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Isotopic Composition of Late Neogene K–Na Alkaline Basalts of Eastern Kamchatka: Indicators of the Heterogeneity of the Mantle Magma Sources

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Abstract—Isotopic composition of Sr, O, Nd, and Pb was determined in K–Na alkaline gabbroids and basaltoids that formed in eastern Kamchatka during Middle Miocene (gabbroids of the subvolcanic complex) and Late Miocene (basaltoids of the volcanic complex) time, before the origin of the Eastern Kamchatka Volcanic Belt. The variations in the isotopic parameters of the gabbroids and basaltoids are, respectively, as follows: $^{87}Sr/^{86}Sr$ = 0.70381–0.70465 and 0.70362–0.70512, no data on $\delta^{18}O$ and $\delta^{18}O$ ranging from +6.0 to +10.4‰, ε_{Nd} ranges from +3.8 to +10.4 and from +2.0 to +7.1, $^{206}Pb/^{204}Pb$ = 17.818–18.164 and 17.880–18.105, $^{207}Pb/^{204}Pb$ = 15.427–15.475 and 15.479–15.537, $^{208}Pb/^{204}Pb$ = 37.542–37.964 and 37.950–38.239. Systematic covariations were detected for isotopes of Sr, O, Nd, and Pb with one another and with some geochemical parameters of the rocks. This led us to propose a two-component mixing model for the initial magmas, which were produced by the melting of the material of an enriched mantle plume (EM 1) and the depleted mantle of the MORB type. Isotopic data provide further evidence that the sources of the Late Cenozoic volcanics of the within-plate and island-arc geochemical types were different.

INTRODUCTION

As was established by studies over the past few years [1–4], the origin of the Pliocene–Quaternary island-arc volcanic belt on Eastern Kamchatka followed the emplacement of K–Na alkaline basalt magma of the within-plate geochemical type, which produced bodies of volcanic (in the eastern offshoots of the Valaginskii Range) and subvolcanic rocks (dikes and sills on the Valaginskii Range, the Kronotskii Peninsula, and the Kamchatka Cape). Although the volume of these volcanic and subvolcanic rocks is fairly limited, they are significant for understanding the geodynamic evolution of the Late Cenozoic island-arc system of the Kamchatka Peninsula and, particularly, some distinctive features of the deep-seated magma genesis.

We examined in detail the composition of K–Na alkaline basalts and gabbroids exposed on Kornilovskaya Mountain on the eastern slope of the Valaginskii Range. The goal of this paper is to analyze data on the isotopic Sr, O, Nd, and Pb composition of the rocks and to reveal the nature of the source of the parental magmas. The location of the study area is shown in Fig. 1.

ANALYTICAL TECHNIQUES

The K–Ar radiogenic age of the volcanic and subvolcanic rocks was determined by D.I. Golovin at the Laboratory of Isotopic Geochemistry and Geochronology of the Institute of Geology, Russian Academy of Sciences. V.I. Vinogradov and V.S. Grigor'ev examined, at the same laboratory, the isotopic composition of Sr on a MAT-260 mass spectrometer. B.G. Pokrovskii determined the oxygen isotopic composition on an MI-1201V mass spectrometer. The isotopic composition of Nd in the lavas and the isotopic compositions of Sr and Nd in the subvolcanic rocks were analyzed at the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences on a TSN-206 mass spectrometer, and the isotopic composition of Pb (and of Sr and Nd in one of our samples) were determined at Cornell University, Ithaca, United States, on a TIMS mass spectrometer. The trace-element chemistry of the rocks was examined by INAA at Cornell University (analysts R.W. Kay and O.N. Volynets) and at the Joint Institute of Geology, Geophysics, and Mineralogy, Siberian Division, Russian Academy of Sciences (analyst S.T. Shestel'). Some elements were analyzed by XRF at the Joint Institute of Geology, Geophysics, and Mineralogy, Siberian Division, Russian Academy of Sciences, and the Vinogradov Institute of Geochemistry and Analytical Chemistry, Siberian Division, Russian Academy of Sciences. The compositions of minerals in the rocks were examined using a Camebax microprobe at the Institute of Volcanic Geology and

Geochemistry, Far East Division, Russian Academy of Sciences (analysts V.M. Chubarov and G.P. Ponomarev). The analytical techniques are described in detail in papers published earlier by workers of the respective laboratories. The errors in the isotopic composition were less than 0.01% for Sr and Nd, less than 0.05% for Pb, and 0.2% for O. To examine the effect of secondary processes on the Sr isotopic ratios, we determined the $^{87}Sr/^{86}Sr$ ratios of three samples after their leaching with hot 4 N HCl solution.

GEOLOGIC SETTING OF THE ALKALINE ROCKS

As of yet, K–Na alkaline volcanics have been encountered only on the eastern offshoots of the Valaginskii range, southeast of Kornilovskaya Mountain, in the drainage area of the Stepanova and Khrustal'nyi creeks. Since a detailed description of the rocks was published earlier [1], we only mention here that lava flows of K–Na alkaline basalt and basanite were encountered as incidental intercalations in the bottom of the molassoid sequence of the Shchapino Formation, whose age was determined, using remnants of fossil fauna and flora, as Late Miocene–Early Pliocene. In addition to lava, the sequence includes incidental beds of basanite aquatuff and basalt or microgabbro dikes. The thickness of the flows varies from 10 to 30–50 m, and that of the dikes is 1–3 m. Lava sheets, dikes, and sills in the upper (Early Pliocene) portion of the Shchapino Formation have a remarkably different composition (they are highly aluminous K–Na subalkaline megaplagiophyric and subaphyric basalts) and are not discussed in this paper.

We examined the rocks of the subvolcanic complex within an adjacent territory, west of Kornilovskaya Mountain, in the upper reaches of the Levaya Kornilovskaya River and the middle reaches of the Mal'tsevskaya River. There, a more eroded part of the succession consists of cherty terrigenous rocks of Early–Middle Pliocene age. In the course of state geological surveying on a scale of 1 : 50 000, M.G. Patoka, V.S. Uspenskii, Yu.A. Maksimova, *et al.* found about a dozen dikes and sill-shaped bodies of high-Ti K–Na alkaline gabbroids. The thickness of the dikes ranges

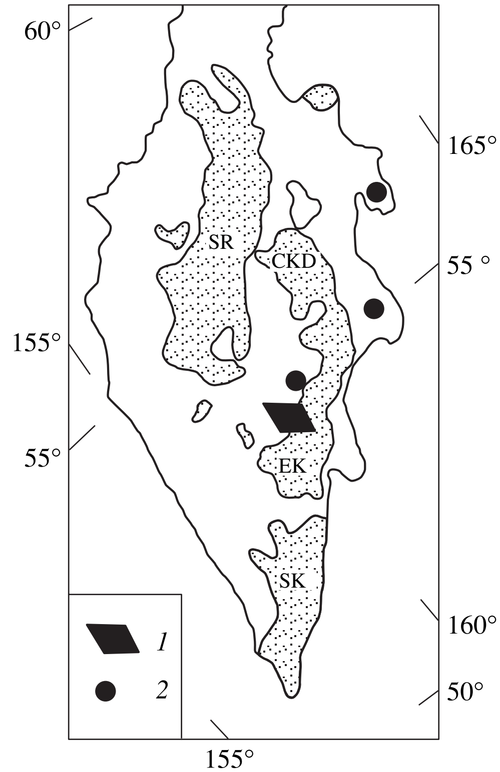

Fig. 1. Schematic map showing the location of (*1*) the study area and (*2*) other occurrences of Late Neogene alkaline rocks in Eastern Kamchatka. Shaded areas indicate island-arc Pliocene–Quaternary volcanic belts of Kamchatka: EK—Eastern Kamchatka, SK—Southern Kamchatka, CKD—Central Kamchatka Depression, SR—Sredinnyi Range.

from 1 to 10 m. They trend northeast and northwest and dip at steep angles and even vertically. The sills are 50–70 m thick. Both dikes and sills are often tectonized and bear slickensides. Compositionally similar dikes were described on the Valaginskii Range, north of our study area along the Konstantinovskaya River [4]; similar sills were encountered on the Kamchatskii Cape; and analogous dikes and sills were described on the Kronotskii Peninsula [3].

The rocks of the lava complex (Table 1) yield a Late Miocene K–Ar age for the alkaline basaltoids and an

Table 1. K–Ar age of K–Na alkaline and subalkaline gabbroids and basaltoids from the Kornilovskaya Mt. area, Valaginskii Range, Kamchatka

No.	Sample	Sampling locality	Rock	Facies affiliation of the rock	K, wt %	^{40}Ar, wt %	Age, Ma
1	7702	Levaya Kornilovskaya R.	Gabbrosyenite	Dike	2.21	0.00122	14.1 ± 0.2
2	7631/1	Stepanova Cr.	Basanite	Flow	1.63	0.000565	9.12 ± 0.14
3	7625	″	Alkaline basalt	Flow	1.12	0.000324	7.4 ± 0.11
4	7637	″	Microgabbro	Dike	1.60	0.000444	7.0 ± 0.11
5	7645	″	Alkaline basalt	Flow	0.99	0.000265	6.8 ± 0.10
6	4090/2	Ploskaya Mt.	Subalkaline basalt	Flow	1.49	0.000287	4.9 ± 0.07

Table 2. Representative analyses of minerals from K–Na alkaline gabbroids and basaltoids

No.	Sample	Phase	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	SUM
1	7743	*Cpx*	47.47	3.09	7.36	0.00	7.86	–	13.49	21.65	0.34	0.00	101.25
2	7743	*Bi*	35.82	6.57	16.13	0.00	13.82	–	14.12	0.02	1.96	7.76	96.21
3	7702	*Pl*	59.71	0.02	25.38	0.00	0.19	0.00	0.03	6.50	7.23	0.62	99.68
4	7702	*Fsp*	64.98	0.00	18.41	0.00	0.00	0.00	0.00	0.04	0.84	15.89	100.17
5	7702	*Anal*	54.65	0.00	22.90	0.00	0.00	0.00	0.00	0.00	13.85	0.00	91.40
6	7702	*TiMt*	1.03	20.57	2.27	0.00	68.80	2.17	0.00	0.98	0.00	0.00	95.82
7	7702	*Kaer*	39.16	6.36	13.01	0.00	13.01	0.00	11.28	11.66	2.18	1.24	97.90
8	7702	*Aeg*	52.49	0.93	1.71	0.00	26.28	0.20	0.46	3.53	12.79	0.04	98.43
9	7893	*Ol*, p	40.94	0.00	0.00	0.00	11.38	0.16	47.65	0.04	0.00	0.00	100.16
10	7893	*Sp*, i	0.00	1.06	14.24	43.05	32.09	0.38	8.52	0.00	0.00	0.00	99.34
11	7893	*Cpx*, m	45.23	2.25	8.44	0.43	7.80	0.12	11.97	23.20	0.41	0.00	99.87
12	3177/1	*Ol*, p	39.21	0.00	0.00	0.00	10.77	0.14	48.11	0.01	0.00	0.00	98.85
13	3177/1	*CrMt*, i	0.03	6.64	12.39	18.92	54.28	0.47	4.73	0.00	0.00	0.00	97.46
14	3177/1	*TiMt*, m	0.00	18.81	1.20	0.04	74.66	0.73	1.44	0.00	0.00	0.03	96.18
15	3177/1	*Il*, m	0.02	49.00	0.00	0.12	43.69	0.74	4.47	0.08	0.00	0.02	98.12
16	3177/13	*Cpx*, m	41.09	4.74	9.68	0.00	9.04	0.11	9.61	22.05	0.66	0.00	96.98
17	3177/1	*Ne*, m	49.91	0.05	29.68	0.00	0.55	0.00	0.00	0.23	16.19	2.52	99.12
18	3177/1	*Anal*, m	52.41	0.08	23.56	0.01	0.54	0.00	0.00	0.77	12.18	0.17	89.43
19	3177/1	*Pl*, m	59.25	0.11	25.85	0.00	0.44	0.00	0.00	6.13	6.96	1.41	100.14
20	3177/1	*Fsp*, m	65.57	0.11	20.44	0.00	0.33	0.01	0.00	1.04	6.35	6.99	100.86

Note: Sample 7743 is titanaugite gabbro from a dike; Sample 7702 is a kaersutite gabbrosyenite from a dike; Sample 7893 is subalkaline basalt from a lava flow; Sample 3177/1 is basanite from a flow. See Table 3 for chemical analyses of the rocks. Mineral symbols: *Ol*—olivine, *Cpx*—clinopyroxene, *Aeg*—aegirine, *Kaer*—kaersutite, Bi—biotite, *Sp*—spinel, *CrMt*—chrome magnetite, *TiMt*—titanomagnetite, *Il*—ilmenite, *Pl*—plagioclase, *Fsp*—alkaline feldspar, *Ne*—nepheline, *Anal*—analcime. Phases: p—phenocryst, i—inclusion in a phenocryst, m—microlite.

Early Pliocene age for the subalkaline basaltoids. These data are in good agreement with geological observations. The only determination of the radiological age of the subvolcanic rocks corresponds to the Middle Miocene, i.e., an age when the Kronotskii terrane was already accreted to Kamchatka [5–6].

PETROGRAPHY AND MINERALOGY

The alkaline rocks of the subvolcanic complex are represented by porphyritic and subaphyric varieties with phenocrysts of magnesian olivine (cores $Fo_{84–89}$) with inclusions of spinel (17–37 wt % Cr_2O_3, 16–45 wt % Al_2O_3, $Mg^{\#}$ = 35–65). Rare varieties contain phenocrysts of both olivine and clinopyroxene (titanous diopside-salite). The variably recrystallized groundmass of the lavas consists of plagioclase (labradorite to, rarely, bytownite), clinopyroxene (titanous salite and, more rarely, fassaite), olivine (ferrous chrysolite), three-component feldspar ($Or_{10–20}$), K–Na feldspar ($Or_{30–55}$), titanomagnetite (16–23 wt % TiO_2), ilmenite, analcime, and minor amounts of glass (Table 2). The basanite differs from the alkaline basalt by smaller amounts of olivine phenocrysts (which are smaller), more leucocratic, and less recrystallized groundmass, the presence of minor nepheline in the groundmass, the more sodic composition of plagioclase microlites (andesine), and the predominance of fassaite over salite in the clinopyroxene of microlites. The microgabbro additionally contains kaersutitic amphibole and titanous (5–6 wt % TiO_2) biotite. The usual secondary minerals are chlorite, which replaces olivine and glass in the groundmass, and carbonate, which fills, together with chlorite, pores. The basanitic aquatuff contains small xenoliths of clinopyroxenite with sodic diopside (up to 1.5 wt % Na_2O) [7].

The rocks of the subvolcanic complex are subdivided into three groups: kaersutite (often pegmatitic) gabbrosyenite (which dominates in the group), gabbro with titanous clinopyroxene (±kaersutite), and amphibole–clinopyroxene microgabbro. All the rocks contain analcime, which is particularly abundant in the gabbrosyenite, along with plagioclase and K–Na feldspar. The gabbro and gabbrosyenite usually contain minor biotite, titanomagnetite, ilmenite, and apatite. The pyroxene of the gabbro is salite or fassaite. The mafic minerals in the gabbro and gabbrosyenite (but not in the microgabbro) are high in Ti: the content of TiO_2 is as high as 6.0–6.5 wt % in the kaersutite, 2.0–4.5 wt % in the clinopyroxene, 5.0–6.5 wt % in the biotite, and 17–24 wt % in the titanomagnetite (Table 2). Kaersutite

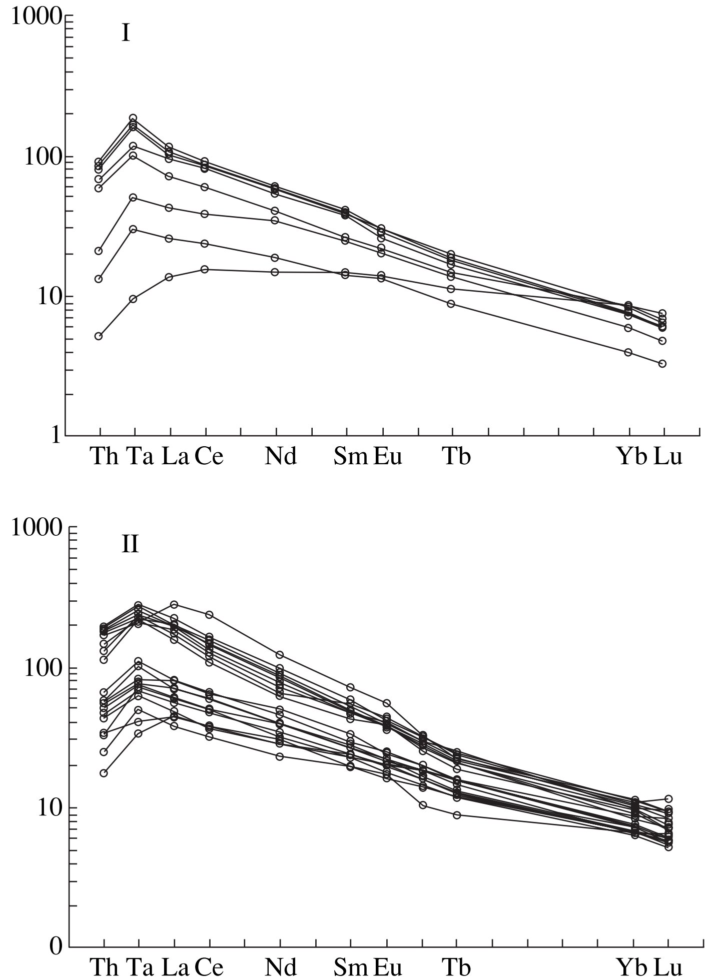

Fig. 2. Leedey chondrite-normalized patterns of Th, Ta, and REEs for (I) Late Neogene alkaline gabbroids and (II) basaltoids of Eastern Kamchatka.

grains in the gabbrosyenite are often mantled by fine-grained aggregates of aegirine and aegirine-hedenbergite. The two latter minerals also occur as poikilitic inclusions in grains of the K–Na feldspar. The rocks are notably (often quite strongly) altered: the plagioclase (andesine-labradorite) is replaced by albite and nearly pure potassic feldspar (Or_{92-99}), the alkaline feldspar is replaced by clay minerals, the mafic minerals are chloritized and sometimes carbonized, and iron hydroxides are developing after the opaque minerals.

MAJOR- AND MINOR-ELEMENT COMPOSITION OF THE ROCKS

Representative major- and minor-element analyses of the alkaline gabbroids and basaltoids are listed in Table 3 and illustrated in Figs. 2 and 3. The gabbroids of the subvolcanic complex are moderately to low magnesian ($Mg^{\#}$ = 45–59), and the basalts and microgabbro of the volcanic complex comprise both moderately magnesian ($Mg^{\#}$ = 56–63) and highly magnesian ($Mg^{\#}$ = 65–72) varieties. Although the $Mg^{\#}$ of the rocks and their trace-element contents are generally well correlated (positively for compatible elements and negatively for incompatible elements), the rocks of the volcanic complex are notably richer in lithophile elements than the rocks of the subvolcanic complex, even if the former are more magnesian.

In chondrite-normalized Th, Ta, and REE plots (Fig. 2, II), the rocks of the volcanic complex compose two distinct groups, which differ in the contents of these elements and have almost no intermediate compositions. One of the groups comprises highly magnesian varieties (alkaline basalts and microgabbro), and the other corresponds to the moderately magnesian rocks (basanite). The two groups also differ by the contents of other trace elements (Table 3), both compatible (Ni, Co, Cr, and Sc) and incompatible (Sr, U, Zr, Hf, Nb, Ti, P, and some others). In spite of these differences, both groups should be classified with alkaline rocks based on their mineralogy (the presence of titanous clinopyroxene, analcime, and nepheline) and geochemistry

Table 3. Major- and trace-element composition of Late Neogene alkaline gabbroids and basaltoids

Component	7741C	7707C	7742C	7743C	7702C	7706C	3166C	7893C
SiO_2	42.61	47.06	46.28	41.91	46.40	45.66	46.29	45.52
TiO_2	1.46	1.32	2.07	3.23	2.51	2.60	1.81	1.47
Al_2O_3	17.61	16.86	17.13	15.71	17.29	17.00	14.60	14.12
Fe_2O_3	2.99	5.77	4.09	6.80	5.45	5.75	1.59	3.22
FeO	4.13	3.77	3.86	5.57	4.49	4.85	6.67	7.00
MnO	0.10	0.15	0.16	0.15	0.25	0.15	0.18	0.13
MgO	8.32	7.16	5.83	6.38	4.61	4.63	10.95	12.76
CaO	10.21	8.17	6.23	9.53	4.44	5.92	8.27	8.86
Na_2O	3.56	4.17	5.96	3.70	4.66	4.92	3.11	2.58
K_2O	0.42	0.81	1.26	0.97	3.59	1.99	1.49	1.29
P_2O_5	0.20	0.23	0.50	0.33	0.84	0.88	0.51	0.43
H_2O^-	–	–	–	–	–	–	1.49	0.94
LOI	7.80	4.04	6.13	5.06	4.69	4.88	2.40	1.62
SUM	99.11	99.51	99.50	99.34	99.22	99.23	99.36	99.94
Cr	288	313	116	101	114	148	433	659
Ni	178	46	41	84	4.4	8.4	245	303
Co	37.4	35.8	26.3	26.3	22.6	31.4	40.3	51.3
Sc	32.9	33.4	20.4	20.4	4.5	7.4	21.6	27.2
V	–	–	–	–	–	–	220	–
Rb	–	–	–	–	–	–	22	–
Cs	1.31	0.11	1.51	1.63	1.90	2.22	0.44	0.29
Ba	237	824	941	308	809	921	252	266
Sr	784	805	192	507	705	506	756	841
Ta	0.64	0.21	2.19	1.08	3.60	2.52	1.62	1.52
Nb	–	–	–	–	–	–	20	–
Hf	2.60	1.81	5.40	4.32	4.79	4.03	3.29	3.81
Zr	100	70	230	140	220	190	144	
Y	–	–	–	–	–	–	20	–
Th	0.66	0.26	2.88	1.04	4.19	3.34	2.61	2.34
U	0.25	0.17	1.07	0.46	1.56	1.08	0.80	0.65
La	9.50	5.05	26.45	15.48	39.80	35.76	22.70	21.20
Ce	22.29	14.63	55.85	35.30	81.25	77.38	48.50	46.50
Nd	12.75	10.19	27.19	23.27	39.63	39.92	22.10	23.60
Sm	3.05	3.20	5.57	5.37	8.04	8.38	5.00	5.81
Eu	1.10	1.13	1.77	1.64	2.09	2.42	1.45	1.61
Gd	–	–	–	–	–	–	–	–
Tb	0.48	0.62	0.80	0.76	0.92	1.00	0.65	0.73
Yb	0.89	1.95	1.87	1.34	1.73	1.76	1.47	1.66
Lu	0.114	0.262	0.237	0.166	0.209	0.211	0.185	0.224
$Mg^{\#}$	68.5	58.7	57.9	49.3	46.7	45.2	70.7	69.7
La/Yb	10.7	2.6	14.1	11.6	23.0	23.4	15.4	12.8
La/Ta	14.8	24.0	12.1	14.3	11.1	10.8	14.0	13.9
Ni/Co	4.8	1.3	1.6	1.9	0.2	0.3	6.1	5.9

Table 3. (Contd.)

Component	112G	7637G	2175/3G	7651G	4078/4C	2138/2C	7658G	3177/1C
SiO_2	47.68	43.52	44.80	47.41	44.94	44.58	43.75	46.72
TiO_2	1.75	1.82	2.17	1.53	2.25	2.15	2.55	2.74
Al_2O_3	15.20	14.58	13.54	15.27	14.56	14.56	14.70	14.40
Fe_2O_3	1.62	2.84	2.95	3.77	7.89	6.03	6.09	3.95
FeO	6.71	6.47	6.78	5.93	1.58	3.30	3.69	6.19
MnO	0.18	0.12	0.15	0.16	0.18	0.25	0.17	0.19
MgO	10.26	11.08	10.60	9.42	7.98	7.20	7.12	7.18
CaO	8.55	8.12	8.52	8.12	7.34	6.90	7.76	7.14
Na_2O	2.60	4.00	2.49	3.74	3.53	4.13	4.48	5.04
K_2O	1.37	1.96	1.14	1.21	1.80	1.90	1.45	2.21
P_2O_5	0.38	0.63	0.52	0.34	1.33	1.38	1.24	1.33
H_2O^-	1.23	0.55	2.63	–	2.17	2.58	–	0.58
LOI	1.69	4.12	2.65	2.45	4.24	4.55	6.24	2.46
SUM	99.22	99.81	99.94	99.35	99.79	99.51	99.24	100.13
Cr	241	297	553	442	319	233	165	219
Ni	160	–	247	218	175	151	127	143
Co	36.0	36.9	52.4	41.5	32.7	31.0	31.8	36.1
Sc	35.0	32.2	22.6	24.9	16.2	14.3	16.4	17.1
V	219	–	–	210	–	135	160	–
Rb	16	–	7	19	–	15	11	14
Cs	0.43	0.63	0.45	0.47	0.38	0.78	0.22	0.90
Ba	317	411	319	227	453	706	665	474
Sr	621	–	810	545	1728	1450	1015	1496
Ta	1.40	1.83	2.29	1.10	6.15	5.52	5.08	6.26
Nb	18	–	24	21	–	94	83	97
Hf	4.00	4.1	4.68	2.80	10.10	10.58	9.2	10.97
Zr	160	–	165	138	267	488	459	525
Y	22	–	20	20	24	26	29	33
Th	2.2	3.0	2.96	1.25	9.75	9.51	5.80	10.23
U	0.65	1.30	0.93	–	2.73	3.30	2.70	3.38
La	18.2	30.3	26.9	14.3	76.8	75.4	75.4	86.2
Ce	34.8	63.0	58.8	30.6	144.5	142.6	132.0	160.5
Nd	19.6	35.0	28.2	16.0	58.9	60.6	54.3	70.0
Sm	4.9	7.4	6.10	4.28	11.10	11.01	11.0	13.10
Eu	1.65	1.97	1.81	1.32	2.99	3.17	3.33	3.48
Gd	5.4	5.8	–	4.1	–	–	8.8	–
Tb	0.87	0.86	0.80	0.67	1.26	1.18	1.37	1.34
Yb	2.00	1.67	1.51	1.60	2.50	2.23	2.27	2.61
Lu	0.300	0.226	0.201	0.210	0.320	0.277	0.265	0.333
$Mg^{\#}$	69.1	68.6	64.6	64.3	62.1	59.5	58.1	56.8
La/Yb	9.1	18.1	17.8	8.9	30.7	33.8	33.2	33.0
La/Ta	13.0	16.6	11.7	13.0	12.5	13.7	14.8	13.8
Ni/Co	4.4	–	4.7	5.3	5.4	4.9	4.0	4.0

Notes: Samples 7741, 7707, 7742, 7743, 7702, and 7706 are rocks of the Middle Miocene subvolcanic (dike) complex; others are rocks of the Late Miocene volcanic complex.

The contents of major components are given in wt %, trace elements are in ppm. Major-element analyses were accomplished at the Institute of Volcanic Geology and Geochemistry, Far East Division, Russian Academy of Sciences, and the Vinogradov Institute of Geochemistry and Analytical Chemistry, Siberian Division, Russian Academy of Sciences; trace elements (except Nb, Zr, Y, and Rb) were determined by INAA at Cornell University, USA, (samples with "C" indexes) and at the Joint Institute of Geology, Geophysics, and Mineralogy, Siberian Division, Russian Academy of Sciences, (samples with "G" indexes); the contents of Nb, Zr, Y, and Rb were determined by XRF at the Vinogradov Institute of Geochemistry and Analytical Chemistry, Siberian Division, Russian Academy of Sciences, and the Joint Institute of Geology, Geophysics, and Mineralogy, Siberian Division, Russian Academy of Sciences.

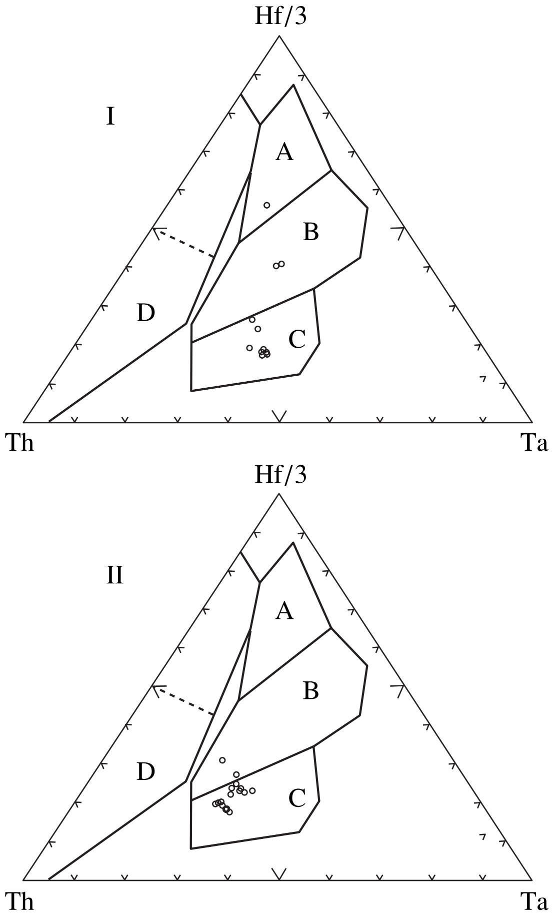

Fig. 3. Th–Ta–Hf systematics of Late Neogene (I) alkaline gabbroids and (II) basaltoids of Eastern Kamchatka. Fields (after [8]): A—N-MORB, B—E-MORB + WPB, C—WPB, D—IAB.

(they contain normative nepheline, have elevated contents of incompatible trace elements, and strongly fractionated REEs).

Similar plots for the subvolcanic complex (Fig. 2 I) illustrate the progressive increase in the contents of incompatible trace elements from the amphibole–clinopyroxene microgabbro (Sample 7707) through the Ti-salite gabbro (Samples 7742 and 7743) to the kaersutite gabbrosyenite (Samples 7702, 7706, and some others). The concentrations of lithophile elements and their patterns are similar to those in E-MORB in the case of the microgabbro but are typically alkaline basaltic in the case of the gabbro and gabbro syenite.

In spite of the above-mentioned compositional differences between the rocks of the volcanic and subvolcanic complexes, all of them show certain features that make these rocks different from normal island-arc lavas. First and foremost, these are the elevated contents of HFSEs (Ti, Nb, and Ta) and low La/Ta, La/Nb, Zr/Nb, and other analogous ratios in which these elements are in the denominators. In chondrite-normalized Th, Ta, and REE plots (Fig. 2), the vast majority of the rocks (except some microgabbros without Ta anomaly) have maxima at Ta, whereas lavas of the island-arc geochemical type usually have Ta minima in analogous plots. In a Th–Ta–Hf diagram [8], most of the rocks of both complexes are plotted within the field of within-plate lavas, two samples of each complex fall in the field of within-plate and E-MORB, and the microgabbro of the subvolcanic complex occurs in the N-MORB field (Fig. 3). These features make it possible to classify the rocks of the volcanic complex with the within-plate geochemical type [1–2]. In spite of the notable differences in the level of Nb and Ta concentrations, the rocks of the subvolcanic complex should also be assigned to this type.

ISOTOPIC COMPOSITION OF THE ROCKS

Data on the remarkable differences between the trace-element chemistries of the rocks of the within-plate and island-arc geochemical types led us to suggest that the two rock families had different magma sources [1–2]. However, when tested by studying the Sr and O isotopic compositions of the within-plate basalts, this hypothesis was not unambiguously confirmed, although it became apparent that the K–Na alkaline basaltoids of Eastern Kamchatka show pervasively higher $^{87}Sr/^{86}Sr$ ratios and $\delta^{18}O$ values than those typical of island-arc lavas [9].

We continued attacking this problem by examining the isotopic compositions of Nd [10] and Pb in the rocks of the volcanic complex (whose Sr and O isotopic ratios were determined earlier) and the isotopic compositions of Sr, Nd, and Pb in the gabbroids of the subvolcanic complex from Kornilovskaya Mountain in Eastern Kamchatka. Table 4 summarizes isotopic data on the rocks, including data published previously and some other geochemical parameters of the rocks.

Analysis of these materials and their comparison with recently published data on the isotopic signatures of island-arc lavas in Kamchatka [11–14] definitely indicate that the within-plate basaltoids and gabbroids generally have higher $^{87}Sr/^{86}Sr$ ratios and $\delta^{18}O$ values than those in lavas of the island-arc type but have lower ε_{Nd} and $^{206}Pb/^{204}Pb$ at similar $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios.

In a variety of plots portraying relationships between radiogenic isotopes (Figs. 4–6), data points of the K–Na alkaline basaltoids and gabbroids of Eastern Kamchatka are generally plotted beyond the field of island-arc lavas of Kamchatka and occupy an intermediate position between N-MORB of the Pacific Ocean and the enriched mantle 1 (EM 1), normally in the field of the Late Cenozoic K–Na alkaline basaltoids of southwestern Japan and the Sea of Japan, i.e., the rocks with similar concentration levels and patterns of trace elements [16, 18]. At the same time, the island-arc volcanics of Kamchatka have Pb and Nd isotopic signatures similar to those of N-MORB, but they differ from these rocks by the higher Sr isotopic ratios [2, 11–14] (Figs. 4–6).

Alkaline igneous rocks of the within-plate geochemical type differ from volcanics of the island-arc type in correlations between isotopic ratios of different elements that are usually detected in the former rocks and some variations of some other isotopic features and geochemical parameters (Figs. 7–10). These correlations occur most typically in rocks of volcanic complexes and only much more rarely can be encountered in all volcanic and subvolcanic varieties (for example, ε_{Nd}–$(La/Sm)_N$, $^{87}Sr/^{86}Sr$–$(La/Sm)_N$, ε_{Nd}–$^{207}Pb/^{204}Pb$, etc.). Sometimes, these correlations are different in rocks of the volcanic and subvolcanic complexes [for example, ε_{Nd}–$Mg^{\#}$, $^{207}Pb/^{204}Pb$–$(Na_2O–K_2O)$]. Note that the contents of many trace elements (for example, Ti, P, Th, Nd, Cr, Ni, etc.) in the alkaline rocks are also correlated with the geochemical parameters used in Figs. 8–10.

The mutually correlated variations in the isotopic–geochemical features of the rocks topples, in our opinion, the concept that the variations in the trace-element and isotopic compositions of the rocks were caused by low-temperature hydrothermal alterations or the interaction between the basaltic magmas and crustal rocks.

For example, it was convincingly demonstrated that the Nd and Pb isotopic systems of lavas remain practically undisturbed during their interaction with seawater [19–21], although the $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values increase [22–23]. Hence, if the isotopic compositions of the rocks were controlled by seawater–rock interaction, this should result in correlations between Sr and O isotopes in the absence of correlations between isotopes of Sr and Nd, Nd and O, and Pb and O. In fact, the rocks of the volcanic complex show a weak correlation

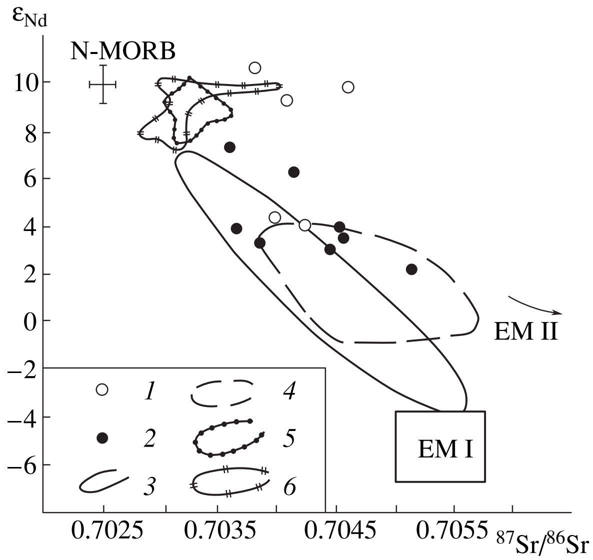

Fig. 4. Isotopic composition of Sr and Nd of Late Neogene alkaline gabbroids and basaltoids in Eastern Kamchatka. (*1*) Middle Miocene alkaline gabbroids of Eastern Kamchatka, (*2*) Late Miocene alkaline basaltoids of Eastern Kamchatka, (*3*) Late Cenozoic within-plate basaltoids of eastern China [15], (*4*) alkaline basalts of southeastern Japan and the Sea of Japan [16], (*5*) Quaternary island-arc lavas of Kamchatka [10, 13, 14, and our unpublished data], (*6*) island-arc lavas of the Kuril Islands [17].

Table 4. Isotopic composition of K–Na alkaline gabbroids and basaltoids

No.	Sample	$Mg^{\#}$	$Na_2O + K_2O$, %	Ta, ppm	La/Sm (N)	LOI, wt %	$\delta\ ^{18}O$	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	εNd	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
1	7707	58.7	4.98	0.21	0.99	4.84	–	0.70415*	0.51230	+8.9	–	–	–
2	7742	57.9	7.22	2.19	2.99	6.13		0.70459	0.51234	+9.6	18.164	15.475	37.952
3	same							0.70465*					
4	7743	49.3	4.67	1.08	1.81	5.06	–	0.70381	0.51238	+10.4	17.818	15.427	37.542
5	7702	46.7	8.25	3.60	3.11	4.69	–	0.70399	0.51206	+4.2	17.883	15.470	37.964
6	7706	45.2	6.91	2.52	2.68	4.88	–	0.70421	0.51204	+3.8	–	–	–
7	3166	70.7	4.60	1.62	2.85	2.40	+8.0	0.70402	–	–	–	–	–
8	7893	69.7	3.87	1.52	2.40	1.62	+6.9	0.70452	–	–	17.942	15.495	37.982
9	112	69.1	3.97	1.40	2.34	1.69	+6.0	0.70362	0.51221	+7.1	18.053	15.479	37.950
10	7637	68.6	5.96	1.83	2.58	4.12	+9.0	0.70363	0.51204	+3.8	–	–	–
11	same							0.703865*	0.512799	+3.15	18.005	15.504	38.113
12	2175/3	64.6	3.63	2.29	2.77	2.65	+6.2	0.70388	–	–	–	–	–
13	7651	64.3	4.95	1.10	2.10	2.45	+6.9	0.70417	0.51216	+6.1	18.105	15.500	37.977
14	4078/4	62.1	5.33	6.15	4.35	4.24	+10.4	0.70442	–	–	17.877	15.522	38.213
15	2138/2	59.5	6.03	5.52	4.31	4.55	+8.5	0.70442	0.51199	+2.8	–	–	–
16	7658	58.1	5.93	5.08	4.31	6.24	+8.9	0.70512	0.51195	+2.0	17.880	15.537	38.239
17	3177/1	56.8	7.25	6.26	4.14	2.46	+8.4	0.70452	0.51201	+3.2	17.880	15.524	38.119

Notes: Samples 1–6 are rocks of the subvolcanic complex; Samples 7–17 are rocks of the volcanic complex. Sample numbers are the same as in Table 3. In samples marked with asterisks, $^{87}Sr/^{86}Sr$ ratios are obtained after hot-acid leaching. The Sr and Nd isotopic composition of Sample 11 was determined at Cornell University (see the section "Analytical techniques" of this paper).

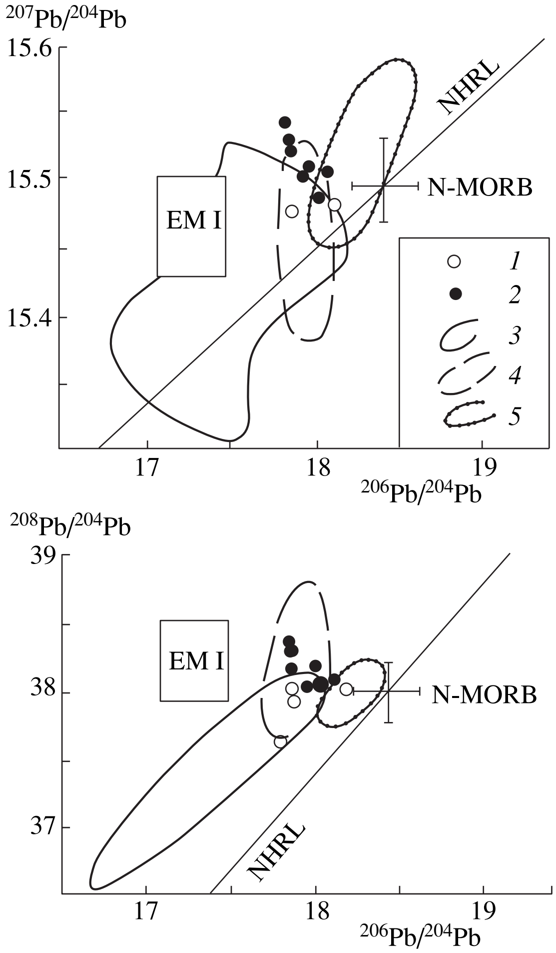

Fig. 5. Isotopic composition of Pb of Late Neogene gabbroids and basaltoids in Eastern Kamchatka. (*1–3*, *5*) Same as in Fig. 4; (*4*) alkaline basalts of the Sea of Japan [18].

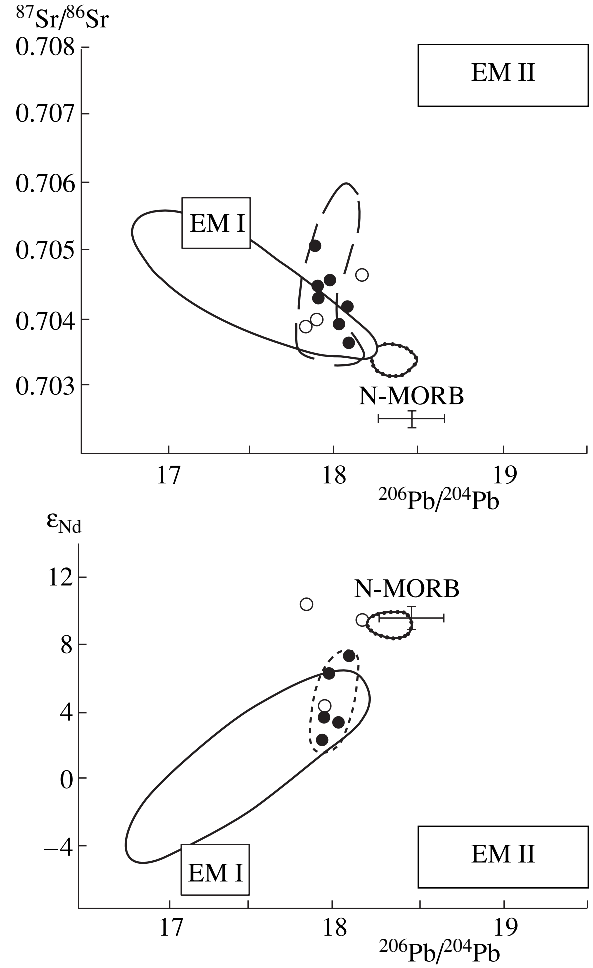

Fig. 6. Correlations between the isotopic compositions of Sr and Nd with that of Pb in Late Neogene gabbroids and basaltoids in Eastern Kamchatka. See Fig. 5 for the legend.

between the $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values but much stronger correlations of the isotopic compositions of Nd and Pb with those of O and Sr, which are positive in the case of $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ but negative in the case of ε_{Nd} and $^{206}Pb/^{204}Pb$ (Fig. 7). Such correlations between $\delta^{18}O$ and radiogenic isotopes of Sr, Nd, and Pb were established for fresh basaltic glasses from Pitcarian Seamounts in the Pacific Ocean [24], for which the glasses were interpreted as primary. Moreover, the $^{87}Sr/^{86}Sr$ ratios measured in two of our samples of fairly strongly altered rocks before and after their leaching with hot hydrochloric acid appeared to be nearly identical (Table 4). Finally, there are pronounced correlations between the isotopic compositions of Sr, Nd, Pb, and O with $Mg^{\#}$ of the rocks (Fig. 8) and some of their other geochemical parameters, for example, the La/Sm ratios (Fig. 9) or Ta (and Nb) concentrations (Fig. 10), which do not change during the hydrothermal alteration of rocks [25–26].

At the same time, the isotopic Nd, Pb, and O signatures of the rocks are relatively well correlated with their LOI values: these correlations are positive for $\delta^{18}O$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$, negative for ε_{Nd} and $^{206}Pb/^{204}Pb$, and absent for $^{87}Sr/^{86}Sr$ in the rocks of the volcanic complex (Fig. 11). If the arguments presented above to prove the absence of any relationships between the Nd and Pb isotopic compositions of the rocks and the degree of their hydrothermal alteration are valid, then we are led to assume that the correlations between the isotopic signatures of the rocks and their LOI values are false.[1] In this case, the correlations are caused by the stronger alterations in the basanite compared with those in the alkaline basalt and microgabbro and by differences in their isotopic compositions (Table 4). The differences between the alteration degrees of these groups of rocks could be related to the different textures of their groundmasses, which are substantially vitrophyric, often apovitrophyric in the basanite and much more granular (pilotaxitic, intersertal, or

[1] In fact, it seems to be more appropriate to discuss not a correlation but merely a tendency, for no clear-cut correlations between these parameters were determined.

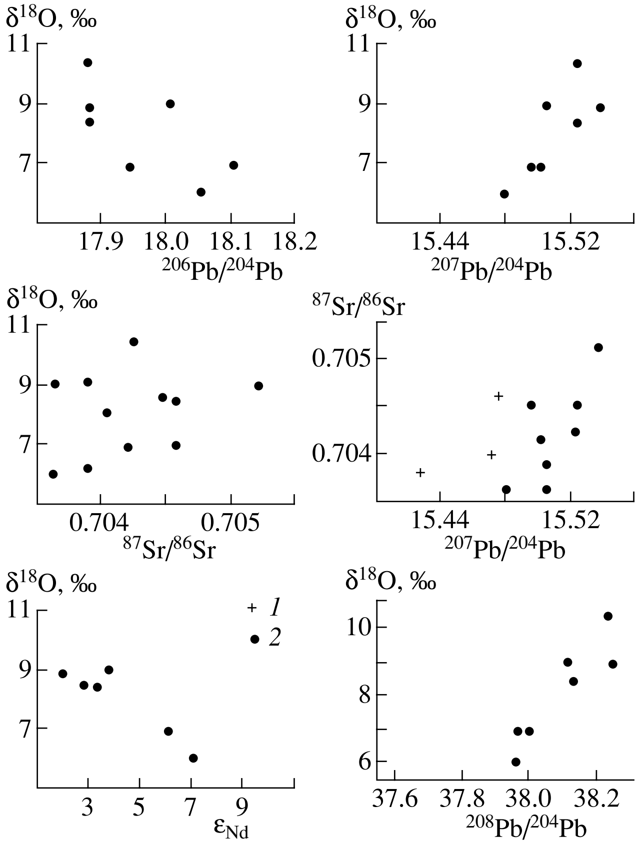

Fig. 7. Covariations between the isotopic compositions of O, Sr, Nd, and Pb of Late Neogene alkaline gabbroids and basaltoids in Eastern Kamchatka. Here and in Figs. 8–11, (*1*) and (*2*) are the same as in Fig. 4.

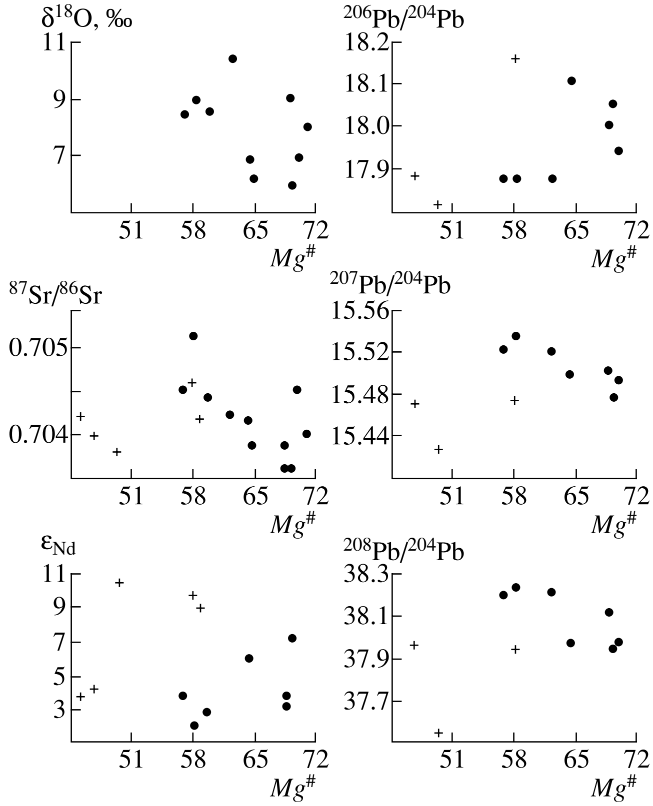

Fig. 8. Covariations between the isotopic compositions of O, Sr, Nd, and Pb with $Mg^{\#}$ [$Mg^{\#}$ = Mg/(Mg + Fe_{tot})] of Late Neogene alkaline gabbroids and basaltoids in Eastern Kamchatka.

doleritic) in the basalt and microgabbro. Low-temperature hydrothermal alterations are much more active and extensive in vitreous rocks than in crystalline rocks. However, distinctive features of the isotopic compositions of the alkaline basaltoids and gabbroids could not be caused by the contamination of the parental basalt magma with the material of the altered oceanic crust, because, again, no correlation can be expected in this case between $\delta^{18}O$ and ε_{Nd}. Conversely, this correlation is quite apparent in our rocks (Fig. 7). Neither could these isotopic features be caused by the contamination with modern pelagic sediments, because our rocks have extremely unradiogenic Pb, unlike all modern pelagic sediments, whose Pb is highly radiogenic.

Finally, the variations in the rock isotopic compositions could hardly be caused by the contamination of the basalt magma with the material of the ancient sialic crust. First, all of the rocks contain normative nepheline, and their alkalinity increases with decreasing $Mg^{\#}$. Evidently, if the magmas were contaminated with the sialic crust, the resultant melts should shift toward hypersthene and quartz-normative varieties. Second, as the $Mg^{\#}$ of the lavas decrease from the alkaline basalts to basanites, the rocks become richer in not only trace lithophile elements (Th, U, La, Ce, etc.) but also Ti and P; this contradicts the idea of contamination with acid material. Third, such high contents of Nb, Ta, and LREEs as in the basanite have never been determined in rocks of the metamorphic complex of Kamchatka [27].

DISCUSSION

Distinctive mineralogical and chemical features of the Middle Miocene gabbroids and Late Miocene basaltoids from the Kornilovskaya Mountain area in Eastern Kamchatka place them among igneous rocks of the alkaline series, and the trace-element characteristics of these rocks allowed us to classify them with the within-plate geochemical type. As was demonstrated above, these rocks also differ from the usual island-arc lavas of Kamchatka by their Sr, Nd, Pb, and O isotopic composition.

The fact that data points of these rocks are situated between N-MORB and EM 1 in plots showing relationships among radiogenic isotopes and data on covariations between the isotopic compositions of different elements and correlations between isotopic and trace-

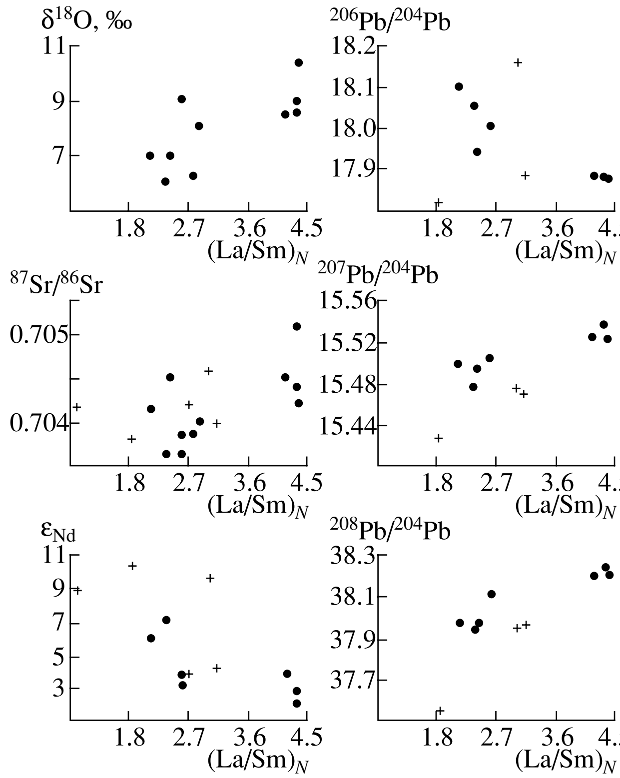

Fig. 9. Covariations between the isotopic compositions of O, Sr, Nd, and Pb with the chondrite-normalized La/Sm ratios of Late Neogene alkaline gabbroids and basaltoids in Eastern Kamchatka.

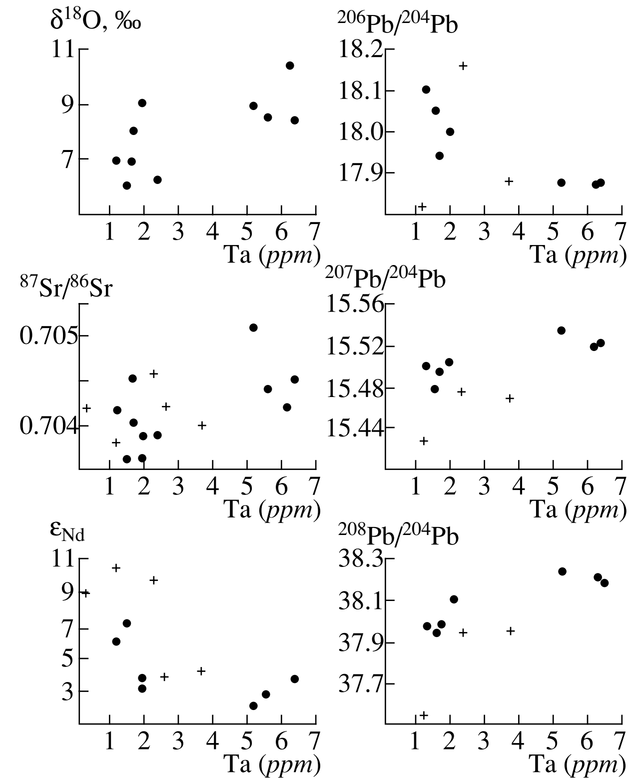

Fig. 10. Covariations between the isotopic compositions of O, Sr, Nd, and Pb with the Ta contents of Late Neogene alkaline gabbroids and basaltoids in Eastern Kamchatka.

element features of the rocks suggests that the origin of their parental melts was related to mixing processes and that there were at least two sources of these magmas. According to the hypothesis advanced earlier in [2] on the basis of the trace-element composition of the rocks, these sources could be the material of an enriched mantle plume (of the EM1 type), which ascended from considerable depths, and the depleted upper mantle material of the MORB type.

A similar model of two-component mixing based on negative correlations of $\delta^{18}O$ with $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ and positive correlations of $\delta^{18}O$ with $^{87}Sr/^{86}Sr$ was used earlier to account for the composition of basalt glasses from the Pitcarian Seamounts [24], and the trend from an N-MORB source to enriched mantle 1 (EM 1) was later referred to as the EM 1 trend [28]. It should be mentioned that there is a great uncertainty in the choice of the isotopic parameters of the end members for the mixing lines (models) used by different scientists. For example, Woodhead *et al.* use the following isotopic parameters of the end members in their models: $\delta^{18}O = +5.7‰$, $\varepsilon_{Nd} > +3$, $^{87}Sr/^{86}Sr < 0.704$, and $^{206}Pb/^{204}Pb > 18.25$ for the N-MORB component and $\delta^{18}O > +7.4‰$, $\varepsilon_{Nd} < -4$, $^{87}Sr/^{86}Sr > 0.7055$, and $^{206}Pb/^{204}Pb < 17.25$ for the plume component (EM 1). Other commonly used values are (Fig. 7) $\varepsilon_{Nd} > +8$ and $^{87}Sr/^{86}Sr < 0.703$ for the N-MORB mantle. The unusually

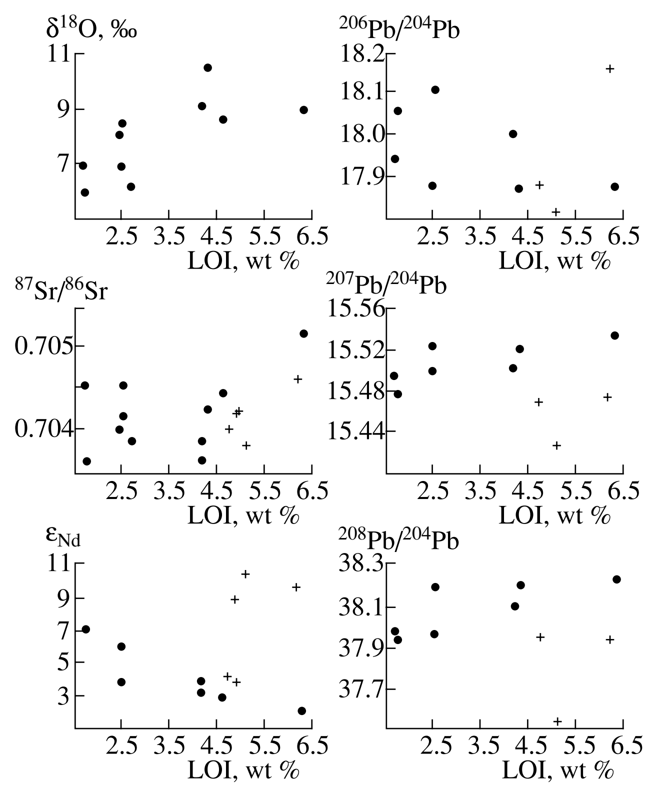

Fig. 11. Covariations between the isotopic compositions of O, Sr, Nd, and Pb with the LOI values of Late Neogene alkaline gabbroids and basaltoids in Eastern Kamchatka.

high (according to current concepts [23]) $\delta^{18}O$ in the material of a mantle plume is controlled by the recycling [24] of the ancient sedimentary mantle material enriched in ^{18}O ($\delta^{18}O > 15‰$). The heterogeneity of the mantle sources in terms of their oxygen isotopic composition is confirmed by studies of statistically significant material [28].

CONCLUSION

In summary, it should be stressed that the source of the basaltoids that were erupted in Kamchatka during Middle–Late Miocene time (an EM 1 mantle plum plus N-MORB upper mantle) differs from the source of the younger (Pliocene–Quaternary) island-arc lavas of the Eastern Kamchatka volcanic belt. The source of the latter rocks was visualized, based on the trace-element chemistry of the rocks, as the peridotitic material of a mantle wedge (of the N-MORB type), which was enriched by fluids derived during the dehydration of a subducted plate [29]. Isotopic studies provide further support for this hypothesis [12, 14], and the contents of ^{10}Be [30–31] and the isotopic composition of Pb [11, 13] suggest that pelagic sediments of a subducted oceanic plate or fluids from these rocks did not play any significant part in magmatic processes in Kamchatka.

The intrusion of alkaline basaltoids of the within-plate geochemical type followed in Eastern Kamchatka the accretion of the Kronotskii terrane to Kamchatka [5, 6] and could be tectonically related to deep collision-related splits in the continental plate. It was no sooner than 10 m.y. after the initial intrusion of magmas of the within-plate geochemical type that subduction-related magmas began erupting in the area.

ACKNOWLEDGMENTS

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REFERENCES

1. Volynets, O.N., Uspenskii, V.S., Anoshin, G.N., *et al.*, Evolution of the Geodynamic Regime of Magmagenesis in Eastern Kamchatka during the Late Cenozoic: Geodynamic Data, *Vulkanol. Seismol.*, 1990, no. 5, pp. 14–27.
2. Volynets, O.N., Geochemical Types, Petrology, and Genesis of Late Cenozoic Volcanic Rocks from the Kurile–Kamchatka Island-Arc System, *Int. Geol. Rev.*, 1994, vol. 36, no. 4, pp. 373–405.
3. Tikhomirova, S.R., Bakhteev, M.K., and Morozov, A.O., Sodic Alkaline Gabbroid Association of Eastern Kamchatka, *Byull. Mosk. O–va Ispyt. Prir., Otd. Geol.*, 1992, vol. 67, issue 4, pp. 99–106.
4. Tikhomirova, S.R., Late Cenozoic Teschenite in Eastern Kamchatka, *Dokl. Akad. Nauk*, 1994, vol. 335, no. 5, pp. 626–629.
5. Watson, B.F. and Fujita, K., Tectonic Evolution of Kamchatka and the Sea of Okhotsk and Implications for the Pacific Basin, *Tectonostratigraphic Terrains*, Howell, D.G., Ed., 1985, pp. 333–348.
6. Kononov, M.V., *Tektonika plit severo-zapada Tikhogo okeana* (Plate Tectonics in the Northwestern Pacific Ocean), Moscow: Nauka, 1989.
7. Koloskov, A.V., Volynets, O.N., Ponomarev, G.P., and Fedorov, P.I., Ultramafic Xenoliths in Various Geochemical Types of Volcanic Rocks of an Island-Arc System, *Petrologiya*, 1997, vol. 5, no. 5.
8. Wood, D.A., The Application of a Th–Hf–Ta Diagram to Problems of Tectonomagmatic Classification and to Establishing the Nature of Crustal Contamination of Basaltic Lavas of the British Tertiary Volcanic Province, *Earth Planet. Sci. Lett.*, 1980, vol. 50, pp. 11–30.
9. Volynets, O.N., Koloskov, A.V., Vinogradov, V.I., *et al.*, Isotopic Composition of Sr and O of the K–Na Alkaline Basalts of the Within-Plate Geochemical Type in Kamchatka, *Petrologiya*, 1995, vol. 3, no. 2, pp. 207–213.
10. Volynets, O.N., Karpenko, S.F., Koloskov, A.V., *et al.*, First Data on the Isotopic Composition of Nd in Late Cenozoic Alkaline Basalts of Kamchatka, *Dokl. Akad. Nauk*, 1996, vol. 350, no. 2, pp. 239–241.
11. Kepezhinskas, P., McDermott, F., Defant, M.J., *et al.*, Pb, Nd, and Sr Isotopic Character of Neogene–Quaternary Volcanics from Kamchatka (Russia), *EOS*, 1993, vol. 74, p. 674.
12. Vinogradov, V.I., Isotopic Evidence of the Conversion of Oceanic Crust in the Continent–Ocean Transition Zone of Kamchatka, *Geochem. Int.*, 1995, vol. 32, no. 3, pp. 70–109.
13. Kersting, A.B. and Arculus, R.J., Pb Isotope Composition of Kluchevskoy Volcano, Kamchatka, and North Pacific Sediments: Implication for Magma Genesis and Crustal Recycling in the Kamchatka Arc, *Earth Planet. Sci. Lett.*, 1995, vol. 136, pp. 133–148.
14. Tatsumi, Y., Kogiso, T., and Nohda, S., Formation of a Third Volcanic Chain in Kamchatka: Generation of Unusual Subduction-related Magmas, *Contrib. Mineral. Petrol.*, 1995, vol. 120, pp. 117–128.
15. Peng, Z.C., Zartman, R.E., Futa, K., and Chen, D.G., Pb, Sr and Nd Isotopic Systematics and Chemical Characteristics of Cenozoic Basalts from Eastern China, *Chem. Geol.*, 1986, vol. 59, pp. 3–33.
16. Nakamura, Y., McCulloch, M.T., and Campbell, T.H., Chemical Geodynamics in the Back-Arc Region of Japan Based on the Trace Element and Sr–Nd Isotope Component, *Tectonophysics*, 1990, vol. 174, pp. 207–233.
17. Zhuravlev, D.Z., Zhuravlev, A.Z., Chernyshev, I.V., *et al.*, Isotopic Zonation of the Kuril Island Arc: Data on the $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ Ratios, *Dokl. Akad. Nauk SSSR*, vol. 280, no. 2, pp. 486–491.
18. Tatsumoto, M. and Nakamura, Y., DUPAL Anomaly in the Sea of Japan: Pb, Nd and Sr Isotopic Variations at the Eurasian Continental Margin, *Geochim. Cosmochim. Acta*, 1991, vol. 55, pp. 3697–3718.

19. O'Nions, R.R., Carter, S.R., Cohen, R.S., *et al.*, Pb, Nd and Sr Isotopes in Oceanic Ferromanganese Deposits and Oceanic-Floor Basalts, *Nature*, 1978, vol. 273, pp. 435–438.
20. Cousens, B.L., Allan, J.F., and Gorton, M.P., Subduction-modified Pelagic Sediments at the Enriched Component in Back-Arc Basalts from the Sea of Japan: Oceanic Drilling Program Sites 797 and 794, *Contrib. Mineral. Petrol.*, 1994, vol. 117, pp. 421–434.
21. Staudiegel, H., Davis, G.R., Hart, S.R., *et al.*, Large-Scale Sr, Nd and O Isotopic Anomaly of Altered Oceanic Crust DSDP / ODP Sites 417 / 418, *Earth Planet. Sci. Lett.*, 1995.
22. Dasch, E.J., Hedge, C.E., and Dymond, J., Effect of Sea Water Interaction on Strontium Isotope Composition of Deep-Sea Basalts, *Earth Planet. Sci. Lett.*, 1973, vol. 19, pp. 177–183.
23. Faure, G., *Principles Of Isotope Geology*, New York: Wiley, 1986. Translated under the title *Osnovy izotopnoi geologii*, Moscow: Mir, 1989.
24. Woodhead, J.D., Greenwood, P., Harmon, R.S., and Stoffers, P., Oxygen Isotope Evidence for Recycled Crust in the Source of EM-Type Oceanic Island Basalts, *Nature*, 1993, vol. 362, pp. 809–813.
25. Hajash, A., Rare-Earth Element Distribution Patterns in Hydrothermally Altered Basalts, *Contrib. Mineral. Petrol.*, 1984, vol. 85, pp. 409–412.
26. Morrison, M.A., The Use of "Immobile" Trace Elements to Distinguish the Paleotectonic Affinities of Metabasalts: Application to the Paleocene Basalts of the Mull and Skye, Northern Scotland, *Earth Planet. Sci. Lett.*, 1978, vol. 39, pp. 407–416.
27. Puzankov, Yu.M., Volynets, O.N., Seliverstov, V.A., *et al.*, Geochemical Systematics of Igneous and Metamorphic Rocks of Kamchatka, *Tr. Inst. Geol. Geofiz. Akad. Nauk SSSR, Sib. Otd.*, Novosibirsk, 1990, issue 390.
28. Harmon, R. and Hoefs, J., Oxygen Isotope Heterogeneity of the Mantle Deduced from Global ^{18}O Systematics of Basalts from Different Geotectonic Settings, *Contrib. Mineral. Petrol.*, 1995, vol. 120, pp. 95–114.
29. Popolitov, E.I. and Volynets, O.N., *Geokhimicheskie osobennosti chetvertichnykh vulkanicheskikh porod Kurilo–Kamchatskoi ostrovnoi dugi i nekotorye voprosy petrogenezisa* (Distinctive Geochemical Features of the Quaternary Volcanic Rocks of the Kuril–Kamchatka Island Arc and Some Petrogenetic Problems), Novosibirsk: Nauka, 1981.
30. Tera, F., Morris, J.D., Leeman, W.P., and Tsvetkov, A.A., Further Evidence from Be–B Systematics for the Homogeneity of the Subducted Component in Arc Magmatism: Case of the Kurile–Kamchatka Arc, *Geochron. Cosmochron. Isotop. Geol.*, 1990, vol. 27, p. 100.
31. Tsvetkov, A.A., Volynets, O.N., Morris, J., *et al.*, The Problem of Subduction of Sediments in Light of Data on the Geochemistry of Be and B in Igneous Rocks from Ocean–Continent Transition Zones, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1991, no. 11, pp. 3–25.