovskiy, 1992; Churikova and Sokolov, 1993; author's unpublished data). The dominant quantity of values of $^{87}Sr/^{86}Sr$ ratios (~70%) range between 0.7030 and 0.7034, and values of more than 0.7040 are found only for four samples. These values are more characteristic of an oceanic (ansimatic) than a continental (ansialic) type of island arcs (Leeman, 1983). These data may indicate that the ancient sialic basement essentially does not influence the composition of magmatic rocks from the Kurile-Kamchatka system. One body of evidence that supports such an arguement is the absence of a correlation between Sr-isotope ratio values and crustal thickness. In reality, the same variations of Sr-isotope values are observed for the volcanics of the Eastern belt, where the "granitic" layer is thin, and for volcanics ol the Central Mange, where the granitic" layer has a thickness corresponding to continental crust (Balesta, 1981; Volvnets et al., 1987).

Studies of the Sr-isotope composition in the Kamchaka volcanics of within-plate geochemical type have been initiated recently (author's unpublished data). The results of these studies show that the values of $^{87}Sr/^{86}Sr$ ratios in lavas of the K-Na alkali-olivine basalt series correspond to those of island-arc Kamchatka basalts, -whereas they are essentially higher in the lavas of K-Na alkali basalt series (Fig. 13). In the latter they are close to the $^{87}Sr/^{86}Sr$ ratios in K-Na alkali basalts of SW Japan, Korea, and NE

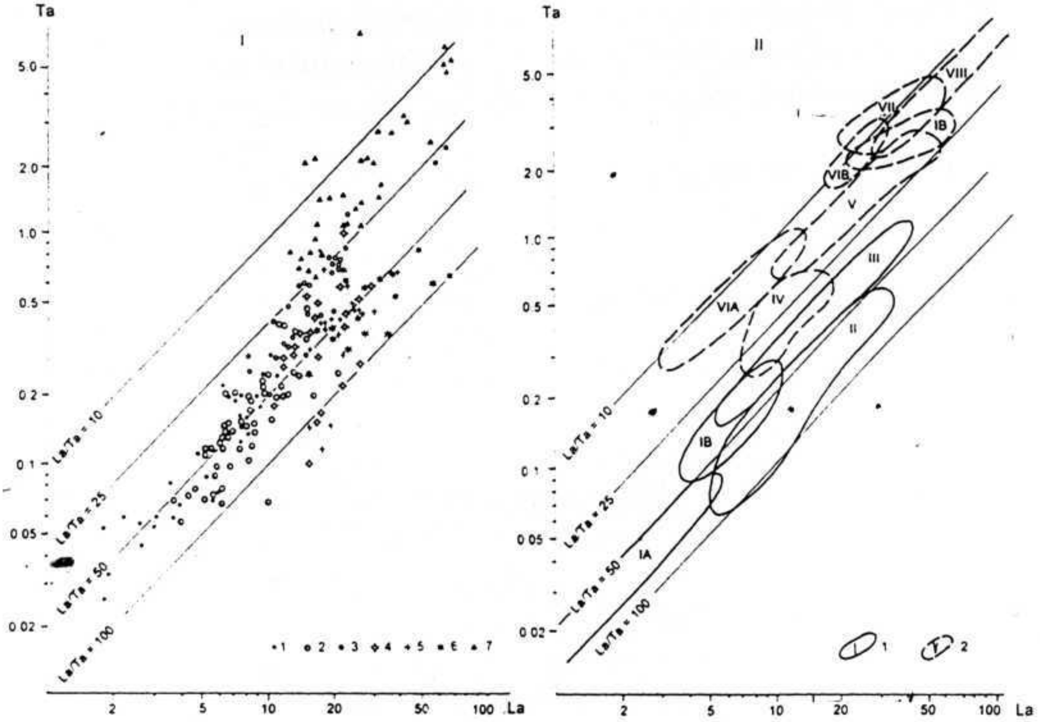


Fig. 11. Ta versus La (ppm) in Late Cenozoic lavas of Kamchatka (I) and other regions (II). Legend: I. 1-5 = rock series of island-arc geochemical type: 1 = low-K. 2-3 = intermediate-K (2 = Southern, Eastern Kamchatka and Central Kamchatka Depression. 3 = Central Range), 4 = high-K,5 = shoshonite-latite; 6-7 = rock series of within-plate geochemical type: 6 = K alkali basalt. 7 = K-Na alkali basalt, alkali olivine basalt, and basalt-comendite. II. 1 = fields of island-arc and active margin volcanic rocks; 2 = fields of within-plate volcanic rocks: I = Japan: A = tholeiitic basalt-andesite series, B = high-Al basalt-dacite series, C = Oki-Dogo trachybasalt-trachyrhyolite series (Wood et al.. 1980): 11 = Southern Chile calc-alkaline basalt-rhyolite series. (Cerlach et al., 1988); III = Santorini calc-alkaline basalt-rhyolite series (Mann. 1983); IV = Rio-Grande Rift basalts (Dungun et al., 1986); Y = Sardinia alkali olivine basalt-trachyte-rhyolite series (Dostal et al., 1982); VI = Hawaii-Emperor Ridge: A = tholeiitic. B = alkaline (Cambon and Bougalt, 1980); VII = Mongolia and Baikal region subalkali and alkali basalts (Kononova et al.. 1986); VIII = East African Rift basalt-pantellerite series (Barbery et al., 1975).

China (Nakamura et al., 1990) and to average values for alkali basalts of continental rifts (Faure, 1986). Thus the magma source for within-plate volcanics differs in Sr-isotope composition from the magma source for island-arc basalts only for K-Na alkali basalts.

Published data on Nd-isotope composition are meager and comprise 26 analyses from Quaternary lavas of the Kuriles (Zhuravlev et al., 1987) and only single analyses for Kamchatka. ^{143}Nd/^{144}Nd values range from 0.512993 to 0.513153 (eNd = 6.9-10.1). In the ^{134}Nd/^{144}Nd-^{87}Sr/^{86}Sr diagram, the Kurile data fall into a small field that is situated on the mantle array and coincides in part with fields of some other island-arcs, first of all the Marianas and Aleutian arcs (Zhuravlev et al., 1987).

The oxygen isotope composition was determined in more than 100 samples of Quaternary island-arc lavas from the Kurile-Kamchatka system (Matsuhisa, 1979; Vinogradov et al., 1986; Ivanov and Ustinov, 1988; Pokrovskiy and Zhuravlev, 1991; author's unpublished data). The d^{18}O values vary from +4.1% to +10.8% (Fig. 14). However, approximately 50% of them fall into the region characteristic of unaltered rocks of mantle genesis: 6.0 + 0.5% (Faure, 1986). Similar features of the distribution of d^{18}O values are found in lavas from volcanic arcs of NE Japan (Matsuhisa, 1979), the

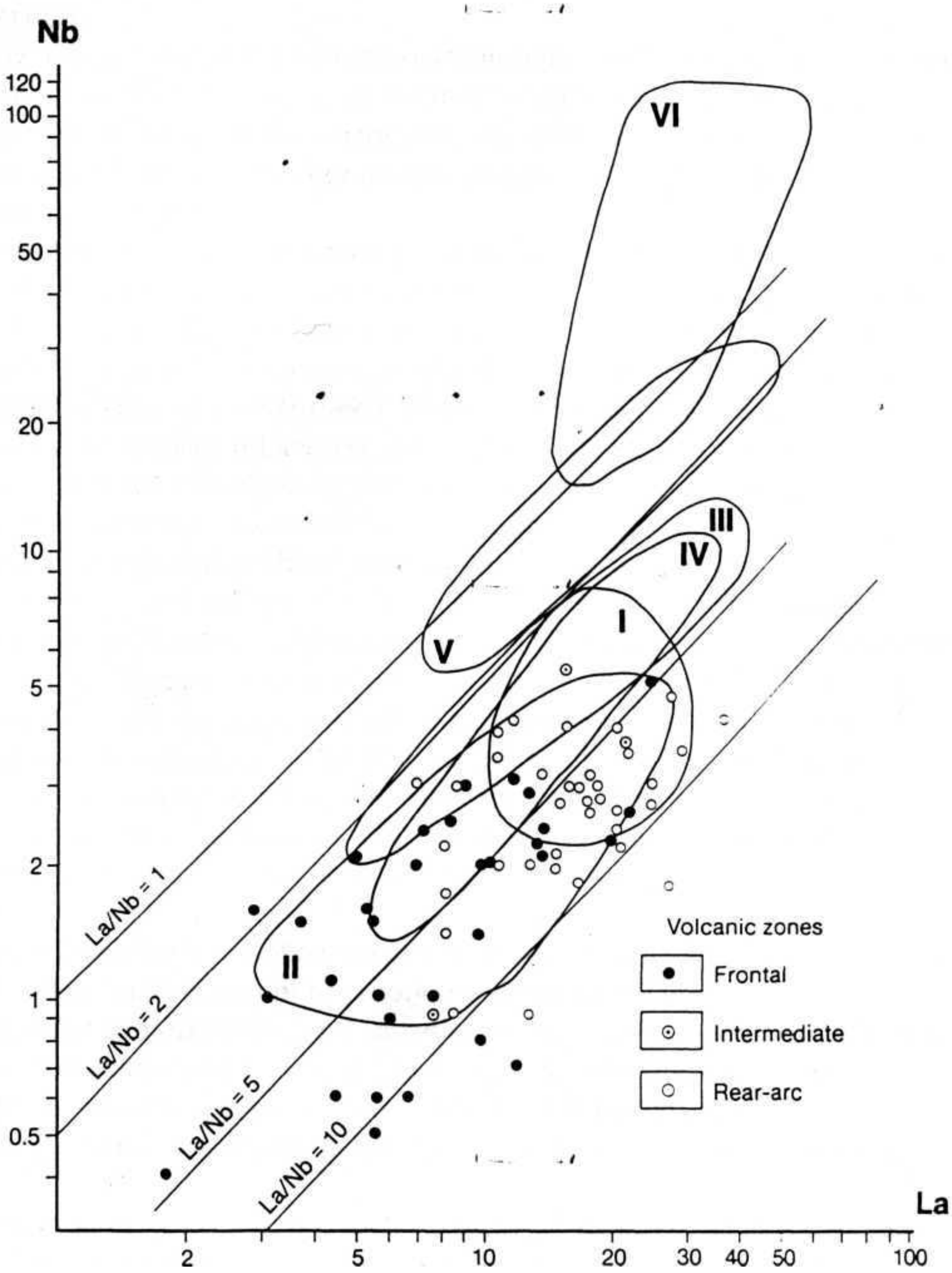


Fig. 12. Nb versus La (ppm) in Quaternary lavas from the Kuriles. Legend: 1-3 = lavas of different volcanic zones of Kuriles: 1 = frontal, 2 = intermediate, 3 = rear-arc; 4 = fields of volcanics from different regions: I = Kamchatka, high-K and shoshonitelatite series (author's data); II = New Hebrides, intermediate-K and shoshonite-latiteseries (Gorton, 1977); III =Santorini, intermediate-K series Mann, 1983); IV= Southern Chile, intermediate-K series (Gerlach et al., 1988); V = Rio-Grande Rift. low-K. intermediate-K. and high-K series (Dungan et al., 1986); IV = Kamchatka, basall-comendite series (author's data).

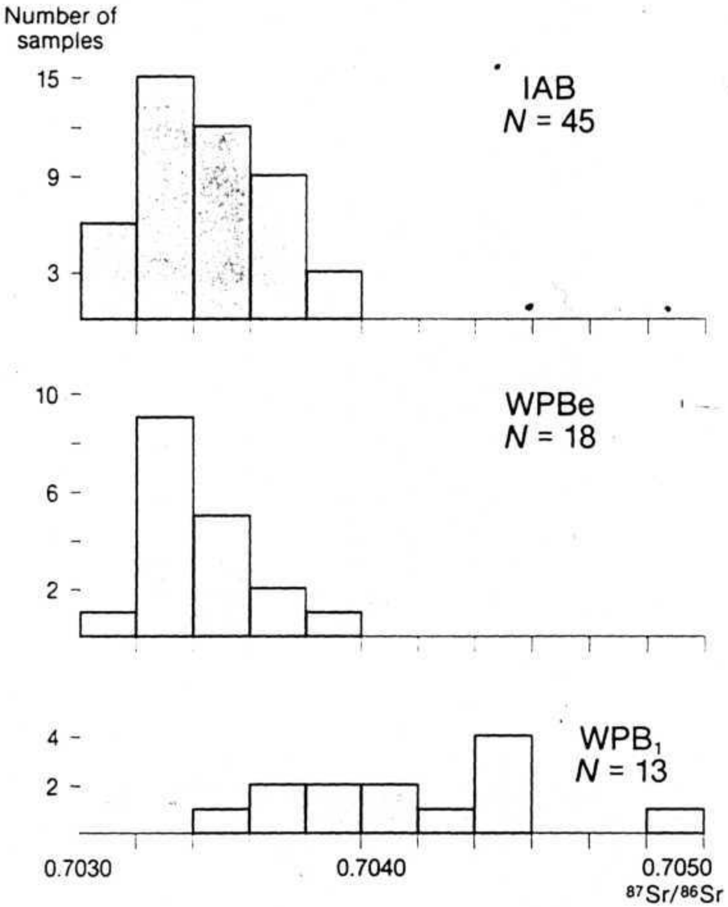


Fig. 13. Variations in Sr isolope composition of the Late Cenozoic basalts from Kamchatka. Legend: 1AB = basalts of island-arc geochemical type; WPB = basalts of within-plate geochemical type: WPB, = K-Na alkali basalt series, WPB- = K-Na alkali olivine basalt and basalt-comendite series.

Aleutians (Kay and Kay, 1994), and the Marianas (Stern and Ito. 1983), whereas the dominant values of d^{18}0 in lavas from volcanic arcs of SW Japan are shifted to the heavier region (Matsuhisa and Kurasawa, 1983). The d^{18}O values heavier than +6.5% in igneous rocks usually are considered to result from magma contamination by sediments, by old sialic basement rocks (Faure, 1986), or by sea water in deep magma chambers (Pokrovskiy and Zhuravlev, 1991).

Most d^{18}O analyses of lavas of K-Na alkali olivine basalt and basalt-comendite series (9 of 15) are within the '"mantle" limits (+6.0 + 0.5%); in other analyses d^{18}O values range from +6.7% to 7.1%. Oxygen-isotope composition in the K-Na alkali basalts varies more essentially (from+6.0% to +10.4%).

Sulfur and carbon isotope compositions have been determined only for island-arc lavas from the Kamchatka segment, constituting 26 and 23 samples, respectively (Mineyev et al., 1986; author's unpublished data). The d^{34}S values fluctuate from +0.4 to 15.3% (plus one abnormal value of +25.6%) and the median value is +8.4%. A heavier-than-meteoritic sulfur-isotope composition is typical of island-arc lavas (Ueda and Sakai, 1984). It usually is interpreted to result from magmatic melt dehydration and contamination by sea water sulfates (Faure, 1986). The d`^{13}C values for high-temperature (>600°C) carbon fractions range from -14.8% to -33.6%. These values are much lighter than those in submarine oceanic basalts (Faure, 1986), but similar to those in subaerial

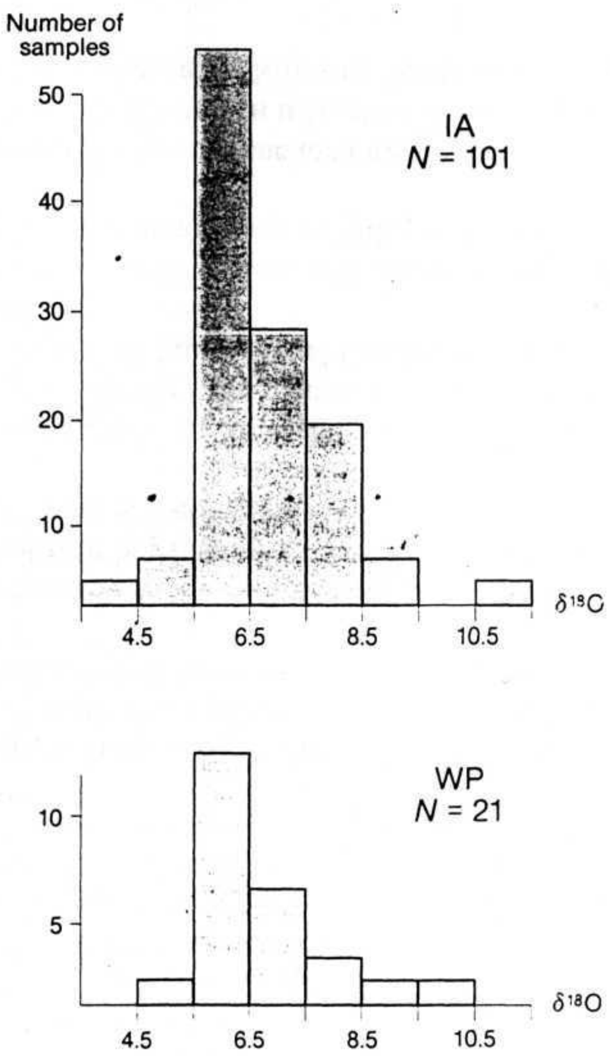


Fig. 14 Variations in oxygen isotope composition of the Late Cenozoic basalts of island-arc (IA) and within-plate (WP) geochemical types from the Kurile-Kamchatka island-arc system.

lavas of Iceland (Galimov and Gerasimovskiy, 1978) and some other regions.

Tera and Morris from the Carnegie Institute (United States) determined ^{10}Be concentrations in 23 lava samples of modern Kamchatka and Kurile volcanic eruptions (Tera et al., 1989; Tsvetkov et al., 1991; Morris et al., 1993). The ^{10}Be contents were found to be 2.2-7.9 * 106 at/g in the Kurile volcanics and 0.0-3.7 * 106 at/g in the Kamchatka volcanics. Calculations based on ^{10}Be data using the Tera method (Tera et al., 1986) demonstrate that the proportion of sediment incorporation for the Kurile magmas is <4.0%, and for Kamchatka magmas is <1.5%. These values are similar to estimations of the sedimentary component involved in the genesis of magmas in certain other island arcs and active margins obtained from ^{10}Be data (Tera et al., 1986). These results confirm also the earlier conclusion, derived from the REE distribution and Sr-Nd isotope data, that a small proportion of sediments participates in the

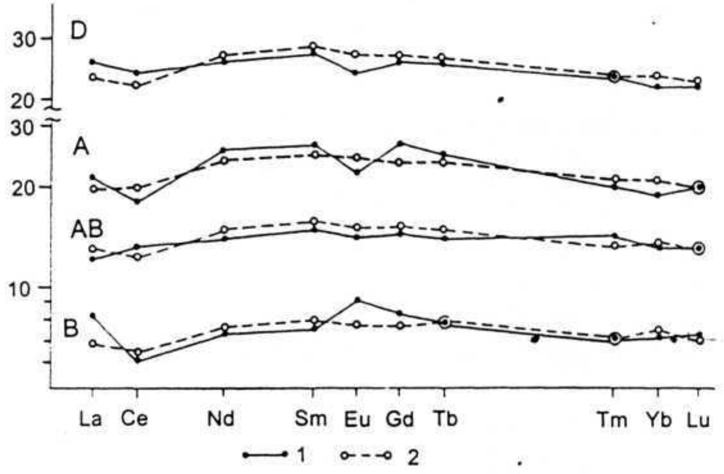


Fig. 15. Correlation of natural and calculated trends of REF distribution in the lavas of Ksudarh caldera, Kamchatka. Legend: H = basalt; AB = basaltic andesite; A = andesite: I) = dacite; 1 = natural trends; *2* = calculated trends.

magma genesis in the Kurile-Kamchatka island-arc system (Zhuravlev et al., 1987).

The Problem of Acidic Magma Genesis

The main features of bulk and rare-element chemistry are inherited from basic to acidic lavas in each geochemical rock series, despite wide variations. For example, in tholeiitic, low-K lavas of the Ksudach (Kamchatka) and Lvinaya Past (Kuriles) calderas, REE concentrations increase 3-4 times but La/Yb ratios remain approximately constant and REE distribution curves are subhorizontal for all rock types (Fig. 15). In differentiated magnesian andesite-rhyodacite rock series from the Piyp submarine volcano in the far western Aleutians, acidic lavas inherit a high magnesian number, high Ni and Cr contents, and depletion of Ba, Cs, and Th with respect to K and La from magnesian andesites (Yogodzinskiy et al., 1994). Intermediate and acidic rocks of basalt-comendite series from the Belogolovskiy volcano, Kamchatka, like the basalts, are enriched in Nb and Ta and have low ("within-plate") La/Ta, Zr/Nb, Th/Ta, and La/Nb ratios (Volynets et al., 1987,1990a). Lavas from Kamchatka and Kurile volcanoes with various SiO2 contents exhibit no systematic difference in Sr-isotope composition (Volynets et al., 1987; Pushcharovskiy, 1992). A similar situation is found for differentiated series at volcanoes in many other island arcs and active continental margins (e.g.. Gerlach et al., 1988; Singer and Myers, 1990: Yogodzinskiy et al., 1994).

The fractional crystallization of basalts with magnetite participation may be an important mechanism of genesis of intermediate and acidic lavas from different geochemical series. It is supported by model calculations made by the least-squares method for main elements and using the Rayleigh equation for trace elements, as well as by data on volcanic rock groundmass compositions. Calculations made for tholeiitic series fractionation commonly are successful (e.g., Fig. 15), whereas for calc-alkaline series positive results usually are obtained only for individual links in differentiated series of volcanics (e.g., Volynets et al., 1990a; Pushcharovskiy, 1992). Thus, in the latter case the participation of other petrogenetic processes may be supposed (magma mixing, liquid immiscibility, etc.). Finally, intermediate (andesitic) melts may be generated directly by the partial melting of a hydrous mantle peridotite, as shown by experimental investigations (Kushiro, 1974; Mysen and Boettcher, 1975). Probably acid melts also may be obtained in the upper mantle (Matsumoto, 1965). The finds of andesitic, dacitic, and occasionally rhyolitic glasses in ultramafic inclusions of Kamchatka (Yermakov et al., 1987), Kuriles (Volynets et

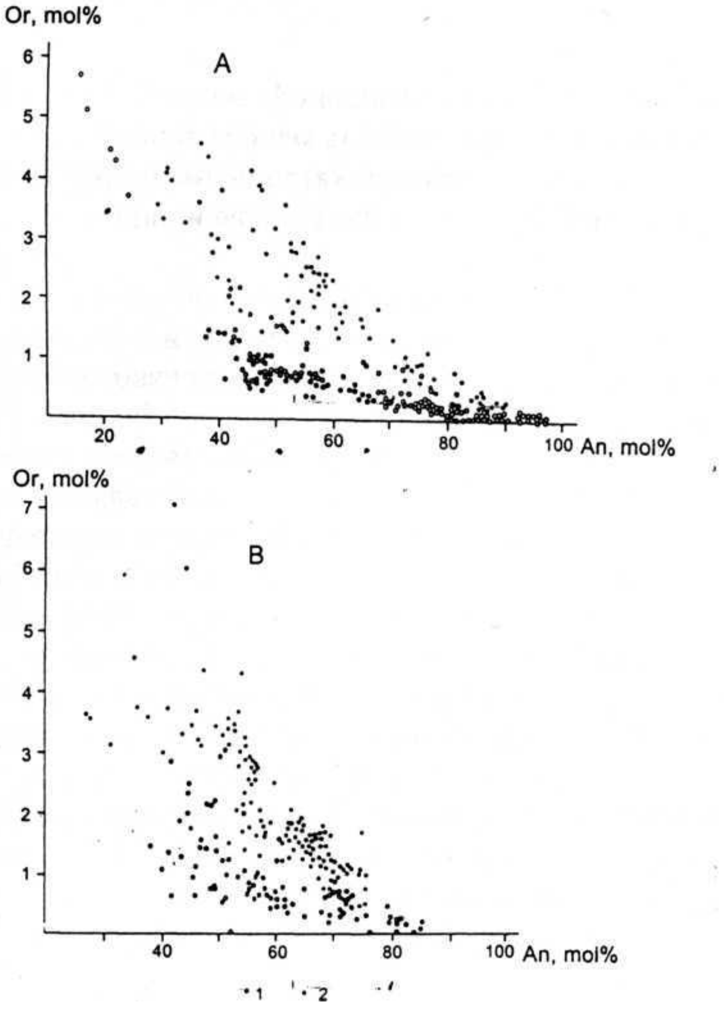


Fig. 16. Or content in plagioclases of Holocene lavas from South Kamchatka, legend: A = phenocryst cores and intermediate zones; B = phenocryst rims and microlites; 1 -2 = volcanic zones: 1 = frontal. 2 = rear-arc and intermediate.

al., 1990c) and other regions (e.g., Murav'yeva et al., 1989) corroborate these experimental data. Studies of these inclusions imply that the partial melting of mantle peridotites usually is preceded by metasomatism with the participation of water fluid. Chromian phlogopites, chromian magnesian amphiboles, and labrador-bytownite plagioclases form during this process (Volynets et al., 1990c).

Lateral Zoning of Volcanic Rock

Across-arc geochemical and mineralogical zoning of volcanics, which is a typical feature of island arcs, is very important for understanding island-arc magma genesis (e.g., Gill, 1981: Kushiro, 1983). It is described in detail for the Kurile-Kamchatka island-arc system (e.g.. Gorshkov, 1973; Popolitov and Volynets, 1982: Volynets et al., 1987; Fedorchenko et al., 1989: Avdeyko et al., 1991; Pushcharovskiy, 1992).

In frontal zones of volcanic belts, lavas are characterized by two-pyroxene assemblages of phenocrysts, whereas in rear-arc zones, basalts rarely contain orthopyroxene phenocrysts, and intermediate and acidic lavas along with pyroxenes commonly have amphibole and mica.

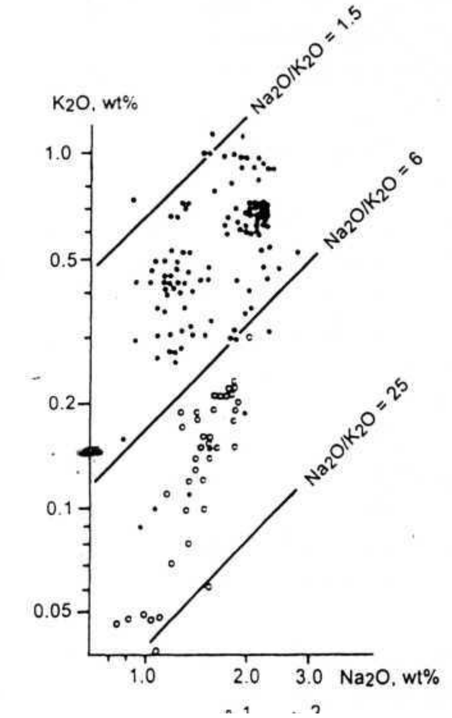


Fig. 17. Alkali content in hornblendes from Kurile and Southern Kamchatka lava, Legend: 1-2 = volcanic zones: =trontal, 2 - rear-arc.

Sometimes these latter two minerals occur here in basaltic andesites and even in basalts. The different distribution of amphibole-bearing phenocryst associations in rear-arc and frontal-arc lavas suggests that rear-arc magmas have higher $H_2$0 content than frontal-arc ones. The results of calculations by magnetite-ilmenite geobarometry-geothermometry (Volynetset al., 1987; Pushcharovskiy, 1992) show that rear-arc melts crystallized at higher oxygen fugacity than frontal-arc melts (by 1.0-1.5 log$f$(O_2)), which conforms with the higher oxidized Fe content in rear-arc lavas (Pushcharovskiy, 1992).

Minerals from lavas of frontal- and rear-arc zones also differ in composition. For example, plagioclases in rear-arc lavas are, on the whole, less calcic, with higher Ba, Sr, and K and a lower Ca/Sr ratio and Fe contents than plagioclases in frontal-arc lavas (Fig. 16). Amphiboles in rear-arc lavas have, accordingly, higher K-Na ratios (Fig. 17). The evolutionary trend in pyroxenes from frontal-arc lavas is tholeiitic, whereas in rear-arc lavas it is calc-alkaline (Fig. 18) (see also Pushcharovskiy, 1992).

Across-arc geochemical zoning, found in all volcanic belts, is studied in more detail for the Kurile segment. This zoning is displayed in increasing contents of K, Rb, Li, Be, Ba, Sr, I . Th, La, Ce, Nb, Ta, Zr, W, Mo, and K/Na, Rb/Sr. La/Yb, Sr/Ca, and Th/U ratios in layas from the volcanic front to rear arc (Fig. 19). In the basic rocks, concentrations of P, F, Hf, Mg, Ni. Cr, and sometimes Ti also increase in this direction. However, concentrations of Fe and V and the values of K/Rb, Fe/Fe+Mg, and Fe^{2+}/Fe3^{+}in lavas and the degree of volcanic series differentiation decrease from frontal to rear-arc zone. In intermediate and acidic lavas, concentrations of Ca, Ti, Cu, Zn, Y, and Yb decrease as well. It is noteworthy that concentration? of most volatiles (H_2O, F, Cl, S) increase across arc and their proportions vary. For example, Fe/Cl and F/B ratios increase (Pushcharovskiy. 1992).

Similar across-arc zoning is found in each volcanic belt of Kamchatka. However, it is complicated here by an increase in many incoherent elements in lavas away from the modern volcanic front (Fig. 20). The main features of across-arc geochemical zoning described for the Kuriles and Kamchatka are typical of island arcs and active continental margins (Gill, 1981).

Across-arc isotope zoning also is revealed in the lavas of the Kurile segment of the island-arc system. Thus, ^{87}Sr/^{86}Sr ratios in lavas distinctly decrease from the volcanic front to rear-arc (Fig. 21) (Vinogradov et al., 1986; Pushcharovskiy, 1992). A similiar relationship is found here also for ^{143}Nd/^{144}Nd ratios (Zhuravlev et al., 1987).

Sr-isotope across-arc zoning corresponding to the Kurile type has been found in certain other island arcs: NE Honsu, Idzu-Ogosavara, Fiji, Sulawesi, New Zealand, and East Aleutians (Gill, 1981; Notsu, 1983; Notsu et al., 1983; Kay and Kay, 1994). Across-arc mineralogical, geochemical, and isotope zoning, which is common for island-arc volcanic series, is not found for within-plate volcanic series" (see Fig. 20).

Along-arc geochemical zoning is observed in the Kurile-Kamchatka island-arc system side by side with across-arc zoning. However, it is not so distinct and so regular as the latter and it is

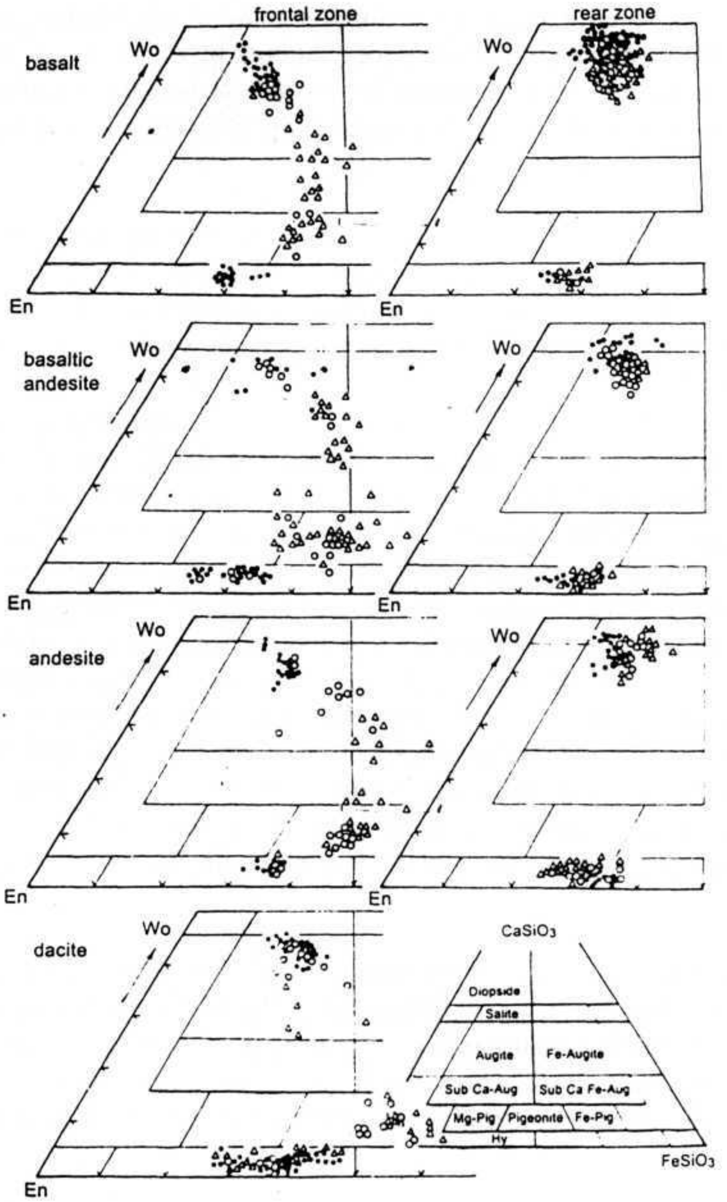


Fig. 18. Composition of pyroxenes in the volcanic rocks from the kuriles. Legend: a = basalt; b - basaltic, andesite; c - andesite; d = acidic rocks; solid circles = phenocryst cores and intermediate zones: open circles = phenocryst rims; triangles = microlites. Left = frontal zone, right = rear-arc zone.

detected only for a few rare elements. Nevertheless, concentrations of Ba, Sr, Be, and B in volcanics increase from the Southern Kuriles to Northern Kuriles and South Kamchatka. However, Th concentration and Th/ U ratios in lavas decrease in the same direction for the arc on the whole, and this is especially ohvious for the rear-arc zones (Puzankov et al., 1991).

The along-arc zoning is much more visible in isotope composition of Sr (Vinogradov et al.. 1986; Bailey et al., 1987; Zhuravlev et al., 1987: Pushcharovskiy, 1992). ^{10}Be (Tera et al., 1989:

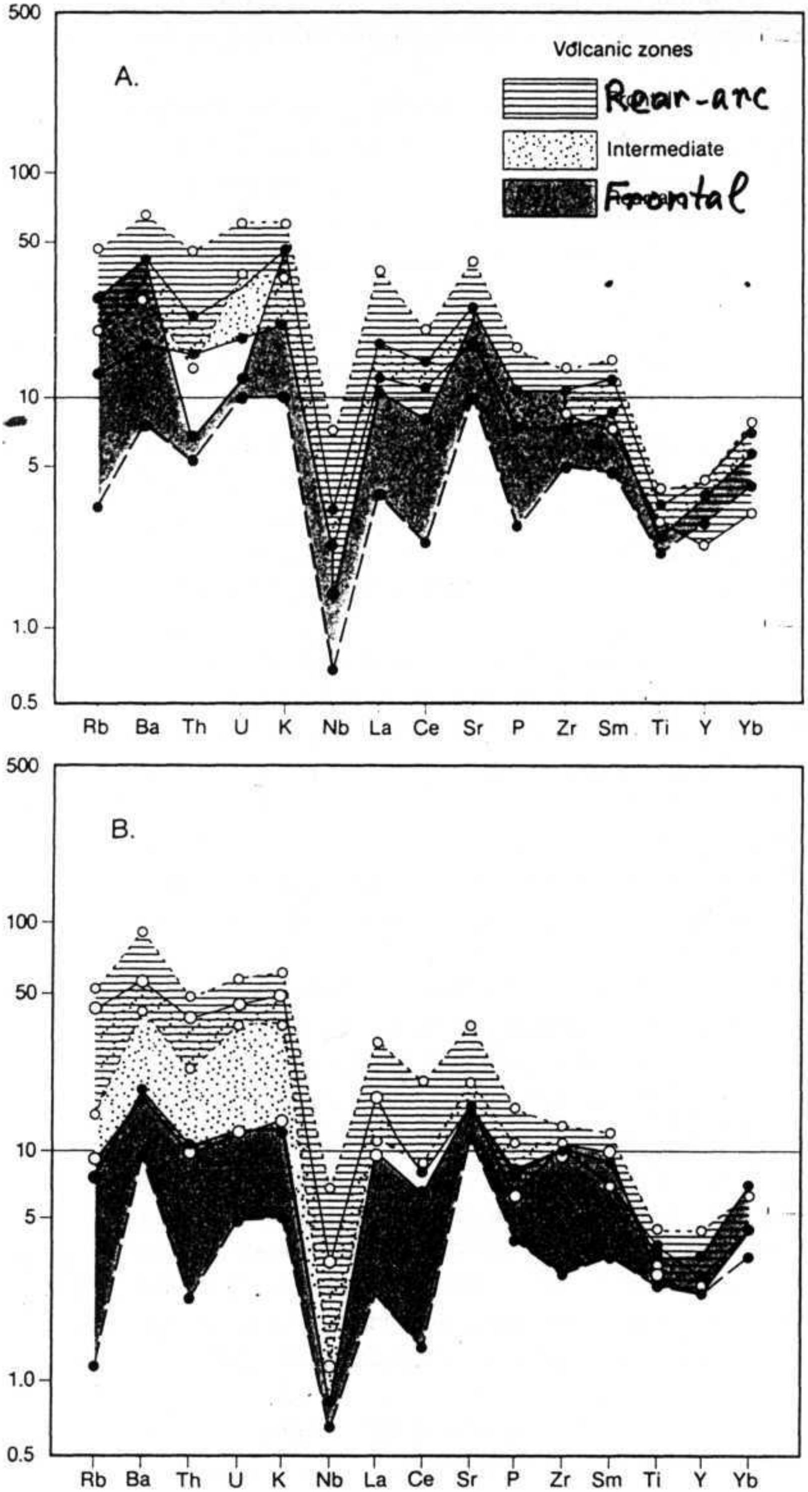


Fig. 19. Spidergrams of hydromagmatophile elements in the basalts of the Northern (A) and Southern (B) Kuriles. Normalized to primordial mantle after Wood (1979).

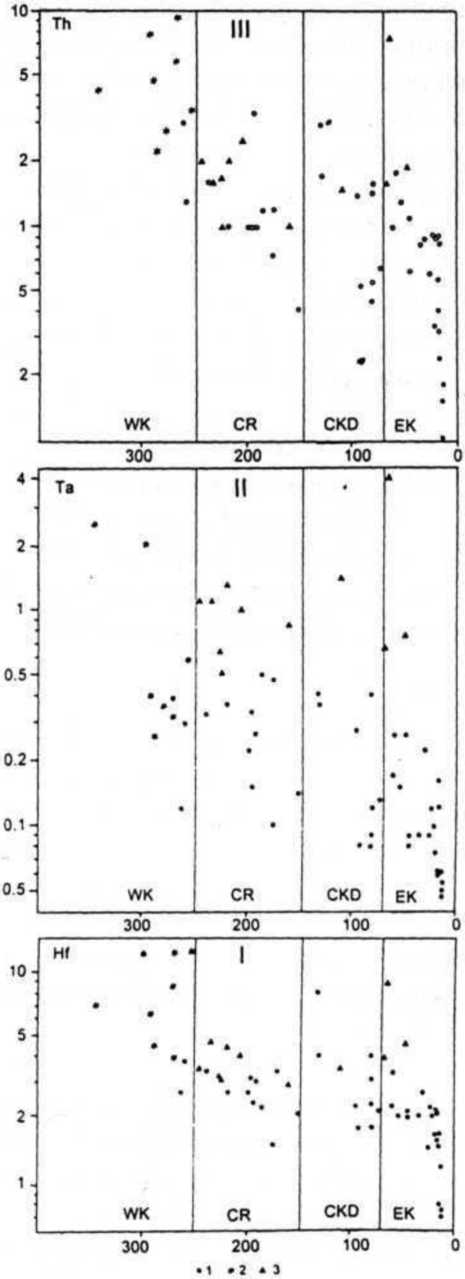


Fig. 20. Variations of Th, Ta, and HF (ppm) in Late Cenozoic basalts of Kamchatka. Legend: \ - lavas of rock series of island-arc geochemical type; 2-3 = lavas of rock series of within-plate geochemical type: 2 = K-Na alkali basalt, alkali olivine basalt, and basalt-comendite, 3 = K alkali basalt. Volcanic belts: EK = Eastern and Southern Kamchatka; CKD = Central Kamchatka Depression; CR = Central Range; WK = Western Kamchatka. On abscissa is the distance from modern volcanic front. Average values are used for each volcano.

Tsvetkov et al., 1991; Morris et al., 1993), H (Taran et al., 1992), and 0 (Fig. 22). Minimum ^{87}Sr/^{86}Sr ratios are found in the Kurile segment of the system and the very lowest ones in the Central Kuriles. But they distinctly increase to the north (toward Kamchatka) and to the south (toward NE Hokkaido) where island-arc structures are situated on more consolidated basement. A similar picture is characteristic of d^{18}O distribution; however, a clear maximum also is observed in the Central Kuriles. The character of variations in ^{10}Be concentrations and dD values is quite opposite to that of ^{87}Sr/^{86}Sr along the Kurile-Kamchatka island-arc system. Volcanic rocks in Central Kuriles are rich in ^{10}Be and D, whereas on the flanks of the system they are depleted in these isotopes.

The Nature of Zoning and the Problem of Island-Arc Magma Genesis

The author believes that the across-arc geochemical and isotope zoning is caused by the inhomogeneity of mantle sources of magmatic melts. This inhomogeneity probably results from differences in deep fluids, which are separated from the subducted plate and which take part in the mantle wedge metasomatism and magma genesis (Popolitov and Volynets. 1982: Pushcharovskiy, 1992). Under the frontal- and rear-arc zones fluids were separated from the first and second layers of the subducted ocean-crust and adjacent portion of the mantle wedge (Tatsumi, 1986) at different temperatures and pressures as a result of dehydration of various water-containing minerals: predominantly amphibole. 14A-clinochlore and serpentine about 100 km beneath the volcanic front and phlogopite and 7A-clinochlore about 190 *km* beneath the rear-arc (Tatsumi, 1986; Avdeyko et al., 1991). Beneath the rear-arc, fluids also may be separated from the deeper part of the subducted plate because of dehydration of serpentinites from the third layer of oceanic crust (Ringwood, 1990). Finally, the composition of rising fluids depends on the prolongation on their interaction with the mantle wedge before-reaching the magma-generation area. The capability of aqueous fluids to release many incompatible elements from the ultramafic substrate and transport them has been demon-

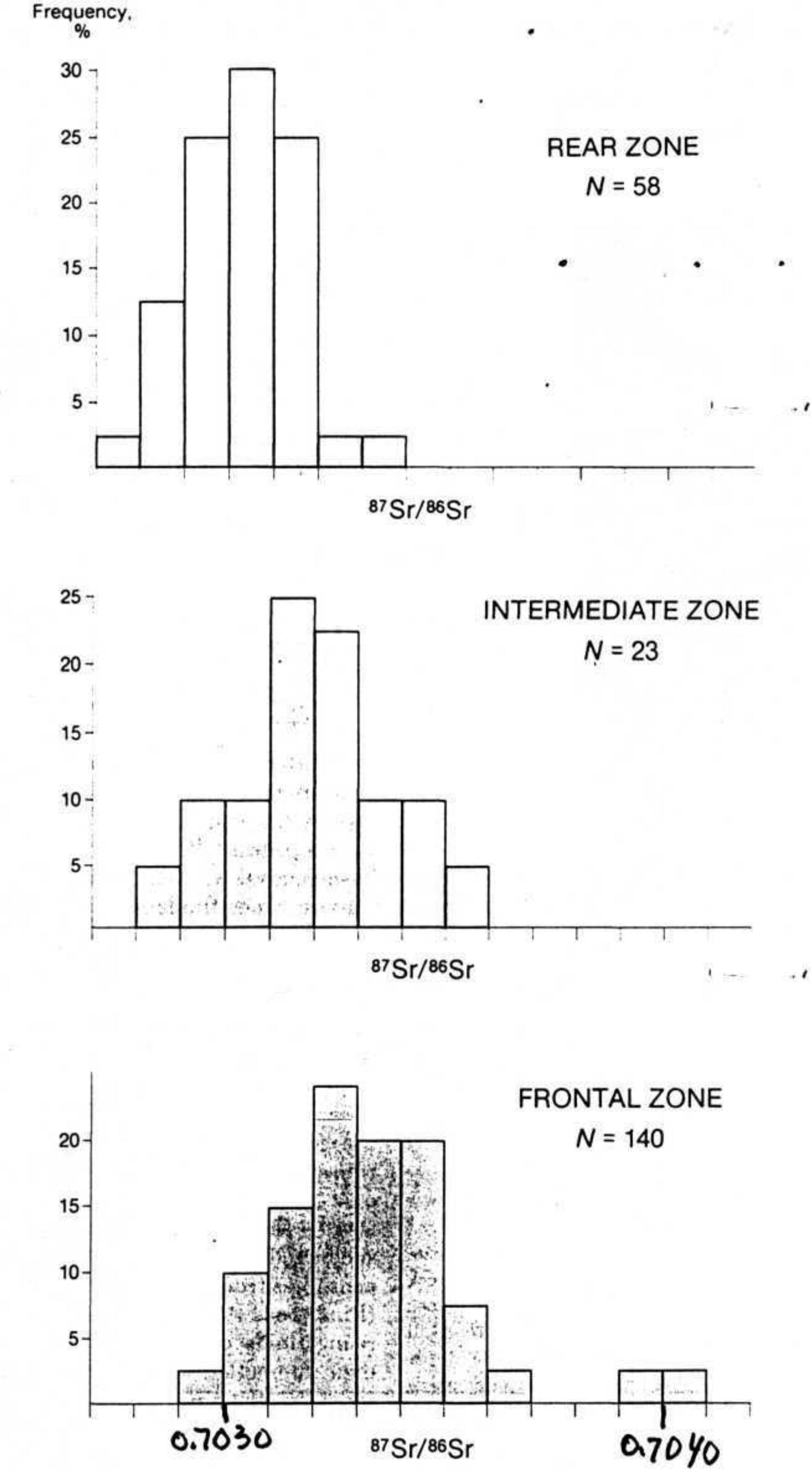


Fig. 21. Variations in Sr isotope composition of Quaternary lavas from the Kuriles.

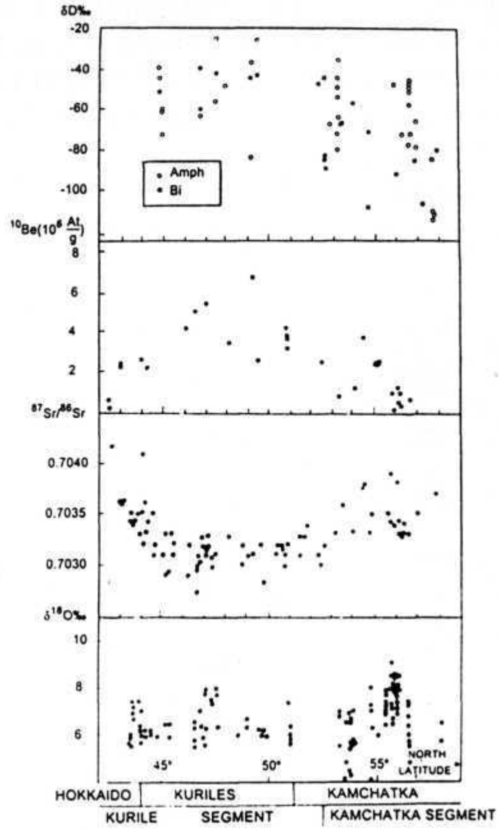


Fig. 22. Variations in isotope characteristics of Late[1] Cenozoic lavas along the Kurile-Kamchatka arc system.

strated by experimental studies (Tatsumi et al., 1986).

Fluids separated beneath the frontal zone probably are closer to the composition of sea water than those beneath the rear-arc zone, which causes the across-arc Sr isotope zoning. Low $^{87}Sr/^{86}Sr$ ratios in combination with higher Rb concentrations and Rb/Sr ratios in rear-arc lavas indicate a geologically recent time of enrichment of rear-arc mantle in Rb (and other incompatible elements). This is in agreement with Gill's model suggested on the basis of short-lived isotopes in the Th-U-Ra geochemical system (Gill and Williams, 1990). According to this model, the processes of fluid transport from the subducted plate to the mantle wedge, partial melting of the latter, and melt ascent to the surface span a period less than 200-300 thousand years.

With respect to along-arc zoning, the aforementioned tendencies in the distribution of Sr, Be, H, and O isotopes may be interpreted to result from contamination of mantle magmas by the crustal material on the flanks of the island-arc system. However, no correlation is found between isotope and trace element compositions of volcanics, which suggests that rocks from the ancient sialic basement are not the only matter contaminating the primary melts.

Island-arc magmas are generated in metosomatically altered mantle. This is comfirmed by findings in lavas of ultramafic inclusions with chromian magnesian amphibole. chromian, phlogopite, plagioclase, and also complicated inclusions in which ultramafic rocks associate with amphibolites and amphibole gabbros. High alumina concentrations in most island-arc lavas and Sr maxima present on the spidergrams of hygromagmatophilic rare elements also may indicate that plagioclase and amphibole occur in the source of island-arc magmas. The deep Nb and Ta minima constantly observed on such diagrams suggest that these elements are not supplied into the island-arc magma source with fluids. At the same time. Nb and Ta concentrations in lavas distinctly increase, by 1.5-3.0 times from the frontal to rear-arc zone, which may indicate that low-volume partial melts from the subducted plate take part in metasomatism of the mantle wedge in rear-arc zones. Finally, data on ^{10}Be contents in Kurile-Kamchatka lavas show that a small proportion of pelagic sediments from the subducted plate (or fluids separated by their dehydration) also participate in island-arc magma genesis. It also is striking geochemical evidence of the reality of the subduction process.

The Problem of the Origin of the Within-Plate Geochemical Type in the Island-Arc System

Geochemical data clearly indicate different magma sources for volcanics of the island-arc and within-plate geochemical types in the Kurile-Kamchatka system. There are at least two hypotheses explaining the generation of volcanic rocks with high Nb and Ta concentrations (and high Ti in basalts) in island-arc systems. These rocks may be classified by their geochemical properties as within-plate.

Ringwood (1990) proposed that the source of magma enrichment in these elements is the same subducted plate, the contribution of which to the genesis of island-arc magmas determines their main geochemical features. The differences in Ti. Nb, and Ta concentrations in island-arc and within-plate magmas is caused by behavior of rutile, the main mineral-concentrator of these elements at the level of eclogite fades at depth.

In the region of island-arc magma generation, where depth to the subducted zone is roughlv 100 km. the mantle wedge is metasomatized bv fluids or partial melts separated from the subducted plate. Experiments (Tatsurni et al.. 1986) have demonstrated that Nb has a verv low solubilitv in aqueous fluid. Consequently the fluid transport mechanism cannot provide the enrichment of the mantle wedge in this element (as well as in Ta and Ti). Analogously enrichment in these elements also is impossible at the expense of partial melts from the subducted plate. Actually, such melts must be acidic in composition under these P-T conditions and, according to Ryerson and Watson experiments (1987), must have low Ti, Nb. and Ta concentrations because these elements remain in relict rutile. Therefore, island-arc magmas generated in the mantle wedge are depleted in Ti, Nb, and Ta compared to K, Rb, Ba. Sr, and LREE.

At greater depths (150-300 km) partial melts from the subducted plate must be less siliceous in water-saturated conditions because of higher temperatures. Rutile is better dissolved in intermediate melts than in acid (Ryerson and Watson. 1987) and it disappears here as a relict phase. As a result, the partial melts from the subducted plate are enriched in Ti, Nb, and Ta and then, while ascending, these melts enrich the mantle wedge in these elements. Accordingly, the magmas that are generated here have higher Ti, Nb, and Ta concentrations.

Another model (Nakamura et al., 1990) suggests that the source of within-plate magmas is complicated. It includes the matter from mantle plumes raised from great depths (may be from the upper/lower mantle boundary) and the depleted matter from the mantle wedge, with which these plumes react.

It is obvious that in the case of Ringwood's model, the magmas enriched in Ti, Nb, and Ta have to be displayed in far rear-arc zones of the island-arc system and have to lag in time with respect to initial (middle) stages of island-arc volcanism. The model of Nakamura et al. does not suppose such limitations. However, it is vague until now why the mantle plumes ascend and how island-arc and within-plate volcanism must correlate in space and time.

Geologic data show that in the Kamchatka case, only K-alkali basalt genesis may be explained using Ringwood's model. In reality, manifestations of these rock series occur in the far rear zone of the Central Range volcanic belt and correspond in time to the late stage of its development. Data on place and time of manifestation of K-Na alkali and subalkali lavas from Kamchatka do not agree with Ringwood's model. For example, in Eastern Kamchatka, eruptions of K-Na within-plate-type basalts preceded the formation of the island-arc volcanic belt. In the Central Range within-plate-type lavas coexist with island-arc volcanics from the Pliocene to Holocene and occur at practically the same localities, although they are confined to different structural elements.

The model for the evolution of the dynamic regime in the Kamchatka segment of the Kurile-Kamchatka island-arc system is shown in Figure 23. Probably, the presence of an inactive ("dead") subducted zone (joes not, prevent deep mantle plumes from ascending (Late Miocene-Holocene in the Central Range). However, active subduction "cuts" off mantle plumes from the mantle wedge and prevents within-plate magmas from occurring in youthful volcanic arcs (Late Pleistocene-Holocene in Eastern Kamchatka). The ascent of mantle plumes is stimulated by deep faults arising in the continental block when a new deep-sea trench and subduction zone are formed.

Conclusions

Among the Late Cenozoic volcanic rocks of the Kurile-Kamchatka island-arc system, lavas of the within-plate geochemical type occur alongside dominant lavas of the ordinary island-arc geochemical type. Geochemical data attest that magma sources differ for within-plate and island-arc volcanics and geologic data show that the origin of these magma types is related to different geodynamic processes.

Volcanic rocks of the island-arc geochemical type occur within the entire Kurile-Kamchatka

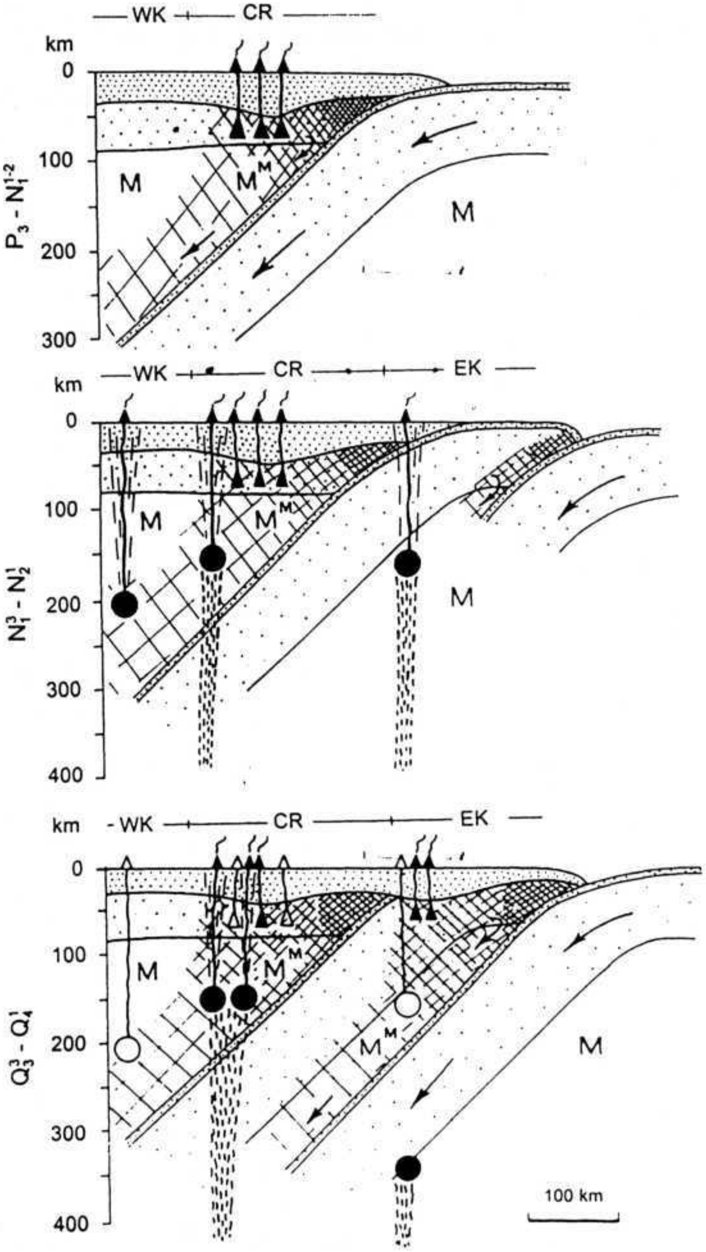


Fig. 23. Evolution of Kamchatka segment of Kurile-Kamchatka arc system in Late Cenozoic time. Darkened symbols denote active volcanoes and their magma chambers for each period of time; open denote the same for inactive ("dead") volcanoes and their magma chambers. Dashed lines show the direction of mantle plume movement and solid circles denote magma chambers originated by decompression. Long arrows show the direction of ocean-plate movement, and short arrows show related movement of mantle wedge. Legend: M (larger) = unaltered mantle of MORB-type; M (smaller) = mantle metasomalized by fluids separated from subducted plate. The position of altered mantle in mantle wedge is shown by hatching and the intensity of hatching reflects the intensity of alternation. Volcanic zones: EK = Eastern Kamchatka; CR = Central Range; WK = Western Kamchatka. The diagram was compiled with consideration of the model for the genesis of alkaline basalts in SW Japan proposed by Nakamura et al. (1990).

system, whereas volcanic rocks of the within-plate geochemical type are found only in the Kamchatka segment of the system, to the north of Avacha Bay. The Kamchatka and Kurile segments of the system differ also in some geologic and tectonic features. In the Kamchatka segment an *en echelon* system of volcanic belts is observed, whereas in the Kurile segment there *is* a single volcanic belt with clear frontal-arc and rear-arc volcanic zones. Pliocene-Quaternary volcanism in the Kamchatka segment is displayed solely in subaerial conditions, whereas in the Kurile segment submarine volcanism occurs along with the subaerial variety. Here, subaerial volcanoes dominate in the frontal zone and submarine volcanoes in the rear-arc zone. The history of geologic development of the Kamchatka segment is longer and more complicated than that of the Kurile segment. There are ample outcrops of the ancient metamorphic basement in the Kamchatka segment, but these are absent in the Kurile segment.

The aforementioned features of the Kamchatka segment make it possible to consider it not as an island-arc but as an active continental margin similar to the North American margin. From this point of view, the Kurile-Kamchatka island-arc system represents a combination of double island-arc (Kurile segment, including NE Hokkaido and Southern Kamchatka) and active continental margin (that portion of Kamchatka north of Avacha Bay).

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REFERENCES

Avdeyko, G. I., Volynets, 0. N., Antonov, A.,Yu, and Tsvetkov, A. A., 1991, Kurile island arc volcanism: Structural and petrological aspects: Tectonophysics, v. 214, p. 271-287.

Balesta, S. T., 1981, The Earth's crust and magma chambers in the region of modern volcanism: Moscow, Nauka Press (in Russian).

Bailey, J. C, Larsen, 0., and Frolova, T. I, 1987, Strontium isotope variations in Lower Tertiary-Quaternary volcanic rocks from the Kurile island arc: Contrih. Mineral Petrol., v. 95. p. 155-165.

Barbery, F, Ferrara, G., Santecroce, R., Treuil, M., and Varet, J., 1975, A transitional basalt-pantellerite sequence of fractional crystallisation, the Boina centre (Afar rift, Ethiopia): Jour. Petrol., v. 16, p. 22-56.

Bartels, K. S., Kinzler, R. J., and Grove. T. L. 1991. High pressure phase relations of primitive high-alumina basalts from Medicine Lake Volcano. Northern California: Contrib. Mineral. Petrol., v. 108, p. 253-270.

Cambon, P., and Bougalt, H., 1980. Emperor Seamounts: Trace elements in transitional" tholeiites. alkali basalts and hawaiites—mantle homogenity or heterogenity and magmatic processes, *in* Initial reports of the DSDP: Washington. DC, v. 18. p. 585-597.

Churikova, T. G., and Sokolov, S. Yu.. 1993, The magmatic evolution of Ploskiye Sopki volcano, Kamchatka (the analysis of strontium isotope geochemistry): Geokhimiya, no. 10. p. 1439-1447 (in Russian).

Dostal, J., Dupuy, C and Venturelli, G., 1982, Geochemistry of volcanic rocks from the Monte Arei (West Sardinia, Italy): Chem. Geol., v. 35, p. 247-264.

Dungan, N. A., Lindstrom, M. M., McMillan, N. J., Moorbach, S., Hoefs, J., and Kaskin, L. A., 1986, Open system magmatic evolution of the Taos plateau volcanic field, northern New Mexico. 1. Petrology and geochemistry of the Serviletta basalt: Jour. Geophys. Res., v. 91, p. 5999-6028.

Ewart, A., 1979, A review of the mineralogy and chemistry of Tertiary-Recent dacitic, latitic, rhyolitic and related salic volcanic rocks, in Barker, E, ed., Trondhjemites, dacites and related rocks: Amsterdam, Elsevier, p. 13-121.

Faure, G., 1986, Principles of isotope geology: New York, John Wiley and Sons, Inc., 340 p.

Fedorchenko, V. I., Abdurchmanov, A. 1., and Rodionova, R. I., 1989, Volcanism of the Kurile island arc: Geology and petrogenesis: Moscow, Nauka Press, 239 p. (in Russian).

Galimov, E. M., and Gerasimovskiy, U. I., 1978, Carbon isotope composition in magmatic rocks of Iceland: Geokhimiya, no. 11, p. 1615-1621 (in Russian).

Gerlach, D. C., Frey, A. E, Moreпoro, H., and Lopes-Escobar, L, 1988, Recent volcanism in the Puyehye-Cordon Caulle region. Southern Andes, Chile (40.5° S): Petrogenesis of evolved lavas: Petrology, v. 28, p. 2, 333-382.

Gill,J. B., 1981, Orogenic andesitesand plate tectonics: Berlin, Springer-Verlag, 390 p.

_________, 1984, Sr-Pb-Nd isotopic evidence that both MORR and OIB sources contribute to oceanic island ar magmas in Fiji: Earth Planet. Sci. Lett., v. 68, p. 443-458.

Gill, J. B., and Williams, R. W. 1990. The isotope and U-series studies II: Subduction-related volcanic rocks: Geochim. et Cosmochim. Acta, v. 54. p. 1427-1442.

Gorshkov, G. S., 1970, Volcanism and upper mantle: Investigations in the Kurile arc: New York, Plenum Press, 385 p.

Gorton, M. P., 1977, The geochemistry and origin of Quaternary volcanism in the New Hebrides. Geochim. et Cosmochim. Acta. v. 11. p. 1257-1270.

Holm, P. E., 1985, The geochemieal fingerprints of different tectono-magmatic environments using hygromagmatophile element abundances of tholeiitic basalts and basaltic andesites. Chem- Geol.. v. 51, p. 303-323.

Ikeda, Y., Katsui, Y., and Kurasawa, H., 1987. Origin of lateral variations in ^{87}Sr/^{86}Sr ratios of Quaternary volcanic rocks from Kurile arc in Hokkaido. Japan: Journ. Fac. Sci. Hokkaido Univ.. v. 22, p. 325-335.

Ivanov, B. V., and Ustinov, V. I.. 1988, Oxygen isotope composition of arulesites from Kamchatka: Volcan. and Seismol., p. 26-32 (in Russian: English translation: 1990, v. 10, p. 880-891).

Kay, S. M., and Kay, R. W.. 1994. Aleutian magmas in space and time, *in* Plafteir. C and Berg, H. C, eds.. The geology of Alaska: Boulder, CO, Geol. Soc. Amer., The Geology of North America, v. C-l.

Khanchuk, A. I., 1983, A new tectonic interpretation for southwestern Kamchatka: Doklady AN SSSR. v. 272, no. 5, p. 1208-121 1 (in Russian).

Kononov, M. B., 1989, The plate tectonics of the northwestern Pacific Ocean: Moscow. Nauka Press, 1()9 p. (in Russian).

Kononova, V. A., Pervov, V. A.. Drynkin, V. I., Kerz.in, A. L, and Andreyeva, E. D.. 1987, Rare earth and rare elements in Cenozoie basic volcanics of the Baikal region and Mongolia: Geochemistry, no. 5, p. 644-659 (in Russian).

Kushiro, 1., 1974, The system forsterite-anorthite-silica-H2O at 15 kbar and the genesis of andesilic magmas in the upper mantle: Washington, DC, Carnegie Inst. Annu. Rept. Dir. Geophys. Lab., 1973-1974, p. 244-248.

_________, 1983, On lateral variations in chemical composition and volume of Quaternary volcanic rocks across Japanese arcs: Jour. Volcanol. Geotherm. Res., v. 18, nos. 1-4, p. 435-447.

Leeman, W. P., 1983, The influence of crustal structure on composition of subduction-related magmas: Jour. Volcanol. Geotherm. Res., v. 18, no. 1-4, p. 561-588.

Legler, V. A., 1977, Development of Kamchatka at the Cenozoie from the plate tectonic viewpoint, *in* Sorokhtin, 0. G., ed., Plate tectonics (The energy sources of tectonic processes and dynamics of plates): Moscow, Institute of Oceanology AN SSSR, p. 137-169 (in Russian).

Mann, A. S., 1983, Trace element geochemistry of high-alumina basalt-andesite-dacite-rhyodacite lavas of the Main series of Santorini volcano, Greece: Contrib. Mineral. Petrol., v. 4, p. 43-57.

Matsuhisa. Y., 1979, Oxygen isotopic compositions of volcanic rocks from East Japan island arcs and their bearing on petrogenesis: Jour. Volcanol. Geotherm. Res.. v. 5. nos. 3-4, p. 271-296.

Matsuhisa. Y.. and Kurasawa. H., 1983. Oxygen and strontium isotopic characteristics of calc-alkalic volcanic rocks from the central and western Japan ares: Evolution of contribution of crustal components to the magmas: Jour. Volcanol. Geotherm. Res., v. 18. nos. 1-1. p. 183-510.

Matsumoto, I., 1965, Some aspects of the formation of primary granitic magmas in the upper mantle, *in* The upper mantle symposium. New Delhi. 1964: Copenhagen, p. 112- 126.

Mineyev. S. D.. Crinenko. V. A.. Volvnels, O. N.. amd Koloskov, A. V.. l986. Isotope composition of sulfur and carbon in voleanics and xcnoliths from the Kamchatka-Kurile-Japan island arc |abs.|: Symp. on Isotope Geochemistry. 1-3 December 1986: Moscow, p. 241-243 (in Russian).

Morris, J. D., Tera, F, Ryan, J., Leeman, W. P.. and Tsvetkov, A., 1993, Cosmogenic and radiogenic isotope systematics of the Kurile-Kamrhatka arc: Along strike and cross arc variations: EOS. v. 74. p. 674.

Murav'yeva. N. S., Polyakov, A. I., and Senin, V. C. 1988; The partial melting of upper mantle in the Baikal rift (by data from a glass study in Ihersolite nodules and megacrysts): Doklady AN SSSR, v. 300. p. 208-213 (in Russian).

Mysen, B. ().. and Boettcher. A. L., 1975, Melting of a hydrous mantle: II. Geochemistry of crustals and liquids forme<J by anatexis of mantle peridotite at high pressures and high tenperalures as a function of controlled activities of water, hydrogen and carbon dioxide: Jour. Petrol., v. 16, p. 549-593.

Nakamura. E., McCulloch. M. T., and Campbell, I. H., 1990, Chemical geodynamics in the back-arc region of Japan based on the trace element and Sr-Nd isotope component: Tectonophysics, v. 174, p. 207-233.

Notsu, K.. 1983. Strontium isotope composition in volcanic rocks from the Northeast Japan arc: Jour. Volcano!. Geotherm. Res., v. 18, nos. 1-4, p. 531-548.

Notsu, K., Isshiki. N.. and Hirano, M., 1983, Comprehensive strontium isotope study of Quaternary volcanic rocks from the Izu-Ogasawara arc: Geochem., v. 17, no. 6. p. 289-302.

Nye, C. J.. and Reid, M. R.. 1986, Geochemistry of primand and least fractionated lavas from Okmok volcano. Central Aleutians: Implications for arc magmatism: Jour. Geophys. Res., v. 91, p. 10271-10287.

Pokrovskiy. B. C and Zhuravlev, D. Z., 1991, New data on geochemistry of isotopes in effusives of the Kurile island arc: Geokhimiya, no. 3, p. 414-419 (in Russian).

Popolitov, Ye. I., and Volynets, 0. N., 1982, Geochemistry of Quaternary volcanic rocks from the Kurile-Kamchatka island arc: Jour. Volcanol. Geotherm. Res., v. 12. nos. 3-4. p. 299-316.

Powell. R., and Powell. M.. 1977, Geothermometry and oxygen barometrv using coexisting iron-titanium oxides: A reappraisal: Miner. Mag., v. 41, p. 257-263.

Puzankov. Yu. M.. Volynets. O. N., Avdeyko, G. P., Anlonov. A. Yu.. and Markov, I. A., 1991, Geochemistry of trace elements in the Quaternary volcanics from the Kurile arc. Radioactive elements, *in* Cavshin. \. M.. ed.. Geochemical associations of trace and radioactive elements in ore magmatic complexes: Novosibirsk. Nauka Press, p. 81-97 (in Russian).

Pushcharovskiy. Yu. M.. ed., 1992, Submarine volcanism and zoning of Kurile island arc: Moscow, Nauka Press, 528 p. (in Russian).

Ringwood, A. E., 1990. Slab-mantle interactions. 3. Petrogenesis of intraplate magmas and structure of the upper mantle: Chem. Geol., v. 82, p. 187-207.

Ryerson, E J., and Watson. E. B., 1987, Rutile saturation in magmas: Implications for Ti-Nb-Ta depletion in island-arc arc basalts: Earth Planet. Sci. Lett., v. 86, p. 225-239.

Sergeyev, K. E. and Krasny. M. L, eds., 1987, Geological-geophysical atlas of the Kurile-Kamchatka island system: Leningrad, VSEGEI Publishers (in Russian).

Shantser, A. E.. and Shapiro, M. I., 1984, The evolution of volcanic zones of Kamchatka in connection with the tectonic development of active continental margin: Volkanol. i Seysmol., no. 2, p. 26-40 (in Russian).

Singer, B. S., and Myers, J. D., 1990, Intra-arc extension and magmatic evolution in the central Aleutian arc, Alaska: Geology, v. 18, p. 1050-1063.

Stern, R. J., and Ito, E., 1983, Trace element and isotopic constraints on the source of magmas in the active volcano and Mariana island arcs, Western Pacific: Jour. Volcanol. Geotherm. Res., v. 18, p. 461-482.

Taran, Yu. A., Pokrovskiy, B. G., and Volynets, O. N.. 1992, Hydrogen isotopes in amphiboles and micas from Quaternary lavas of Kamchatka-Kurile arc system: Rept. Geol. Surv. Japan, no. 279, p. 187-189.

Tatsumi, Y., 1986, Role of induced convection and mantle diapir in generation of subduction zone magmas: Bull. Volcanol. Soc. Jap., v. 31 (1), p. 39-44.

Tatsumi, Y., Hamilton, D. L, and Nesbitt, R. W, 1986, Chemical characteristics of fluid phase released from a subducted lithosphere and origin of arc magmas: Evidence from high-pressure experiments and natural rocks: Jour. Volcanol. Geotherm. Res., v. 29, nos. 1-4, p. 293-309.

Tera, E, Brown, L., Morris. J., Sacks. I. S.. Klein, J., and Middleton, R., 1986, Sediment incorporation in island-arc magmas: Inferences from ^{10}Be: Geochem. et Cosmochim. Acta., no. 4, p. 535-550.

Tera, E, Morris, J., and Tsvetkov. A. A., 1989, ^{10}Be/^{9}Be and geochemistry of Kurile-Kamchatka arc [ahs.]: 28th IGC, abstracts, v. 3/f3. Washington, DC. p. 227-228.

Tsvetkov, A. A., Volynets, 0. N.. Morris, J., and Tera, F., 1991, The problem of sediments subduction as shown by data on geochemistry of Be and B in magmatic rocks from the ocean-continent transitional zone: Izvestiya AN SSSR, ser. geol., no. 11, p. 3-25 (in Russian).

Ueda, A., and Sakai, H., 1984, Sulfur isotope study of Quaternary volcanic rocks from the Japanese islands arc: Geochim. et Cosmochim- Acta,- 'v. 48, p. 1837-1848.

Vinogradov, V. I., Grigor'yev, V. S., and Pokrovskiy, B. G., 1986, Isotope composition of oxygen and strontium in the rocks of the Kurile-Kamchatka island-arc—the key to genetic structure, *in* Shukolyukov, Yu. A., ed., Evolution of the crust-mantle system: Moscow, Nauka Press, p. 78-103 (in Russian).

Vlasov, G. M., ed., 1964, Geology of the USSR, v. 31, Kamchatka, Kurile and Commander Islands, Part 1. Geological description: Moscow, Nedra Press, 733 p. (in Russian).

Volynets, O. N.. Flerov, G. B., Shantser, A. E., and Melekestsev, I. V., 1987, The Kurile-Kamchatka arc. Kamchatka's segment, *in* Bogatikov, O. A., Dmitriyev, Yu. I., and Tsvetkov, A. A.,eds., Petrology and geochemistry of island arcs and marginal seas: Moscow, Nauka Press, p. 56-85 (in Russian).

Volynets, 0. N., Puzankov, Yu. M., and Anoshin. G. N., 1990a, Geochemistry of Neogene-Quaternary volcanic rock series of Kamchatka, in Krivenko. A. P., ed., Geochemistry of magmatic and metamorphic rocks of Kamchatka: Novosibirsk, Transactions of Institute of Geology and Geophysics, no. 390, p. 73-114 (in Russian).

Volynets, 0. N., Uspensky, V. S., Anoshin, G. N.. Valov, M. G., Patoka, M. G., Puzankov, Yu. M., Anan'yev, V. V., and Shypitsyn, Yu. G., 1990b, Evolution of geodynamic regime of magma generation in East Kamchatka at the Late Cenozoic (by geochemical data): Volkanol. i Seysmol., no. 5, p. 14-27 (in Russian).

Volynets, O. N., Avdeyko, G. P., Tsvetkov. A. A., Anan'yev, V. V, Antonov, A. Yu, Gladkov, N. G.. anfd - Markov, I. A., 1990c, Ultramafic inclusions in the Quaternary lavas of the Kurile island arc: Izvestiya AN SSR, ser. geol., no. 3, p. 43-57 (in Russian) (English translation in INT. GEOL. REV.. V. 32. p. 321-332).

Wood, D.A, 1979, A variably veined suboceanic upper mantle—genetic significance for mid-ocean ridge basalts from geochemical evidence: Geology, v. 7. p. 199-503.

_________, 1980, The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establish the nature of crustal contamination of basaltic lavas of the British Tertriary Volcanic Province: Earth Planet. Sci. Lett., v. 50, p. 11-30.

Yermakov, V. A., 1987, The peculiarities of development of volcanism and tectonic structure in the Kurile-Kamchatka island-arc in modern (Pliocene-Quaternary) time, *in* Belousov. V. V. ed.. Essays on the tectonic development of Kamchatka: Moscow, Nauka Press, p. 165-218 (in Russian).

Yermakov, V. A., Volynets. 0. N.. and Koloskov, A. V.. 1987, Inclusions in volcanic rocks of the Kurile-Kamchatka island-arc and their significance for understanding of petrogenesis. *in* Bogatikov, 0. A.. Dmitriyev, Yu. I., and Tsvetkov. A. A..eds., Petrology and geochemistry of island-arcs and marginal seas: Moscow, Nauika Press, p. 293-312 (in Russian).

Yogodzinsky, G. M., Volvnets. 0. N.. Koloskov, A. V., Seliverstov. N. I., and Matveyenkov. V. V., 1994, Magnesian andesites and the subduction component in a strongly calc-alkaline series at Pivip volcano, far western Aleutians: Jour. Petrol., v. 35, part 1. p. 163-204.

Zhuravlev, D. Z., Tsvetkov. A. A.. Zhuravlev, A. Z.. and Ghernyshev. I. V., 1987. ^{u}Nd/^{1v1}Nd and ^{87}Sr/^{86}Sr ratios in recent magmatic rocks of the Kurile island arc: Chem. Geol., v. 66. p. 227-243.