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Variations in Isotopic and Trace-Element Composition of Lavas from Volcanoes of the Northern Group, Kamchatka, in Relation to Specific Features of Subduction

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Abstract—Two associations were revealed among the Northern group volcanoes in Kamchatka by study of chemical and isotopic composition of their lavas. The first association includes volcanoes located north of the Kamchatka River, e.g., Shiveluch, Zarechnyi, Kharchinskii volcanoes, and Kharchinskii regional zone of cinder cones. The second association comprises volcanoes located south of this river, e.g., Klyuchevskoi, Ploskie Sopki, Tolbachik, Nikolka volcanoes, as well as Tolbachik and Ploskie Sopki regional zones of cinder cones. The volcanic rocks of the first association differ from those of the second one in higher magnesium contents; elevated Sr; lower Ca, Sc, Y, and Yb; higher Sr/Y, K/Ti, La/Yb, Zr/Y, Th/Yb, Ni/Sc, Cr/Sc and lower Ca/Sr and U/Th ratios. Variations of Sr and Nd isotopic ratios in volcanics of these associations overlap. The covariations between Sr and Nd isotope characteristics and isotopic ratios with some major- and trace-element contents differ in these two associations. We concluded that the parental melts for the rocks of these associations were formed during the metasomatic transformation of mantle wedge under the influence of two different agents: partial melts generated within the subducted slab, for the northern volcanoes; and fluids derived from the subducted slab, for the southern ones. This discrepancy is probably related to different subduction conditions: oblique, gently dipping, slow subduction (like in the western Aleutians) beneath the northern volcanoes; and orthogonal subduction of ancient oceanic crust beneath the southern ones.

Several important publications on the geochemistry and isotopic composition of lavas of the Northern group volcanoes in Kamchatka have been issued recently [1–9] and amplified earlier papers of Russian researchers devoted to this problem [10–15]. However, the major part of these papers are dealt with the volcanoes located south of the Kamchatka River (SVNG—Southern Volcanoes of the Northern Group) and only a few papers cover the data on the rocks of Kharchinskii group of cinder cones, Shiveluch, Kharchinskii, and Zarechnyi volcanoes, i.e., on the volcanic rocks for the NVNG (Northern Volcanoes of the Northern Group). Our preliminary study of the rocks of the latter three volcanoes revealed their specific features as compared to the rocks of the southern volcanoes.

First, the magnesian rocks are predominant among the lavas of the NVNG; not only magnesian basalts but also magnesian andesites have been found on Shiveluch and Zarechnyi volcanoes [13, 14, 16, 17]. The total volume of magnesian basalts on these volcanoes is 5–10 times larger than on all the other Kamchatka volcanoes together including the southern volcanoes of the Northern group [18]. Second, the magnesian basalts of the NVNG differ from their southern counterparts by higher K, Ba, Sr, and lower Ca, Sc, Yb concentrations and have higher La/Yb, La/Ta, and Ni/Sc ratios. They are also richer in water and crystallized at elevated oxygen fugacity [16]. Third, magnesian andesites of Shiveluch and Zarechnyi volcanoes have lower $^{87}Sr/^{86}Sr$ values than comparable rocks of Ploskii volcano south of the Kamchatka River [19]. All these data allow us to suggest compositionally different sources for the magmas of volcanoes located north and south of the Kamchatka River [16, 20].

This paper continues the comparative study of trace-element and isotopic compositions of lavas of volcanoes of the northern group for better understanding the causes of the differences mentioned above. We use only our original data for the rocks of the NVNG (Table 1), while the rocks of the SVNG (Table 2) are characterized generally by the data compiled in literature, especially the isotopic data.

GEOLOGICAL AND STRUCTURAL SETTING OF THE NORTHERN GROUP VOLCANOES

The volcanoes of the northern group occupy the widest part of the Central Kamchatka Depression, a graben separating the Eastern and Sredinnyi Kamchatka

Table 1. Representative compositions of rocks of the northern volcanoes of the Northern group (oxides in wt %, trace elements in ppm)

Component	1	2	3	4	5	6	7
SiO_2	51.18	50.06	51.46	54.22	55.84	56.84	57.50
TiO_2	0.72	0.67	0.77	0.8	0.82	0.56	0.52
Al_2O_3	13.67	12.27	13.77	15.66	15.72	16.66	16.57
Fe_2O_3	3.2	3.12	2.69	2.55	3.76	3.07	2.59
FeO	5.55	5.52	5.69	5.17	3.48	3.16	3.59
MnO	0.18	0.13	0.15	0.16	0.14	0.08	0.09
MgO	12.08	15.02	11.33	8.40	7.05	5.93	5.54
CaO	8.36	8.16	6.32	9.02	7.17	7.30	7.24
Na_2O	2.55	2.31	2.38	3.05	3.99	3.87	4.17
K_2O	1.67	1.68	1.16	1.28	1.33	1.43	1.48
P_2O_5	0.37	0.56	0.12	0.27	0.33	0.23	0.23
LOI	0.80	0.64	4.08	0.07	0.56	0.68	0.18
Total	100.33	100.14	99.92	100.65	100.19	99.81	99.70
Mg#	0.719	0.763	0.713	0.667	0.647	0.641	0.625
Cr	790	884	722	483	438	208	307
Ni	234	230	–	114	84	50	72
Co	47	47	46	34	31	31	26
Sc	39	33	24	29	26	24	19
V	112	248	–	29	26	–	–
Rb	32	41	–	–	22	17	24
Cs	–	1.0	1.3	0.6	0.7	1.7	0.7
Ba	452	509	238	330	323	445	481
Sr	406	462	310	526	481	316	497
Ta	0.13	0.08	0.15	0.11	0.15	0.14	0.16
Nb	2.2	2.3	–	1.0	–	3	–
Hf	–	2.57	2.27	–	2.61	3.40	2.82
Zr	73	86	–	–	–	97	–
Ti	4316	4017	4616	4796	4916	3357	3117
Y	19	20	–	16	–	17	–
Th	–	0.9	1.6	0.9	0.9	1.7	1.2
U	–	0.6	0.5	0.5	0.6	0.4	0.7
La	11.0	9.0	8.2	7.5	8.0	9.0	9.1
Ce	21.2	22.3	19.5	18.9	20.5	20.8	22.3
Nd	12	15	–	11	15	12	12
Sm	3.60	4.20	2.65	2.99	3.42	3.07	2.98
Eu	1.10	1.23	0.76	0.86	0.99	1.04	0.84
Gd	–	–	–	–	–	–	–
Tb	0.87	0.60	0.40	0.41	0.56	0.51	0.42
Yb	2.1	1.7	1.3	1.6	2.0	1.4	1.4
Lu	0.28	0.25	0.19	0.23	0.29	0.26	0.21
$^{87}Sr/^{86}Sr$	0.703703	0.703805	0.703780	0.70347*	0.70353*	0.70338*	0.70341*
±2δ	14	18	15	7	3	3	7
$^{143}Nd/^{144}Nd$	0.513059	0.513039	0.512954	0.513089*	0.513098*	–	0.513112*
±2δ	10	8	8	8	10	–	6
εNd (±2δ)	8.21(20)	7.82(16)	6.16(16)	8.80(16)	8.97(20)	–	9.25(12)
Sr/Y	21.4	23.1	–	32.9	–	18.6	–
Ti/Sr	10.6	8.7	14.9	9.1	10.2	10.6	6.3
La/Yb	5.2	5.3	6.3	4.6	4.0	–	6.6

Table 1. (Contd.)

Component	8	9	10	11	12	13	14
SiO_2	51.76	41.99	43.00	52.54	51.64	52.30	57.49
TiO_2	0.98	–	–	0.86	0.90	0.87	0.69
Al_2O_3	16.6	1.65	0.56	12.37	12.36	12.53	14.40
Fe_2O_3	4.43	4.32	1.55	3.08	4.32	3.45	2.55
FeO	4.28	6.28	5.08	5.7	4.9	5.44	5.04
MnO	0.09	0.15	0.13	0.16	0.16	0.16	0.15
MgO	6.74	45.30	48.26	11.48	11.20	11.88	6.88
CaO	8.4	0.43	0.10	8.50	8.74	8.62	6.92
Na_2O	3.43	0.10	0.16	2.84	2.76	2.69	3.35
K_2O	1.16	0.22	0.06	1.42	1.42	1.35	1.70
P_2O_5	0.21	–	–	0.24	0.23	0.23	0.25
LOI	1.75	0.20	0.38	0.40	0.57	0.43	0.45
Total	99.83	100.64	99.28	99.59	99.20	99.95	99.87
Mg#	0.592	0.888	0.930	0.707	0.694	0.712	0.626
Cr	–	–	2600	906	1068	1029	518
Ni	–	–	2100	186	213	209	85
Co	–	–	140	46	40	47	32
Sc	–	–	3	30	30	29	26
V	–	–	40	–	–	–	–
Rb	–	–	1	14	–	–	19
Cs	–	–	n.d.	0.53	0.56	0.42	0.58
Ba	–	–	n.d.	756	816	726	462
Sr	–	–	21	710	707	696	527
Ta	–	–	0	0.09	0.08	0.14	0.11
Nb	–	–	3	3	–	–	2
Hf	–	–	–	2.03	2.11	2.00	2.29
Zr	–	–	17	79	–	–	83
Ti	5875	–	n.d.	5156	5396	5216	4137
Y	–	–	11	18	–	–	18
Th	–	–	n.d.	0.86	0.84	0.91	0.83
U	–	–	n.d.	0.59	0.52	0.61	0.62
La	–	–	0.5	9.5	9.8	9.1	8.1
Ce	–	–	35	25.7	24.3	24.4	20.4
Nd	–	–	–	16	16	15	14
Sm	–	–	0.03	3.97	4.10	3.86	3.34
Eu	–	–	–	1.09	1.14	1.09	0.83
Gd	–	–	–	–	–	–	–
Tb	–	–	–	0.52	0.52	0.45	0.45
Yb	–	–	–	1.5	1.5	1.5	1.3
Lu	–	–	–	0.22	0.22	0.23	0.19
$^{87}Sr/^{86}Sr$	0.703406	0.703720	0.704847	0.70349*	0.70333*	0.70339*	0.70347*
±2δ	14	20	27	6	7	5	7
$^{143}Nd/^{144}Nd$	0.513125	–	–	0.513083*	–	–	0.513069*
±2δ	10	–	–	10	–	–	9
εNd (±2δ)	9.50(20)	–	–	8.68(20)	–	–	8.41(18)
Sr/Y	–	–	1.9	39.4	–	–	29.3
Ti/Sr	–	–	–	7.3	7.6	7.5	7.9
La/Yb	–	–	–	6.2	6.5	6.2	6.1

Table 1. (Contd.)

Component	15	16	17	18	19	20	21
SiO_2	59.00	59.81	50.78	49.52	53.14	50.76	52.60
TiO_2	0.86	0.61	0.86	0.89	0.73	0.67	0.83
Al_2O_3	15.20	16.04	13.89	13.96	14.05	10.61	13.78
Fe_2O_3	3.80	6.07	4.92	4.00	4.74	1.97	3.30
FeO	1.89	–	4.18	5.20	2.42	6.39	6.54
MnO	0.11	0.12	0.17	0.18	0.12	0.23	0.14
MgO	5.07	4.58	11.03	12.05	8.38	18.68	9.52
CaO	6.74	6.24	8.86	9.26	7.75	6.50	8.90
Na_2O	4.05	4.55	2.87	2.85	3.55	2.13	2.44
K_2O	1.65	1.52	1.09	1.04	2.71	0.92	1.30
P_2O_5	–	0.16	0.19	0.20	0.41	0.24	0.22
LOI	1.24	0.58	0.66	0.40	1.21	1.00	0.16
Total	99.61	100.28	99.50	99.55	99.21	100.10	99.73
Mg#	0.630	0.599	0.696	0.709	0.691	0.803	0.641
Cr	198	442	636	826	393	1878	647
Ni	46	44	190	235	191	–	109
Co	20	20	44	48	35	60	46
Sc	–	16	37	36	24	24	38
V	175	150	250	225	208	–	–
Rb	22	21	10	11	33	15	–
Cs	–	0.59	0.40	0.12	0.46	0.41	0.38
Ba	771	950	375	362	1320	353	381
Sr	610	663	472	488	1100	223	429
Ta	–	0.15	0.07	0.07	0.14	0.09	0.03
Nb	3	2	–	–	2	2	–
Hf	–	2.47	1.70	2.10	3.34	1.64	1.87
Zr	98	100	–	112	144	73	–
Ti	5156	5096	4496	5336	4376	4017	4976
Y	18	17	–	17	17	17	–
Th	–	1.03	0.65	0.41	4.35	0.46	0.60
U	–	0.71	0.40	0.37	2.12	0.50	0.42
La	–	8.1	5.2	6.2	23.9	5.0	5.8
Ce	–	20.3	11.6	14.8	52.6	12.7	16.2
Nd	–	9	9	10	25	–	12
Sm	–	2.41	2.44	2.74	6.79	2.34	3.36
Eu	–	0.76	0.79	0.90	2.03	0.73	0.99
Gd	–	–	2.6	2.8	–	–	–
Tb	–	0.34	0.51	0.52	0.83	0.37	0.63
Yb	–	1.3	1.6	1.6	1.5	1.1	2.0
Lu	–	0.19	0.20	0.21	0.21	0.18	0.28
$^{87}Sr/^{86}Sr$	0.70354*	0.70345*	0.703552	0.703543	0.703652	0.703590	0.703680
±2δ	5	5	17	15	14	14	18
$^{143}Nd/^{144}Nd$	0.513098*	–	0.513099	0.513079	0.513113	0.513091	0.513084
±2δ	7	–	12	13	10	8	14
εNd (±2δ)	–	–	8.99(18)	8.60(25)	9.25(10)	8.84(16)	8.70(27)
Sr/Y	33.9	39.0	–	28.7	64.7	13.1	–
Ti/Sr	8.5	7.7	9.5	10.9	4.0	18.0	11.6
La/Yb	–	6.5	3.3	3.9	16.1	4.5	2.9

Note: (1)–(10) Shiveluch volcano: (1) magnesian high-K *Ol–Amph–Cpx* basalt, sample 5734; (2) magnesian high-K *Ol–Amph–Cpx–Phl* basalt, sample 1188/1; (3) moderately K *Ol–Cpx Amph*-bearing basalt, sample 90099b/7; (4) magnesian moderately K *Ol–Cpx* basaltic andesite, sample 5764C; (5) magnesian moderately K *Ol–Cpx–Amph* basaltic andesite, sample 5749/1C; (6) magnesian moderately K *Amph–Pl* andesite, sample 5738; (7) same, sample 5740; (8) aluminous moderately K *Ol–Px–Pl* basalt, sample 5746; (9) harzburgite, xenolith in andesite pumice, sample 5702/49; (10) dunite, xenolith in andesite pumice, sample 5702. (11)–(16) Zarechnyi volcano: (11) magnesian moderately K *Ol–Cpx* basalt, sample 1002/1C; (12) same, sample 1002/2C; (13) same, sample 1002/4C; (14) magnesian moderately K *Ol–Cpx* andesite, sample 1004C; (15) magnesian moderately K *Amph–Pl* andesite, sample 7700; (16) same, sample 7701. (17)–(19) Kharchinskii volcano: (17) magnesian moderately K *Ol–Cpx* basalt, sample 5601GG; (18) same, sample 5606GG; (19) *Ol–Cpx–Amph–Phl* absarokite, sample 5612/AKop. (20, 21) Kharchinskii regional zone of cinder cones: (20) magnesian moderately K *Ol* basalt, sample 1023; (21) magnesian moderately K *Ol–Cpx* basalt, sample 1006C.

Here and in Table 2, analyses of REE, Ta, Th, U, Hf, Cs, and a part of Ba, Sr, Cr, Ni, Co, and Sc determinations are performed by neutron activation in the University of Cornwall, in the New Mexico Institute of Mining and Technology, USA, and in the Joint Institute of Geology, Geophysics, and Mineralogy (JIGGM), Siberian Division, Russian Academy of Sciences (RAS). Another part of Ba, Sr, Cr, Ni, Co, and Sc determinations, as well as Zr, Y, V, and Nb analyses were obtained by XRF technique in the JIGGM RAS and in the University of Copenhagen. Major elements were analyzed in the Institute of Volcanology, Far East Division, Russian Academy of Sciences. Isotope analyses were performed on Sektor-54 and MI-1320 (marked with *) mass-spectrometers in the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences. Dashes denote not determined elements.

Table 2. Representative compositions of basalts some of the southern volcanoes of the Northern group (oxides in wt %, trace elements in ppm)

Component	1	2	3	4	5	6	7	8
SiO_2	49.76	50.22	51.45	50.22	52.96	51.96	52.16	50.30
TiO_2	0.89	1.55	0.95	0.92	0.95	1.12	1.15	0.76
Al_2O_3	14.91	17.00	13.65	14.13	14.61	18.28	17.01	13.70
Fe_2O_3	1.76		2.46				2.90	2.80
FeO	7.52	10.49	6.76	9.33	8.92	9.60	6.78	6.29
MnO	0.19	0.20	0.17	0.18	0.20	0.15	0.20	0.14
MgO	9.74	5.22	9.70	10.12	9.27	4.44	5.92	11.78
CaO	11.62	9.24	11.68	10.93	9.26	9.04	8.95	10.74
Na_2O	2.03	3.49	2.40	2.38	2.93	4.00	3.16	2.30
K_2O	0.81	2.16	0.88	0.88	0.75	1.20	1.20	0.87
P_2O_5	0.23	0.47	0.21	0.28	0.15	0.24	0.25	0.21
LOI	0.26	–	0.30	–	–	–	0.18	0.12
Total	99.72	100.04	100.61	99.37	100.00	100.03	99.86	100.01
Mg#	0.656	0.470	0.658	0.659	0.649	0.452	0.529	0.704
Cr	626	123	376	651	520	35	56	846
Ni	113	64	92	137	113	26	30	202
Co	32	35	39	43	43	35	32	48
Sc	46	26	40	43	37	32	33	38
V	–	–	295	–	–	–	250	260
Rb	18	50	17	–	–	15	15	9
Cs	0.54	4.97	–	0.54	0.45	0.54	0.50	–
Ba	221	509	248	246	258	476	442	233
Sr	319	305	284	318	320	412	345	239
Ta	0.14	0.43	–	0.13	0.13	0.16	0.13	–
Nb	–	2.0	2.8	–	–	2.6	–	1.9
Hf	2.13	5.23	–	2.07	2.04	2.86	2.60	–
Zr	80	200	77	–	–	98	–	63
Ti	5336	9292	5695	5515	5695	6714	6894	4556
Y	20	33	20	–	–	25	–	19
Th	0.56	2.08	0.48	0.56	0.48	0.79	0.51	–
U	0.37	1.28	0.43	0.50	0.40	0.56	0.44	–
La	7.00	18.48	6.10	6.91	5.08	7.90	6.50	5.00
Ce	19.20	45.30	13.00	18.20	13.80	21.00	16.20	13.00
Nd	12.90	28.60	9.70	12.20	13.60	13.70	11.20	8.00
Sm	3.68	7.34	2.83	3.47	2.89	4.10	3.38	–
Eu	1.08	1.85	0.92	0.98	0.91	1.29	1.06	–
Gd	–	–	3.2	–	–	–	4.30	–
Tb	0.66	1.11	0.55	0.63	0.56	0.76	0.71	–
Yb	2.13	3.63	1.92	2.03	1.99	2.91	2.76	–
Lu	0.30	0.53	0.27	0.29	0.30	0.43	0.40	–
$^{87}Sr/^{86}Sr$	–	–	0.703352	–	0.703559	–	–	–
±2δ	–	–	15	–	20	–	–	–
$^{143}Nd/^{144}Nd$	–	–	0.513074	–	0.513099	–	–	–
±2δ	–	–	9	–	8	–	–	–
εNd (±2δ)	–	–	8.52(18)	–	8.99(16)	–	–	–
Sr/Y	16.0	9.2	14.2	–	–	16.5	–	12.6
Ti/Sr	16.7	30.5	20.1	17.3	17.8	16.3	20.0	19.1
La/Yb	3.3	5.1	3.2	3.4	2.6	2.7	2.4	–

Note: (1)–(4) Tolbachik dale: (1)–(3) Large Tolbachik fissure eruption 1975–1976: (1) magnesian moderately K *Ol–Cpx* basalt, Northern eruption, sample 6011; (2) aluminous subalkaline *Ol–Cpx–Pl* basalt, Southern eruption, sample 6100C; (3) magnesian moderately K *Ol–Cpx* basalt, Northern eruption, sample 6024Ko; (4) magnesian moderately K *Ol–Cpx* basalt, Peschanye Gorki, sample F857C. (5)–(8) Klyuchevskoi volcano: (5) magnesian moderately K *Ol–Cpx–Pl* basalt, side eruption, sample 85025C; (6) aluminous moderately K *Ol–Cpx–Pl* basalt, historical side eruption, sample 7400C; (7) aluminous moderately K *Ol–Cpx–Pl* basalt, historical side eruption, sample 808GG; (8) magnesian moderately K *Ol–Cpx* basalt, sample VPK5Ko. In samples 2, 4–6 total iron is given as FeO.

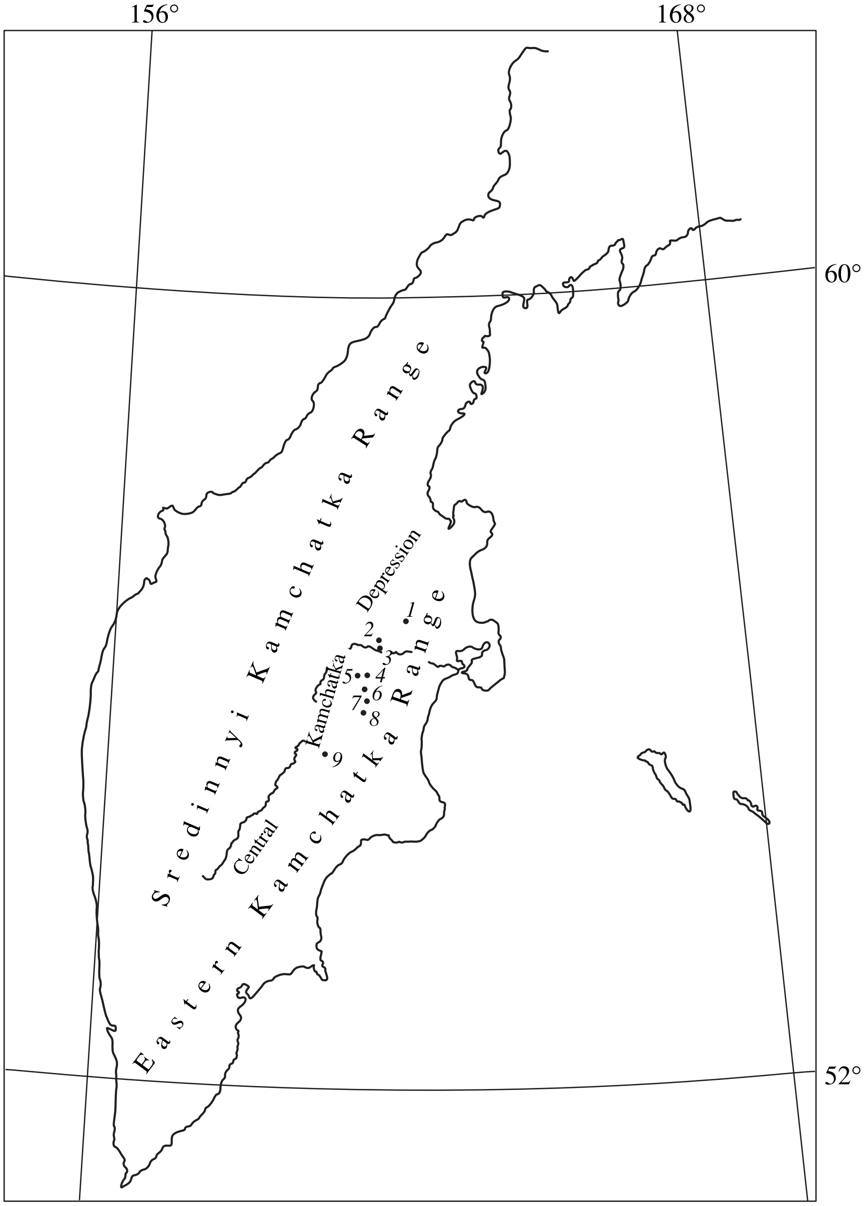

Fig. 1. Location of volcanoes of the Northern group (simplified after [21]).
Volcanoes: (*1*) Shiveluch, (*2*) Kharchinskii, (*3*) Zarechnyi, (*4*) Klyuchevskoi, (*5*) Ushkovskii (Ploskii), (*6*) Bezymyannyi, (*7*) Tolbachik, (*8*) Bol'shaya Udina, (*9*) Nikolka.

ranges (Fig. 1). This extension structure is traced parallel to oceanic trench from the Litke Strait in the north to the Golygin depression in the south of Kamchatka and further south as the Kurile back-arc basin. The formation of the Central Kamchatka Depression began in the Early Pliocene and some researchers consider it as a continental back-arc rift [22]. The northern part of this group of volcanoes is located in the junction zone between the Kurile–Kamchatka and Aleutian island arcs, where a zone of sublatitudinal lateral dislocations extends the Aleutian trench to the west up to the town of Klyuchi [23]. According to some researchers [8, 23, 24], this dislocation zone, the Aleutian trench, and other large-scale structures of the western termination of the Aleutian arc (Bering, Shteller, and Alpha faults and their continuation as sublatitudinal tectonic zones in Kamchatka) separate old (about 100 Ma) oceanic lithosphere in the south and young (about 15 Ma), formed during the opening of the Commander basin, oceanic lithosphere in the north. According to the seismologic data [25], the upper edge of the subduction zone is located at a depth of about 160 km beneath the Klyuchevskoi volcano and no deeper than 100 km beneath the Shiveluch volcano.

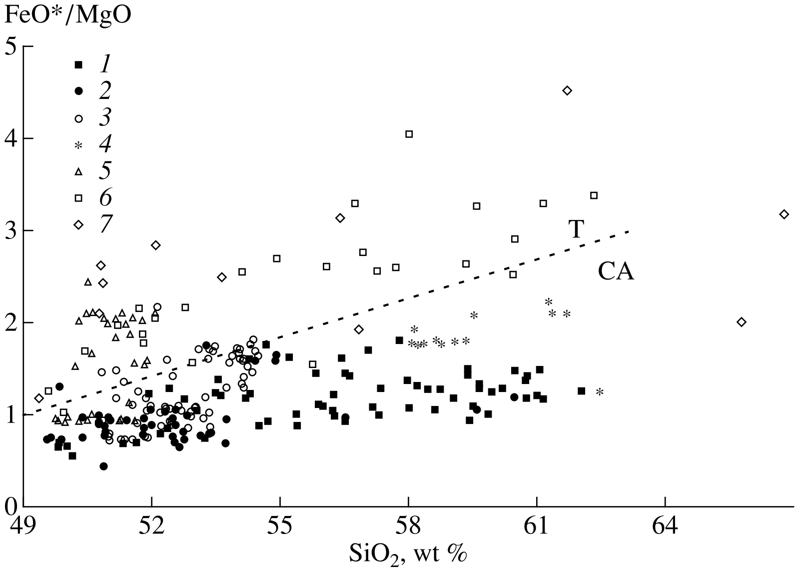

Fig. 2. Variation of FeO*/MgO with SiO_2 in volcanic rocks. Volcanoes: (*1*) Shiveluch, (*2*) Zarechnyi and Kharchinskii, (*3*) Klyuchevskoi, (*4*) Bezymyannyi, (*5*) Large Tolbachik fissure eruption 1975–1976 and Tolbachik dale, (*6*) Ploskie Sopki, (*7*) Nikolka. FeO* is total iron as FeO. Dashed line separates the rocks of the tholeiite (T) and calc-alkaline (CA) series [28].

The Northern group includes five active volcanoes (Klyuchevskoi, Shiveluch, Bezymyannyi, Ploskii Tolbachik, and Ushkovskii), ten dormant volcanoes, and three regional zones of cinder cones (Kharchinskii, Ploskie Sopki, and Tolbachik, with modern activity in the latter). The SVNG are built up on the Pliocene–Early Pleistocene lava plateau, while the NVNG are located on the Neogene sedimentary basement. The total productivity of volcanoes of the Northern group in the Late Pleistocene–Holocene amounts to about 3500 km^3 (for the last 50 Ka), which is much higher than the productivity of the other Kamchatka volcanoes [26]. Two of the most productive active volcanoes, basaltic Klyuchevskoi and andesitic Shiveluch, are also comprised to the Northern group. In general, the volcanoes of the Northern group are located in the region of continuous downwelling. Beneath the Klyuchevskoi volcano, this tendency is also pronounced even at the Moho discontinuity [26]. The recent data indicate that the downwelling is of compensation nature and is related to extensive volcanic activity.

MAJOR-ELEMENT CHEMISTRY AND MINERAL COMPOSITION

The volcanic rocks vary from basalts to andesites (Tables 1, 2). Dacites are rare and are found only in some volcanoes (Bol'shaya Udina). Some volcanoes are generally composed of basalts and basaltic andesite (Klyuchevskoi, Tolbachik, and Tolbachik regional zone of cinder cones), while some other dominate by basaltic andesites and andesites (Shiveluch, Bezymyannyi, Ploskie Sopki regional zone of cinder cones). Most rocks belong to the moderately potassic series; however, high-potassium varieties are also encountered (Nikolka and Ploskie Sopki volcanoes, and Tolbachik regional zone of cinder cones). Some rocks of the Nikolka and Kharchinskii volcanoes can be classified with absarokite–shoshonite–latite series. High-alumina basalts dominate among the basic rocks. However, high-magnesium basalts also occur in some localities of the Tolbachik regional zone of cinder cones (among the products of the past 2000 years [27]), among the lavas of the side eruptions of Klyuchevskoi volcano, one lava flow of the Ploskii volcano, and Holocene tephra of the Shiveluch volcano [20]. The high-magnesium basalts dominate the products of Zarechnyi and Kharchinskii volcanoes and the Kharchinskii regional zone of cinder cones.

The lavas of the NVNG belong to the calc-alkaline series (Fig. 2). In comparison, in the SVNG, the volcanics with tholeiitic affinity in terms of FeO*/MgO–SiO_2 variation (high-K basalts of the Tolbachik dale, high-K lavas of Ploskie Sopki, Nikolka and other volcanoes) are abundant among the calc-alkaline rocks (basalts and basaltic andesites of Klyuchevskoi volcano, magnesian basalts of the Tolbachik dale, many basaltic andesites and andesites of Bezymyannyi volcano). The calc-alkaline affinity is more typical of the lavas of the NVNG than of the rocks of the SVNG. It is particularly characteristic of the basaltic andesites and andesites. By their high magnesium number, andesites of Shiveluch and Zarechnyi volcanoes can be considered as magnesian andesites. Additionally, the high-Al high-K basalts of the Tolbachik regional zone of cinder cones and Nikolka and Ploskie Sopki volcanoes have higher TiO_2 content than the aluminous moderately potassic and magnesian basalts of those and other volcanoes of the Northern group.

Phenocrysts in basalts of the SVNG are represented by *Ol*, *Cpx*, *Sp*, and *Pl*. Additionally to these minerals, the intermediate rocks also contain *Opx* and *Amph* phenocrysts; magnetite crystallizes instead of spinel. *Amph* is rare and is found in andesites and dacites of Bezymyannyi and Udina volcanoes. It is more abundant in lavas of the NVNG and is one of the main minerals of the phenocrysts. Amphibole occurs there not only in magnesian andesites, together with *Pl*, Ti-magnetite, minor *Opx*, *Cpx*, and even *Ol*, but also in magnesian basaltic andesites with the same mineral assemblages and in magnesian basalts (in an assemblage with *Ol*, *Sp*, *Cpx*, and *Amph* in the moderately potassic varieties, and additional *Phl*, in high-K basalts and absarokites). Variations of amphibole proportion in the rocks are related to water contents in magmas and their oxidation degree. According to ilmenite–magnetite oxygen barometry, the tholeiitic rocks devoid of phenocrysts of water-bearing mafic minerals crystallized at oxygen fugacity higher than nickel–bunsenite buffer conditions by 0.5–1.5 logarithmic units, while the oxygen fugacity during the crystallization of the amphibole-bearing calc-alkaline rocks exceeded the nickel–bunsenite buffer by 2–2.5 logarithmic units [29].

The minerals in the rocks of the NVNG and SVNG significantly differ in some components due to compositional differences of their host rocks. For example, olivine phenocrysts in magnesian basalts are similar in forsterite proportion, but differ in CaO, which is lower in olivines of the NVNG rocks due to the lower CaO in the bulk rock compositions [20]. Clinopyroxene in the NVNG basalts has lower TiO_2 content than that in the SVNG basalts richer in TiO_2. A similar correlation between the mineral and rock compositions is also typical of amphibole: magnesian andesites of Shiveluch and Zarechnyi volcanoes include more magnesian amphibole than andesites of the SVNG [16].

TRACE ELEMENTS IN THE ROCKS OF THE NORTHERN GROUP OF VOLCANOES

As was mentioned above, magnesian basalts of the NVNG differ from those of the SVNG in some geochemical features [16]. The NVNG volcanics are enriched in Sr, depleted in Ca, Sc, Y, and Yb, and have elevated Sr/Y, K/Ti, La/Yb, Zr/Y, Th/Yb, Ni/Sc, Cr/Sc and lower Ca/Sr and U/Th ratios (Tables 1, 2). Consequently, the data points of the NVNG and SVNG lavas occupy separate fields in the various geochemical diagrams (Figs. 3–5).

It is probable that the differences between the NVNG and SVNG lavas are caused by various compositions of their magma sources including the rocks of the mantle wedge and input of some components from the subducted slab (fluids or partial melts from metamorphosed oceanic basalts of the second layer and/or sediments of the first layer). The existence of such melts or fluids that alter metasomatically the rocks of the mantle wedge is supported by the trace-element composition of lavas and the occurrence of high-Mg amphibole and phlogopite in ultramafic xenoliths in the rocks of Shiveluch volcano and some more ferroan amphibole in similar xenoliths in the rocks of Klyuchevskoi volcano [30].

According to recent geochemical data on ^{10}Be [31, 32] and Pb [5, 9] isotope composition in the rocks of the Northern group volcanoes, the contribution of the sedimentary component of the subducted slab to the magma composition is insignificant (<2%) in this region.

The transition in trace-element features from SVNG to NVNG volcanics corresponds to the trend of enrichment of a mantle magma source by partial melts from the subducted slab. This idea was advanced recently by Kepezhinskas and coauthors [9] for the origin of magmas of Shiveluch and Kharchinskii volcanoes. Actually, the magmas from the subducted slab are generated under the condition of garnet stability (by melting of eclogites and amphibole eclogites) and, according to calculations based on experimental data [33–38], they are enriched in Sr and depleted in Yb, Y, Sc, and Ti, and have high La/Yb, Sr/Y, K/Ti, Ni/Sc, Cr/Sc and low Ca/Sr and Ti/Sr ratios due to the existence of garnet and titanite and absence of plagioclase in restite.

Such melts were referred by Defant and Drummond [34] as "adakites" and have the composition of dacites–trondhjemites with high La/Yb (up to 30–40) and Sr/Y (up to 100–120), and low Ti/Sr (3–4) ratios [35], whereas these values are 5–15, 10–50, and 7–15, respectively, in typical island arc lavas. Partial melt from the subducted slab becomes more mafic (up to andesite) due to its interaction with the mantle wedge rocks. Its Mg number and Cr and Ni concentrations increase, and Ni/Sc and Cr/Sc ratios decrease. The same melt could metasomatize the mantle rocks by such a way that the magmas derived from these rocks could have transitional geochemical features between mantle melts (high Mg number and Cr and Ni contents) and adakites (elevated Sr content and La/Yb and Sr/Y ratios). These partial melts with transitional geochemical characteristics could have composition of magnesian andesites [39]. The magnesian andesites of the first type (i.e., products of crystallization of partial melts from the subducted slab, which were contaminated by mantle wedge rocks) were termed as A-type andesites by G. Yogodzinski [38] (by an Adak Island geochemical prototype, Central Aleutians), while the magnesian andesites of the second type (derivatives of the metasomatized mantle wedge rocks), as P-type andesites (their geochemical prototype is andesite of Piip underwater volcano, Western Aleutians). According to calculations, about 4% of adakite melt should be added to the mantle wedge material to obtain a P-type magnesian andesite magma [37].

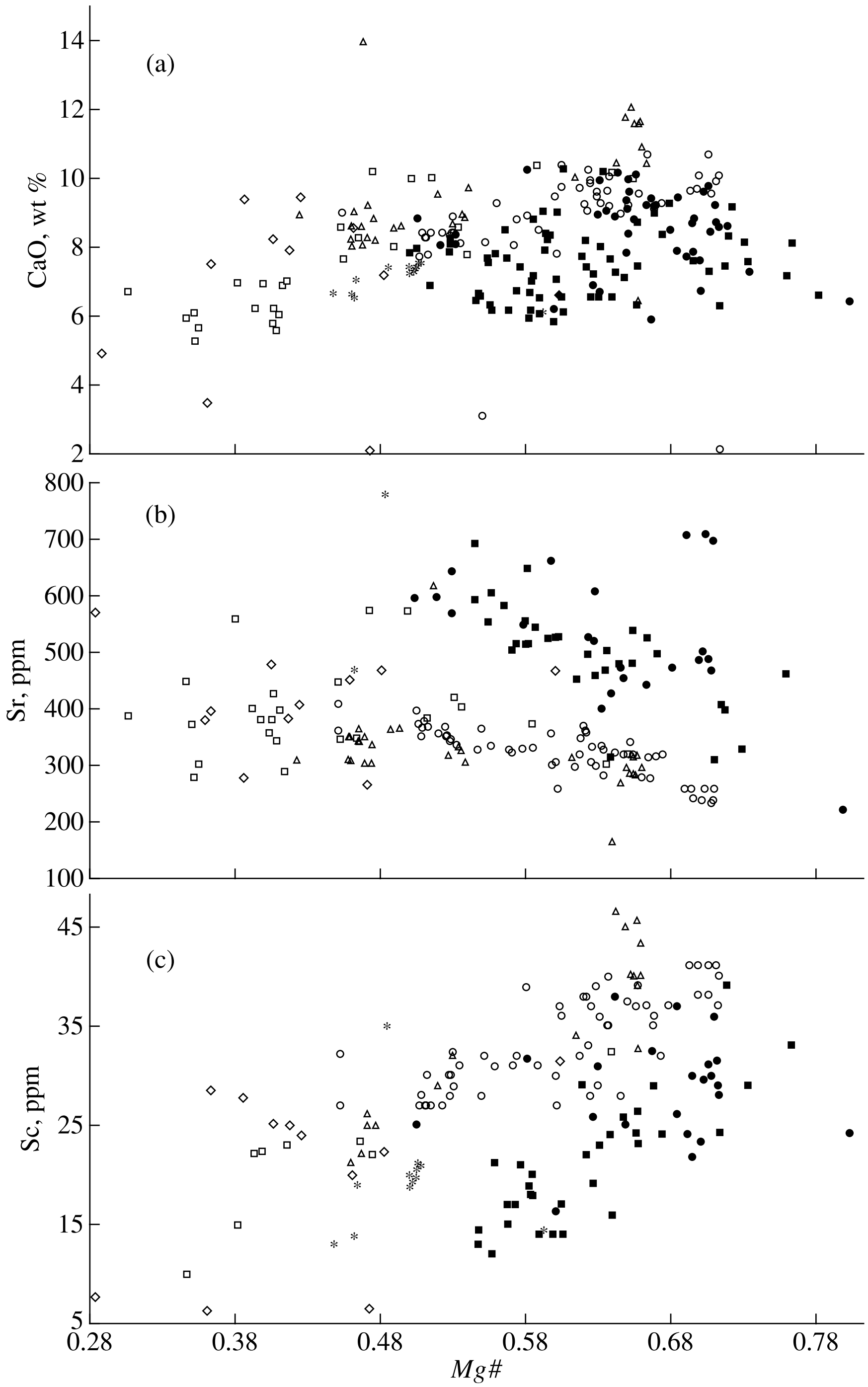

Fig. 3. Variations of CaO (a), Sr (b), and Sc (c) with *Mg*# = MgO/(MgO + FeO_{tot}), at. %, in volcanic rocks. Symbols are explained in Fig. 2.

Note that, additionally to andesites, the NVNG also include basalts with similar geochemical features (Table 1, Figs. 3–5). Based on geochemical data, we have demonstrated recently [20] that magnesian andesites in the NVNG cannot be derived by fractionation of a magnesian basaltic magma. They were most likely formed either by an AFC mechanism [40], when a magnesian basaltic magma interacts at relatively shallow depths with the mantle wedge rocks, or by partial melting of metasomatized material of the mantle wedge, i.e., by mechanism similar to that of basaltic magma generation, but at a smaller melting degree.

According to the calculation of model of two-component mixing, the magmas of basalts and andesites of the NVNG were formed by partial melting of mantle

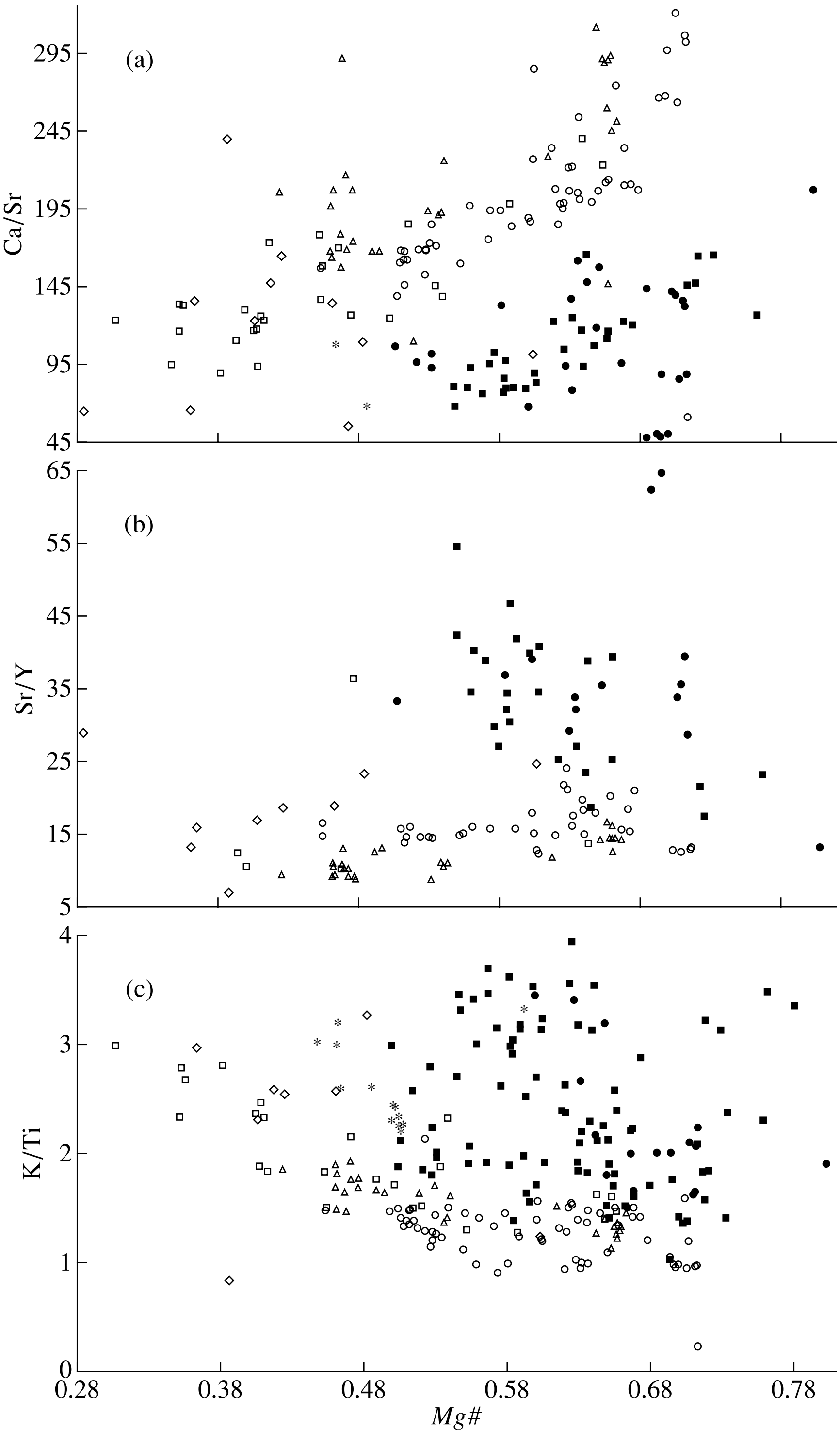

Fig. 4. Variations of Ca/Sr (a), Sr/Y (b), and K/Ti (c) with *Mg#* in volcanic rocks. Symbols are explained in Fig. 2.

wedge material with addition of 5–15% adakite melt (Fig. 6).

The geochemical features of the rocks of the SVNG indicate the involvement of a fluid (rather than melt) from the subducted slab in the metasomatic transformation of the material of the mantle wedge, which subsequently underwent partial melting. Additionally to the above geochemical data, a reliable indicator of the fluid flux is U/Th ratio, because the coefficient of U partitioning in aqueous fluid is much higher than that of Th, and U, but not Th, is mobilized in fluid derived from the subducted slab [41, p. 564]. The available data (Fig. 7)

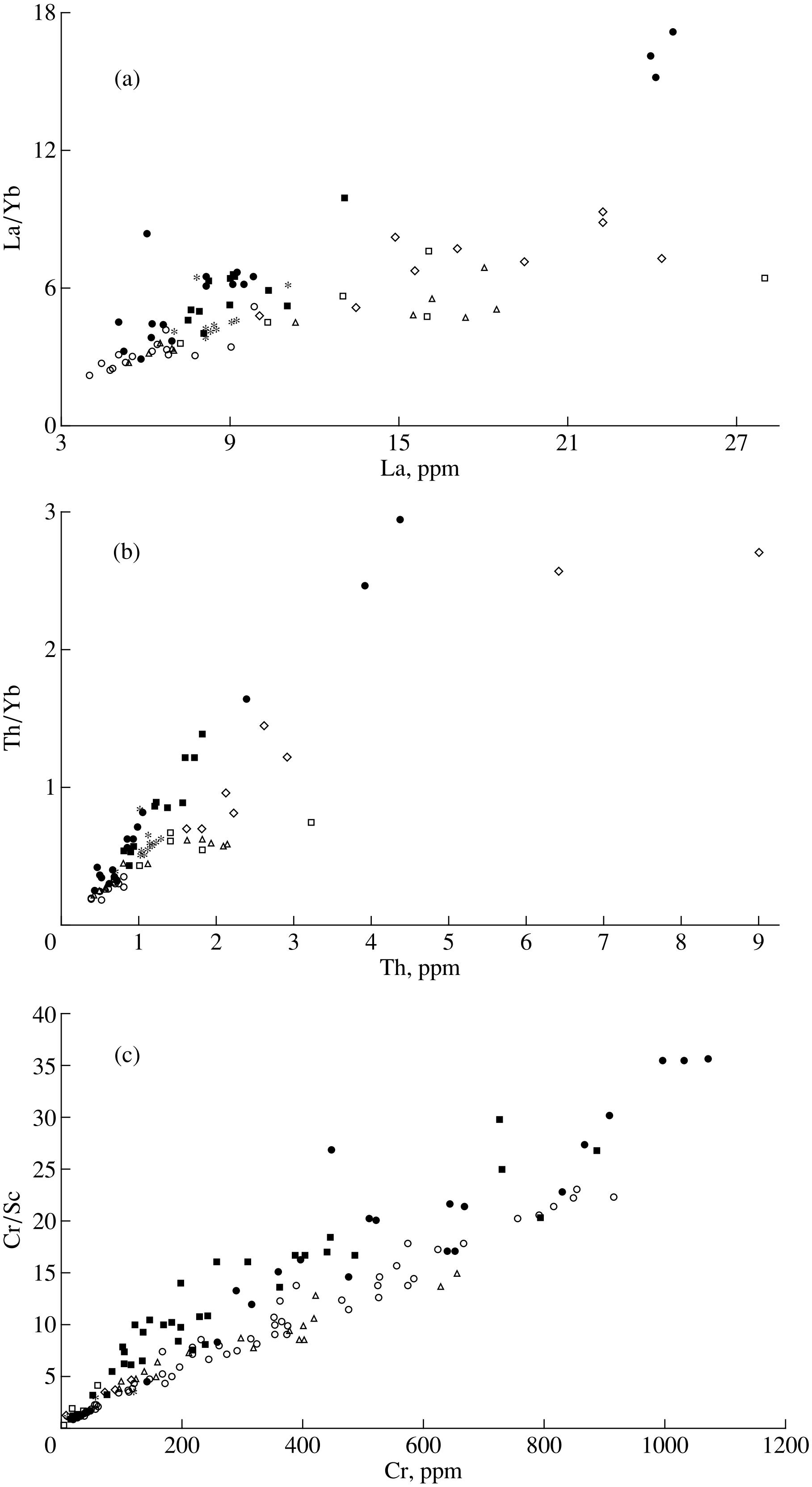

Fig. 5. Diagrams La/Yb–La (a), Th/Yb–Th (b), and Cr/Sc–Cr (c) in volcanic rocks. Symbols are explained in Fig. 2.

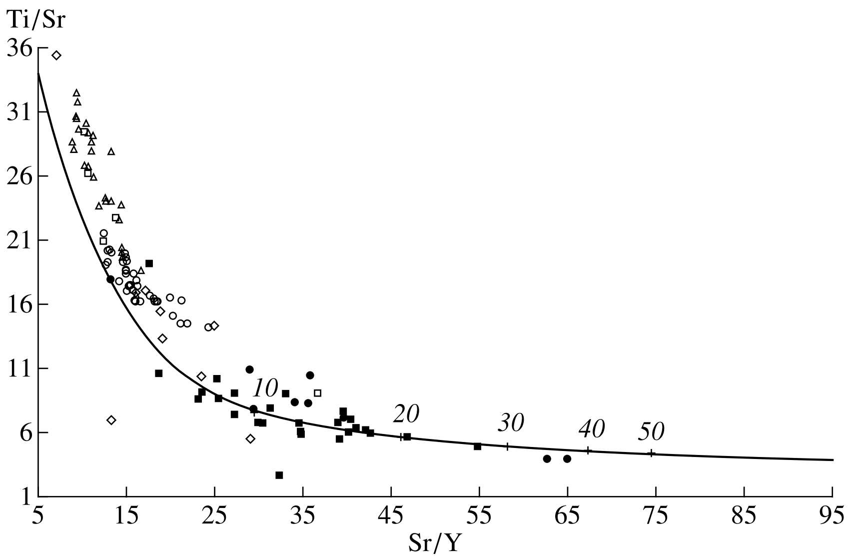

Fig. 6. Variations of Ti/Sr with Sr/Y ratios in volcanic rocks. The mantle–adakite mixing curve is shown. Figures near the curve denote proportion of adakite melt. Symbols are explained in Fig. 2.

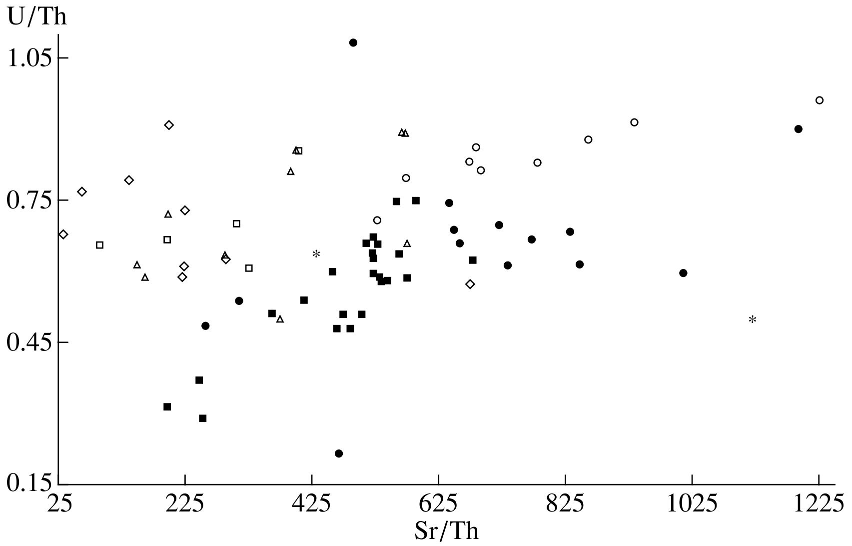

Fig. 7. Variations of U/Th with Sr/Th ratios in volcanic rocks. Symbols are explained in Fig. 2.

show that lavas of the SVNG often have higher U/Th ratios than those of the NVNG at similar Sr/Th ratios.

Sr AND Nd ISOTOPIC SYSTEMATICS OF VOLCANIC ROCKS

The Sr and Nd isotopic compositions in lavas of the NVNG and SVNG overlap and plot within the fields of typical island arc volcanics, closer to the rocks of ensimatic rather than those of ensialic island arcs (Tables 1, 2). However, the covariation between Sr and Nd isotopic ratios and their correlations with some major and trace elements differ in the rocks of the NVNG and SVNG. For example, $^{87}Sr/^{86}Sr$ ratios and ε_{Nd} values in lavas of the NVNG have a distinct negative correlation, whereas any correlation between these parameters is absent in lavas of the NVNG (Fig. 8). SiO_2 contents correlate with $^{87}Sr/^{86}Sr$ ratios for the basic rocks, while such a correlation is not observed for the more siliceous rocks (Fig. 9a). The correlation between these parameters is negative for basalts of the NVNG and positive for the SVNG. The $^{87}Sr/^{86}Sr$ ratios are higher in the NVNG rocks for basalts and in the SVNG rocks for basaltic andesites and andesites. In NVNG lavas ε_{Nd} values correlate with SiO_2 contents (positively) and with Sm/Nd ratios (negatively); while Sr contents correlate with $^{87}Sr/^{86}Sr$ ratios (positively). Such correlations are absent in the rocks of the SVNG (Fig. 9b). Finally, the

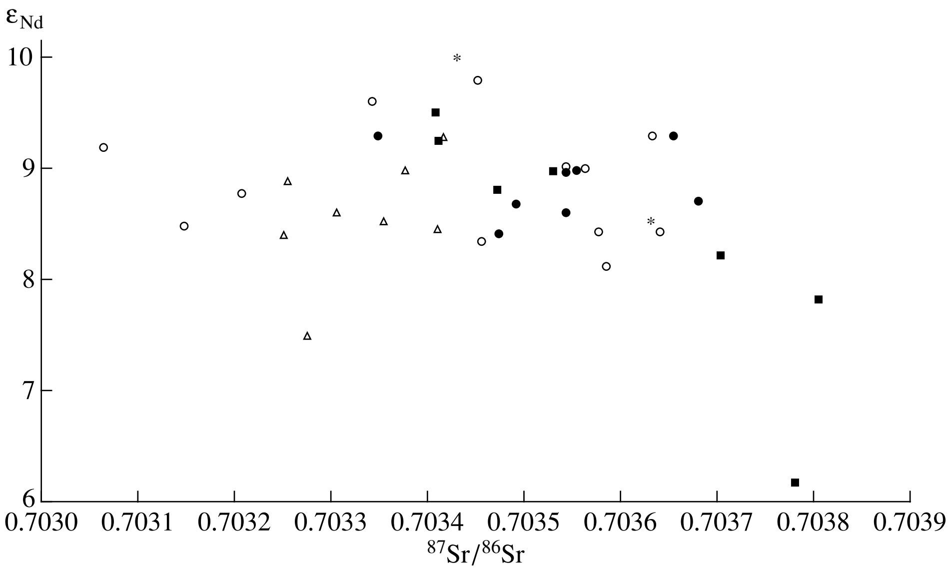

Fig. 8. Variations of ε_{Nd} with $^{87}Sr/^{86}Sr$ ratios in volcanic rocks. Symbols are explained in Fig. 2.

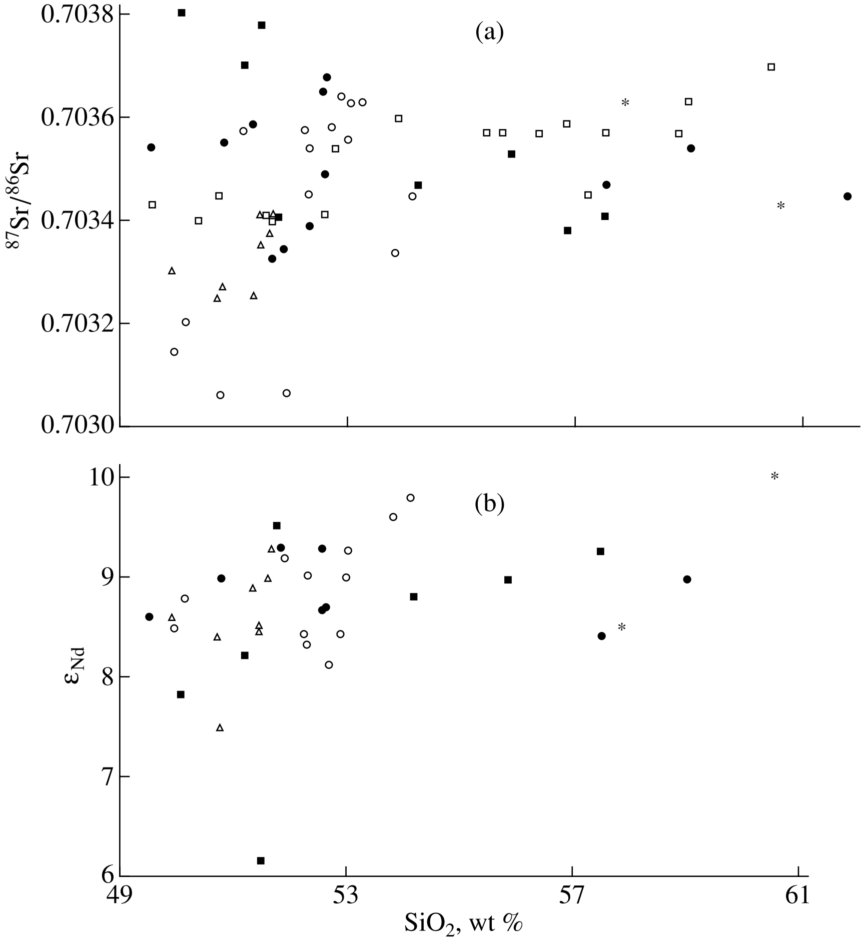

Fig. 9. Variations of $^{87}Sr/^{86}Sr$ ratios (a) and ε_{Nd} (b) with SiO_2 in volcanic rocks. Symbols are explained in Fig. 2.

NVNG and SVNG rocks show opposite tendencies in correlation of $^{87}Sr/^{86}Sr$ ratios with K/Ba, Sr/Y, and Sr/Zr values.

DISCUSSION

The available isotopic and chemical data suggest the existence of two-component sources of magmas. For the NVNG rocks, one of these components has high $^{87}Sr/^{86}Sr$, Sm/Nd, K/Ba ratios, and Mg number at low ε_{Nd}, SiO_2, Sr, Sr/Y, and Sr/Zr and can approximate the ultramafic mantle material. Unusual isotopic characteristics of this mantle material could be caused by preceding metasomatic processes and partially confirmed by data on ultramafic xenoliths in NVNG lavas (Table 1). The second source for these rocks has opposite characteristics, i.e., low $^{87}Sr/^{86}Sr$ ratios and high ε_{Nd} values at high SiO_2, Sr, Sr/Y, and Sr/Zr and low Sm/Nd, K/Ba, and Mg number and corresponds by these parameters to the adakite composition [35] or A-type magnesian andesite [38]. However, the calculation of model of two-component mixing shows that this source should have a $^{87}Sr/^{86}Sr$ ratio of about 0.7033, but not 0.7028, as it is in the A-type magnesian andesites from western Aleutians [38].

The sources of the SVNG lavas have distinct isotopic and trace-element characteristics. A high-magnesium and low-silica source (ultramafic mantle material) has low $^{87}Sr/^{86}Sr$ ratio and moderately high ε_{Nd}. A silica richer source (a fluid from the subducted slab) has high $^{87}Sr/^{86}Sr$ ratio at ε_{Nd} values similar to those in the ultramafic source. As compared to the adakite-like source of the NVNG rocks, the second source for the SVNG lavas has significantly lower Sr contents and Sr/Y and Sr/Zr ratios. The causes of different isotopic composition of mantle rocks beneath the NVNG and SVNG are not clear yet and require a special study. A comparative investigation of isotopic compositions of ultramafic xenoliths in lavas of these volcanoes could solve this problem.

SOME GEODYNAMIC CONSEQUENCES

If our suggestion on the different magma sources for the NVNG and SVNG lavas is correct, then we could make a conclusion on geodynamic conditions of subduction in this region.

It is popular opinion that the partial melting of the subducted slab is not typical of the young island arcs and active continental margins, while the metasomatic alteration of the mantle wedge rocks with fluids from the subducted slab is common. It is also suggested that the partial melting of the slab is related to specific subduction conditions, i.e., either the subduction of young (less than 5–15 Ma) oceanic lithosphere [34], slow gentle subduction [37, 38], or subduction of an oceanic ridge [42].

The CVNG are located on the continuation of the junction zone between the Aleutian and Kurile–Kamchatka island arc, and the oblique gentle subduction typical of the western Aleutians also operates in the studied region. The latter suggestion is very probable, because the sublatitudinal strike-slip tectonic dislocations typical of the western extension of the Aleutian trench [23] separate NVNG and SVNG. Note that the territory to the north from the Aleutian–Kamchatka junction zone has young basaltic crust, which was formed during the opening of the Commander deep-water basin [23, 24] and plunges beneath the northern Kamchatka [35]. According to the above-mentioned seismologic data [25], the subducted slab beneath the NVNG is located at a smaller depth and is gentler than in the SVNG region. This is probably related to the subduction of hotter and lighter lithospheric block at the northern termination of the Kurile–Kamchatka arc than at its southern segments [23]. According to Seliverstov [23], underwater structures at the western termination of the Aleutian trench are distinct in their elevated heat flow caused by a young tectonomagmatic activation of the lithosphere in this region. Note that this researcher also suggested that the field of activated lithosphere also comprises the Obruchev Rise, the western continuation of which is subducted beneath the SVNG region.

CONCLUSIONS

(1) Study of the mineralogical, geochemical, and isotopic features of rocks of the Northern group volcanoes of Kamchatka revealed their heterogeneity. Two associations were distinguished. The first association includes volcanoes located north of the Kamchatka River, e.g., Shiveluch, Zarechnyi, Kharchinskii volcanoes, and Kharchinskii regional zone of cinder cones (NVNG). The second association comprises the volcanoes located south of this river, e.g., Klyuchevskoi, Ploskie Sopki, Tolbachik, Nikolka and some other volcanoes, as well as Tolbachik and Ploskie Sopki regional zones of cinder cones (SVNG).

(2) The NVNG volcanic rocks differ from SVNG lavas in generally higher Mg number and Sr concentration at lower Ca, Sc, Y, and Yb contents, as well as in higher Sr/Y, K/Ti, La/Yb, Zr/Y, Th/Yb, Ni/Sc, Cr/Sc and lower Ca/Sr and U/Th ratios. Variations of Sr and Nd isotopic ratios in volcanics of these associations overlap. However, the covariation between Sr and Nd isotopic ratios and their correlations with some major and trace elements differ in the rocks of the distinguished associations.

(3) The metasomatic transformation of mantle wedge occurred under the influence of two different agents: partial melts generated within the subducted slab, for the northern volcanoes; and fluids derived from the subducted slab, for the southern ones.

(4) The regions of these two volcano associations probably differ in subduction conditions: oblique, gen-

tly dipping, slow subduction (like in the western Aleutians) beneath the northern volcanoes; and orthogonal subduction of ancient oceanic crust beneath the southern ones.

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