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The Space–Time Relationships between Volcanic Associations of Different Alkalinities: The Belogolovskii Massif in Kamchatka's Sredinnyi Range. Part 1. The Geology, Mineralogy, and Petrology of Volcanic Rocks

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Abstract—We proposed a geological and petrologic model for the generation of the Belogolovskii Late Pliocene to Early Pleistocene volcanic massif. We identified two petrochemical series of rocks with varying alkalinities, viz., normal and moderate. The evolution of volcanic products and the mineralogic composition of rocks of varying alkalinities provide evidence that the sources of parent magmas are spatially independent and reside at different depths. Crystallization differentiation is the leading process that is responsible for the generation of the initial melts that give rise to the range of rocks within a series. The evolution of the alkaline basaltic magma occurred stepwise, producing autonomous daughter melts with the following compositions: trachybasalt–trachyandesite–trachyte–trachyrhyolite and comendite. These melts were localized in intermediate magma chambers at different depths.

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Several petrochemical rock series that differ in alkalinity are identified among Late Cenozoic volcanic rocks in the Kuril–Kamchatka island arc system. Each series is characterized by special features of material composition and magma generation, occurs in a geological structural zone of its own, and reflects a different geodynamic setting for the generation of rock associations of a specific geochemical type, the island-arc type proper and the intraplate type [Volynets et al., 1986, 1987, 1990a; Volynets, 1993; Perepelov, 1989; Perepelov et al., 2007; Koloskov, 1999, 2006]. At the same time, there are geological features where volcanic rock associations of different petrogeochemical series occur together; the relationships among these are of interest for magma petrogenesis. In particular, the Sredinnyi Range contains several features of this kind, viz., the Uksichan caldera, and the Kekuknai and Belogolovskii volcanic massifs [Antipin et al., 1987; Flerov et al., 2009; Koloskov et al., 2011, 2013]. The present paper reports on the results of **petrologic** surveys of the Belogolovskii massif that we conducted in the network of the first Belogolovaya and Moroshka rivers in 2005 and 2007, as well as using data from [Volynets et al., 1990b] and materials from a geological survey.[1]

THE GEOLOGICAL STRUCTURE OF THE MASSIF

The **Belogolovskii paleovolcanic massif** is situated in the southwestern part of the Late Cenozoic volcanic belt in the Sredinnyi Range of Kamchatka on the western slope of the latter in the upper reaches of the first Belogolovaya and Moroshka rivers 20–25 km north of Ichinskii Volcano (Fig. 1). The massif is a morphologically poorly expressed, strongly eroded, volcano-tectonic feature and is complicated with numerous discontinuities of

[1] Khasanov, Sh.G., *Geological Structure and Mineral Deposits in the Basins of the Pravaya Rassoshina, Kopyl'e, Bystraya (Khairyuzovka), Bystraya (Kozyrevka), and Sukhariki Rivers*, A report of the Central Kamchatka Team on additional geological studies in previously surveyed areas to scale 1 : 200 000 and the preparation for printing of a set of the State Geological Map of the Russian Federation to scale 1 : 200 000 (second edition) conducted in 2003–2007. Sheets N-57-II, III, Petropavlovsk-Kamchatskii: FGU KamTFGI, 2007. Archives of the Kamchatgeologiya OAO.

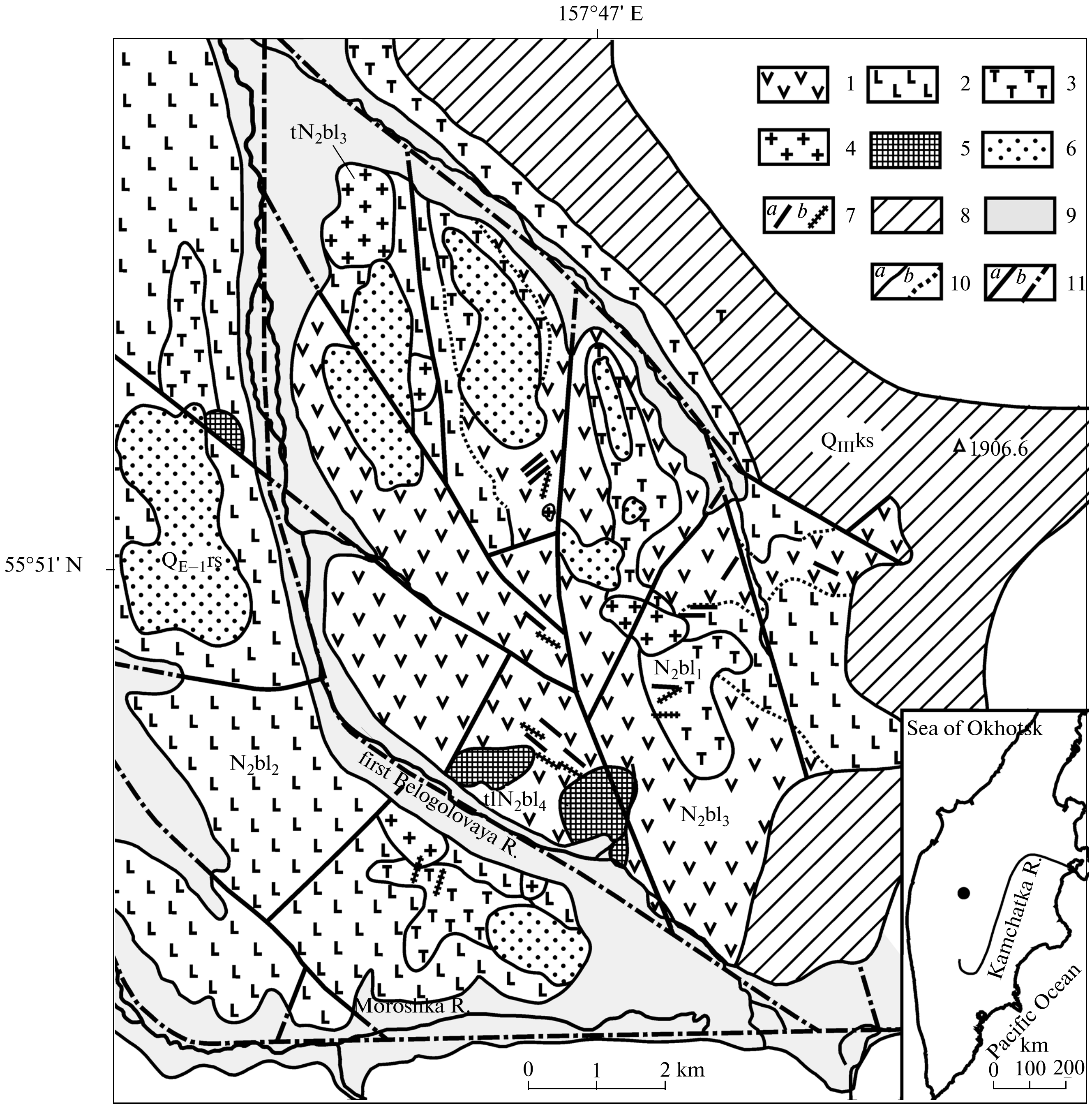

Fig. 1. A geological map of the Belogolovskii massif.

(1–5) Belogolovskii complex (N_2): (1) basaltic andesites, andesites, dacites of rock sequence 2 (N_2 bl_1); (2) trachybasalts, basaltic trachyandesites, and trachyandesites of rock sequence 2 (N_2 bl_2); (3–4) trachytes of rock sequence 3 (N_2 bl_3): lava flows and tuffs (3), extrusions (4); (5) subvolcanic bodies consisting of trachyrhyolites and comendites (N_2 bl_4); (6) basaltic andesites and andesites of Rassoshina complex (Q_{E-1}rs); (7) dikes of basic and intermediate compositions in Belogolovskii and Rassoshina complexes (*a*), dikes consisting of trachytes, trachyrhyolites, and comendites (*b*); (8) olivine basalts of Kozyrevsk complex (Q_{III} ks); (9) unconsolidated Quaternary deposits; (10) geological boundaries, certain (*a*) and inferred (*b*); (11) discontinuities, certain (*a*) and hidden under unconsolidated deposits (*b*). Inset shows the area of study. The map was made by the present authors using materials of geological surveys (Sh.G. Khasanov[1]).

differing directions and lengths that divide the massif into blocks. It is a fragment of the eponymous complex, which includes sheet and subvolcanic formations of normal alkalinity and subalkaline in composition in a wider range of silica content. The sheet formations consist of alternating basaltic andesites, andesites, basalts, their tuffs and breccias, trachybasalts, basaltic trachyandesites, trachyandesites, trachytes and their tuffs, and trachydacites. Layers and beds of tuff sandstone, tuff aleurolite, tuff gravelite tuffs and tuff conglomerates are rare. The age of the complex was estimated to be Pliocene (N_2) in the time span of 1.6–2.8 Ma as inferred from geology, potassium–argon dating, and paleomagnetic evidence. Its thickness is 850 m. Geologically speaking, it occupies a position between the underlying Kakhtun basaltic andesite complex (N_{1-2}) and the Rassoshina trachybasaltic to basaltic Eopleistocene complex (Q_{E-1}rs)[1] that overlies it unconformably.

Within the massif the Belogolovskii complex consists of three stratigraphically uniform lava–pyroclastic rock sequences that have the following compositions:

(1) Basaltic andesites and andesites, and dacites in considerably smaller amounts (N_2 bl_1). A single flow of strongly altered basalt was identified. The sheet volcanic rocks are intimately related to vent formations and subvolcanic occurrences of gabbro porphyries, pyroxene diorite porphyries. The complete section of this rock sequence is exposed beyond the Belogolovskii massif along the Nosichan River, where it consists of a rock series ranging from basalt to rhyodacite.

(2) Trachybasalts and trachyandesites, and trachydacites in considerably smaller amounts (N_2 bl_2).

(3) Trachytes (N_2 bl_3).

The first two rock sequences are in indeterminate stratigraphic relationships, but the constituent volcanic rocks exhibit associated areal occurrences that are related to autonomous, spatially separated, eruptive centers. The deposits of these sequences are composed of two adjacent tectonic blocks that are separated by an arcuate fault along the first Belogolovaya River. The virtual centers of volcanism are supposed to lie in the middle of the massif (normal alkalinity) and in the southwestern part of it (subalkaline). The section is reconstructed from the exposed fragments to show a homodrome directivity of volcanism at each of these centers. At the same time, one notes a spatial conjunction of their occurrences, with alternating basaltic andesite and trachyandesite flows within a single section. These relationships suggest nearly synchronous eruptions of magmas of differing alkalinity, which is reflected in the presence of intermediate rock varieties. The trachytes in this sequence lie startigraphically higher and consist of lavas, less so of lava breccias and tuffs. In the same way they form dikes and extrusions. The latter lie within the exposure of sequence 1 rocks and have a well-defined surface expression in the relief. The Belogolovskii volcanic rocks are penetrated by numerous stocks, sills, and dikes that have compositions like that of the complex. In some areas the dikes form a continuous dense network, which form dike fields. The generation of this complex culminates in the penetration of small trachyrhyolite and comendite bodies. The contacts with the host rocks are both discontinuous and tectonic. All formations in this complex are overlain by lavas that have the composition of the basaltic andesites and andesites in the Rassoshina complex, which everywhere compose the ridge parts of the mountain ranges and are cut through by dikes of the same composition. The youngest volcanic formations consist of olivine basalts of the Quaternary Kozyrevsk complex (Q_{III} ks) which have produced a sheet at the northeastern and eastern circumference of the massif.

The diagrams in Fig. 2 definitely show discrete sets of data points that display the rock compositions of the Belogolovskii complex, which correspond to quite specific natural associations that compose the rock sequences described above.

Normal alkalinity rocks. I. Basaltic andesites–andesites–dacites. This association also contains the volcanic rocks of the Nosichan R. sequence, expanding the compositional range from basalts to rhyodacites.

Moderately alkaline rocks: II. Trachybasalts–basaltic trachyandesites; III. Trachyandesites–trachydacites; IV. Trachytes.

Moderately alkaline and alkaline rocks: V. Trachyrhyolites and comendites.

According to the classification of LeBas et al. [1986], the trachybasalts and trachyandesites consist of both K–Na and Na–K rock varieties as inferred from the alkali ratio. While the trachybasalts (II) have a single range of silica content corresponding to it, the concentration of SiO_2 (wt %) in the trachyandesites (III) increases from sodic varieties toward potassic ones in the ranges of 54.9–56.7 and 56.6–61.2, respectively. Their geological setting in the continuous section that is exposed in the right tributary of the Moroshka River allows one to determine the timing of their generation during the production of high alkali magma: K–Na trachybasalts to Na–K trachybasalts to Na–K trachyandesites to K–Na trachyandesites to trachytes. The Rassoshina basaltic andesites and andesites occupy an intermediate position between normal and moderately alkaline compositions. Some representative rock compositions of the sets identified are listed in Table 1.

ROCK PETROGRAPHY

Rocks of normal alkalinity. The basaltic andesites have non-wadite serial–porphyric or serial–porphyraceous textures, with fine-porphyry texture for andesites and dacites. The volume ratio of phenocrysts and subphenocrysts in the basaltic andesites reaches 75% of the rock volume, with this figure decreasing to 35% in intermediate and acidic varieties. The phenocrysts of all rocks have plagioclase (always dominant), clinopyroxene, and orthopyroxene. Relatively large exhalations of the ore mineral are not characteristic for these rocks; its inclusions in minerals are few. The relationship and availability of mafic impregnations are largely governed by basicity. The basal-

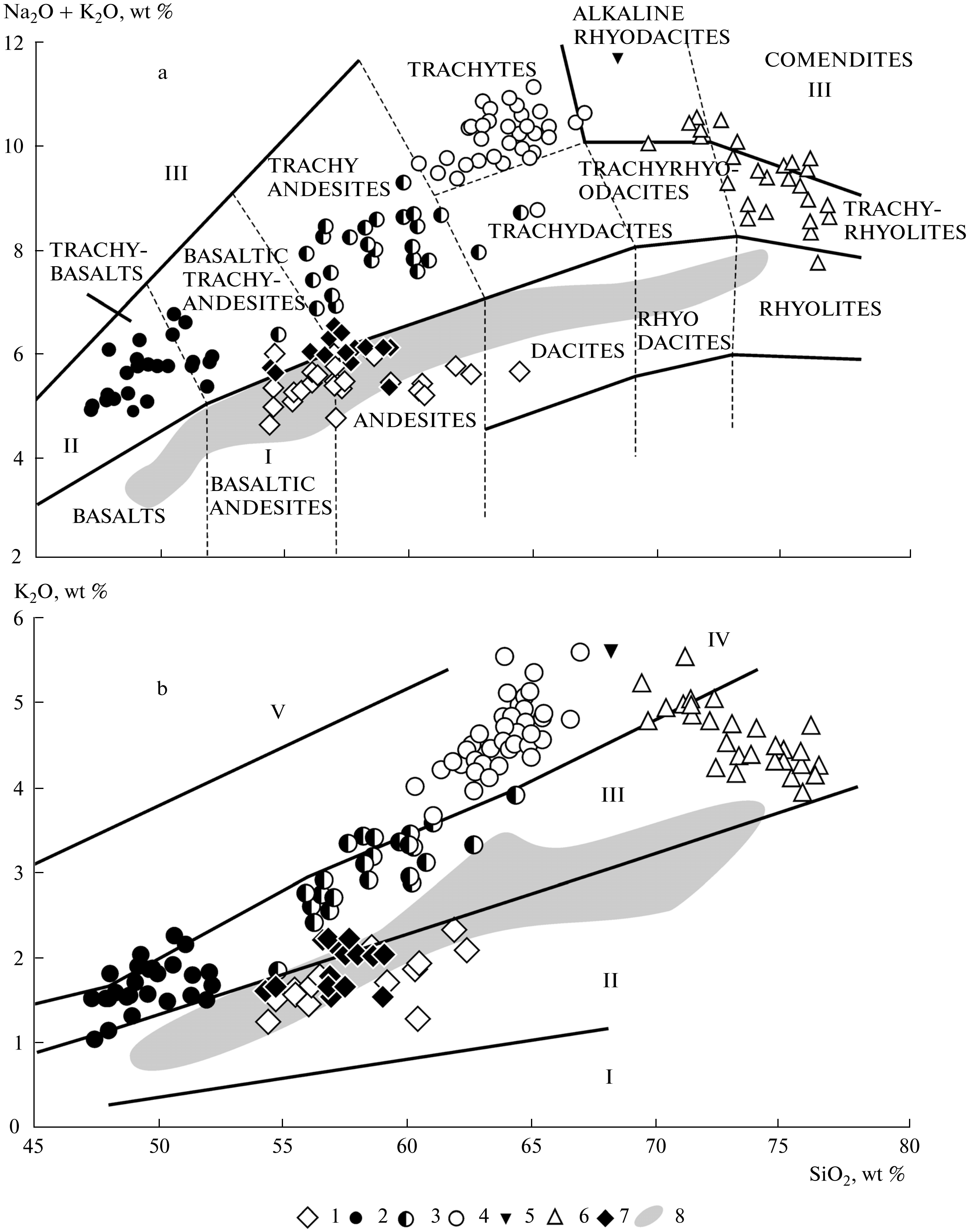

Fig. 2. The relationship (($Na_2O + K_2O$)–SiO_2 (a) and K_2O–SiO_2 (b) in Belogolovskii rocks.

(1–7) Belogolovskii volcanic massif: (1) andesites and basaltic andesites (association I); (2) trachybasalts and basaltic trachyandesites (association II); (3) trachyandesite (association III); (4) trachytes (association IV); (5, 6) trachyrhyodacites and comendites of extrusive dike complex (association V); (7) andesites and basaltic andesites of Rassoshina complex; (8) basalts, basaltic andesites, dacites, and rhyodacites of Nosichan paleovolcano (N_2^1). The classification diagrams are after [*Petrograficheskii codeks* ..., 2009] (a) and [Poccerillo and Taylor, 1976] (b). Roman numerals denote fields of the following series: a normal alkalinity (I), moderately alkaline (II), alkaline (III); b low potassic, moderately potassic calc-alkaline (II), high potassic calc-alkaline (III), subalkaline (IV).

Table 1. Representative compositions (% wt) for Belogolovskii rocks

Components	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	47.27	49.59	47.35	50.31	49.23	52.11	56.54	56.12	58.31	60.09	59.74	65.04
TiO_2	2.15	2.18	2.26	2.09	2.19	1.85	1.67	1.67	1.35	1.17	1.23	0.75
Al_2O_3	17.20	17.44	17.67	17.09	17.90	18.05	17.26	17.36	17.18	17.47	17.18	16.94
Fe_2O_3	7.80	4.41	4.26	5.75	3.25	4.58	3.38	4.35	4.51	3.93	3.87	2.49
FeO	3.59	5.75	6.64	5.03	6.47	5.03	4.13	3.22	2.33	1.98	2.15	1.44
MnO	0.15	0.16	0.15	0.17	0.16	0.16	0.17	0.14	0.14	0.11	0.15	0.09
MgO	6.74	4.98	6.26	4.27	4.88	3.72	2.06	2.61	2.26	1.58	1.92	1.29
CaO	8.39	8.27	8.02	8.44	8.29	7.74	4.96	5.63	4.49	3.97	3.99	2.26
Na_2O	3.35	3.85	3.90	4.22	4.19	4.23	5.55	4.80	4.99	4.60	5.23	4.41
K_2O	1.55	1.88	1.07	1.51	2.06	1.70	2.77	2.62	3.11	3.47	3.41	4.36
P_2O_5	0.53	0.68	0.54	0.71	0.67	0.66	0.84	0.74	0.54	0.56	0.56	0.28
LOI	1.69	1.59	2.46	0.17	1.35	0.32	0.56	0.92	0.48	1.20	0.70	0.68
Total	100.41	100.76	100.58	99.75	100.63	100.15	99.89	100.17	99.69	100.12	100.13	100.03
Components	13	14	15	16	17	18	19	20	21	22	23	24
SiO_2	62.33	64.99	61.44	74.85	75.96	54.41	60.47	64.30	57.53	57.11	58.60	57.24
TiO_2	0.88	0.78	0.95	0.16	0.12	1.30	0.94	0.87	1.29	1.27	1.11	1.04
Al_2O_3	17.72	16.80	17.72	13.42	12.58	17.37	16.52	14.40	16.99	17.43	16.64	17.73
Fe_2O_3	4.51	3.08	3.55	1.65	1.28	4.15	2.99	2.19	2.78	3.87	3.01	3.67
FeO	0.29	0.57	0.79	0.22	0.22	4.24	3.23	4.81	4.31	3.23	3.77	3.41
MnO	0.14	0.11	0.17	0.02	0.01	0.12	0.10	0.10	0.12	0.12	0.11	0.12
MgO	0.98	0.80	1.11	0.05	0.05	4.58	2.88	1.69	3.22	3.18	3.24	3.80
CaO	2.10	1.78	2.63	0.09	0.15	8.06	6.19	5.13	6.17	6.09	5.90	6.85
Na_2O	6.03	5.73	5.62	5.16	4.51	3.33	3.45	3.54	4.06	4.12	3.96	3.75
K_2O	4.34	4.63	4.18	4.49	4.00	1.27	1.95	2.08	2.05	2.16	2.03	1.56
P_2O_5	0.29	0.22	0.40	0.03	0.04	0.39	0.28	0.19	0.46	0.46	0.42	0.42
LOI	0.46	0.27	1.14	0.57	1.15	1.14	1.13	0.63	0.94	0.93	1.08	0.71
Total	100.07	99.75	99.70	100.70	100.07	100.36	100.13	99.93	99.91	99.96	99.87	100.30

(1–6) association II: potassic trachybasalt (1–2), sodic trachybasalt (3–5), basaltic trachyandesite (6); association III: trachyandesites (7–11), trachydacite (12); (13–15) association IV trachytes; (16–17) association I comendite and trachyrhyolite; (18–21) association I: basaltic andesite (18), andesite (19), dacite (20), intermediate andesite (21); (22–24) Rassoshina andesites. The analyses were carried out by X-ray fluorescence spectroscopy using a CPM-25 spectrometer at the Vinogradov Institute of Geochemistry at the Siberian Branch of the Russian Academy of Sciences.

tic andesites occasionally contain olivine in impregnations, as well as in resorpted grains and oval microinclusions in orthopyroxene, 0.3 and 0.05 mm across, respectively; in glomeroporphyric aggregates one observes the change of paragenesis from Pl + Ol ± Cpx to Pl + Opx + Cpx. The pyroxene diorite porphyries are dominated by Opx among mafic minerals; one also encounters varieties with a hypersthene–plagioclase paragenesis of impregnations. Andesites and dacites are bipyroxene varieties dominated by Opx. One encounters olivine microinclusions similar to those described above in impregnations of orthopyroxene and plagioclase from andesites. The mineral associations in the groundmass for all rocks are in agreement with those in impregnations, the ore mineral is invariably present. The andesites occasionally contain quartz.

The groundmass in the basaltic andesite rocks generally has intersertal and microdolerite microtexture. However, the porphyraceous subvolcanic varieties frequently show transitions to fine-grained gabbro–ophitic, poikilophytic, hypidiomorphic groundmass texture. The acidic andesites and dacites have hyalopilitic and fluidal groundmass microtextures, with the pilotaxitic microtexture being less frequent. The andesites from subvolcanic rocks have intersertal texture.

The Rassoshina basaltic andesites and andesites are also bipyroxene varieties that occasionally contain olivine. The andesites with serial–porphyric texture prevail, but one also encounters subaphyric varieties. The groundmass microtexture ranges from hyalopilitic to intersertal and microdolerite. The ore minerals frequently compose impregnations and subphenocrysts. There are also several other differences from the Belogolovskii andesites: the groundmass contains orthoclase in microlites and metastasis; one also encounters amphibole in the microlite and as a rim on clinopyroxene, as well as apatite.

Moderately alkaline rocks. The rocks of association II are mostly subaphyric, oligoporphyraceous, olivine–plagioclase dolerites, more rarely varieties that contain glass in the groundmass. The impregnations make up as much as 10–15 wt %. Clinopyroxene is rare in the trachybasalts, and then only in phenocrysts. In basaltic trachyandesites it is commonly encountered in subphenocrysts in association with titanomagnetite. Olivine frequently contains spinel inclusions. Orthopyroxene in the rocks of association II was only occasionally found in crushed rock samples; it occasionally forms fringes on olivine in basaltic trachyandesites. Microlite paragenesis is found in the form Pl + Ol + Cpx + Fsp + TiMt; apatite is also present. Orthoclase is found, not only in microlites, but also in rims on plagioclase, as well as metastasis. These rocks typically exhibit microdolerite and micro-poikilophytic microtextures, but one also encounters varieties with hyalopilitic, intersertal, and micro-poikilophytic groundmass.

All rocks of associations III–IV–V contain large exhalations (megacrysts) of the earlier Pl and their growths. These are frequently corroded by the groundmass, are overfilled with glassy microinclusions, and are frequently enclosed in orthoclase rims. The percentage of impregnations and subphenocrysts reaches ~30% of the rock volume, with salic minerals in obvious preponderance. The impregnation parageneses in the rocks of association III are Pl + Cpx + Ol ± Opx ± Hbl in basic trachyandesites and Pl + Opx + Cpx ± Ol ± Hbl + Mt in acidic trachyandesites (Opx invariably prevails over Cpx). We found microinclusions of olivine in plagioclase and ones of Mt and Ap in mafic minerals. The rocks of associations IV and V almost always contain Hbl and/or Bt and alkali feldspar (including perthite) in parageneses: Pl + Fsp + Cpx ± Ol ± Opx, Pl + Fsp + Cpx + Mt ± Hbl ± Bt ± Opx ± Q in trachytes and Pl + KFsp + Bt + Mt ± G; Pl + Cpx + Mt in comendites and trachyrhyolites.

The set of groundmass microlites, usually in various combinations, mimicks the set of impregnations (hydroxyl-bearing minerals are found only in impregnations in basic trachyandesites), apatite is always present. Quartz is common in the rocks of associations IV and V, as well as zircon is encountered. As well, the comendites after [Volynets et al., 1990b] were found to contain sphene, corundum, and orthite. Subalkaline rocks commonly have serial–porphyric (serial–porphyraceous) and magnophyric textures, even megaporphyritic (megaporphyraceous). We found microtextures of basic groundmasses: microdolerite in basic trachyandesites, hyalopilitic, trachytic, vitrophyric, and felsitic in acidic varieties of trachyandesites and trachytes. Trachyrhyolites and comendites commonly contain subaphyric and aphyric textures (occasionally these were fused glassy rocks) with the following groundmass microtextures: vitrophyric, spherulitic, fluidal, felsitic, and microgranitic.

ROCK MINERALOGY

The mineral compositions were determined using a CAMEBAX microprobe at the Institute of Volcanology and Seismology at the Far East Branch of the Russian Academy of Sciences (Tables 2 through 5). These studies were conducted in polished sections and in monomineral cartridges that included grains more than 0.25 mm across from crushed samples weighing less than 300 grams. The method of mineral cartridges was used in order to obtain some statistical information on impregnation minerals that might be absent from the object of investigation. Since the microlite compositions usually continue the evolutionary trends of impregnation minerals and are frequently in correspondence with those of subphenocrysts in the compositional diagrams, the microlite and phenocryst compositions are shown with a single symbol.

Olivines from normal alkaline rocks of association I in the Belogolovskii complex were found as individual crys-

Table 2. Representative compositions (% wt) of olivines from Belogolovskii rocks

Components	1	2	3	4	5	6	7	8	9	10	11	12
	Ph	incl. in Opx	B	B	B	B	M	B	B	B	B	M
SiO_2	38.77	37.14	37.94	40.17	38.84	38.94	36.78	39.31	37.99	37.87	36.75	37.01
FeO	19.96	28.71	27.43	14.53	21.12	19.92	33.31	17.94	27.52	25.96	29.15	31.52
MgO	40.54	34.17	34.13	43.23	39.63	39.79	29.16	40.73	35.56	36.23	34.25	31.42
CaO	0.11	0.16	0.40	0.19	0.22	0.25	0.40	0.12	0.28	0.21	0.25	0.29
MnO	0.09	0.32	0.27	0.00	0.10	0.10	0.51	0.23	0.26	0.37	0.33	0.35
NiO	0.01	0.03	0.00	0.16	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00
Total	99.67	100.60	100.19	98.28	99.91	99.00	100.19	98.51	101.60	100.71	100.73	100.60
Fo, at. %	78.37	67.96	68.92	84.13	76.98	78.07	60.93	80.21	69.73	71.35	67.68	63.98
Components	13	14	15	16	17	18	19	20	21	22	23	24
	Ph	mlt	Ph	Ph	Ph	Ph	Ph	Ph	mlt	incl. in Opx	Ph	incl. in Opx
SiO_2	37.35	36.52	39.18	39.18	39.19	37.18	37.41	38.09	36.74	35.08	34.49	36.07
FeO	28.65	36.73	17.11	20.12	16.84	28.65	25.61	25.05	37.48	39.94	42.80	34.18
MgO	32.81	26.97	42.94	39.69	43.62	33.70	36.48	34.78	24.57	23.52	19.87	29.15
CaO	0.21	0.31	0.10	0.15	0.12	0.11	0.14	0.20	0.22	0.02	0.10	0.14
MnO	0.37	0.62	0.14	0.22	0.16	0.56	0.43	0.43	1.08	2.25	2.19	0.52
NiO	0.00	0.00	0.17	0.17	0.02	0.00	0.00	0.07	0.00	0.00	0.00	0.00
Total	99.41	101.20	99.66	99.55	100.04	100.26	100.13	98.62	100.13	100.87	99.53	100.06
Fo, at. %	67.12	56.69	81.75	77.87	82.20	67.70	71.74	71.24	53.90	51.24	45.31	60.34

(1–2) association I: basalt (1), basaltic andesite (2); (3–12) association II: potassic trachybasalt (3–7), sodic trachybasalt (8–12); (13–21) association III trachyandesites; (22, 23) association IV trachyte; (24) Rassoshina andesite. Columns 2, 22, 24: inclusion in Opx; here and below Ph stands for phenocryst and mlt for microlite.

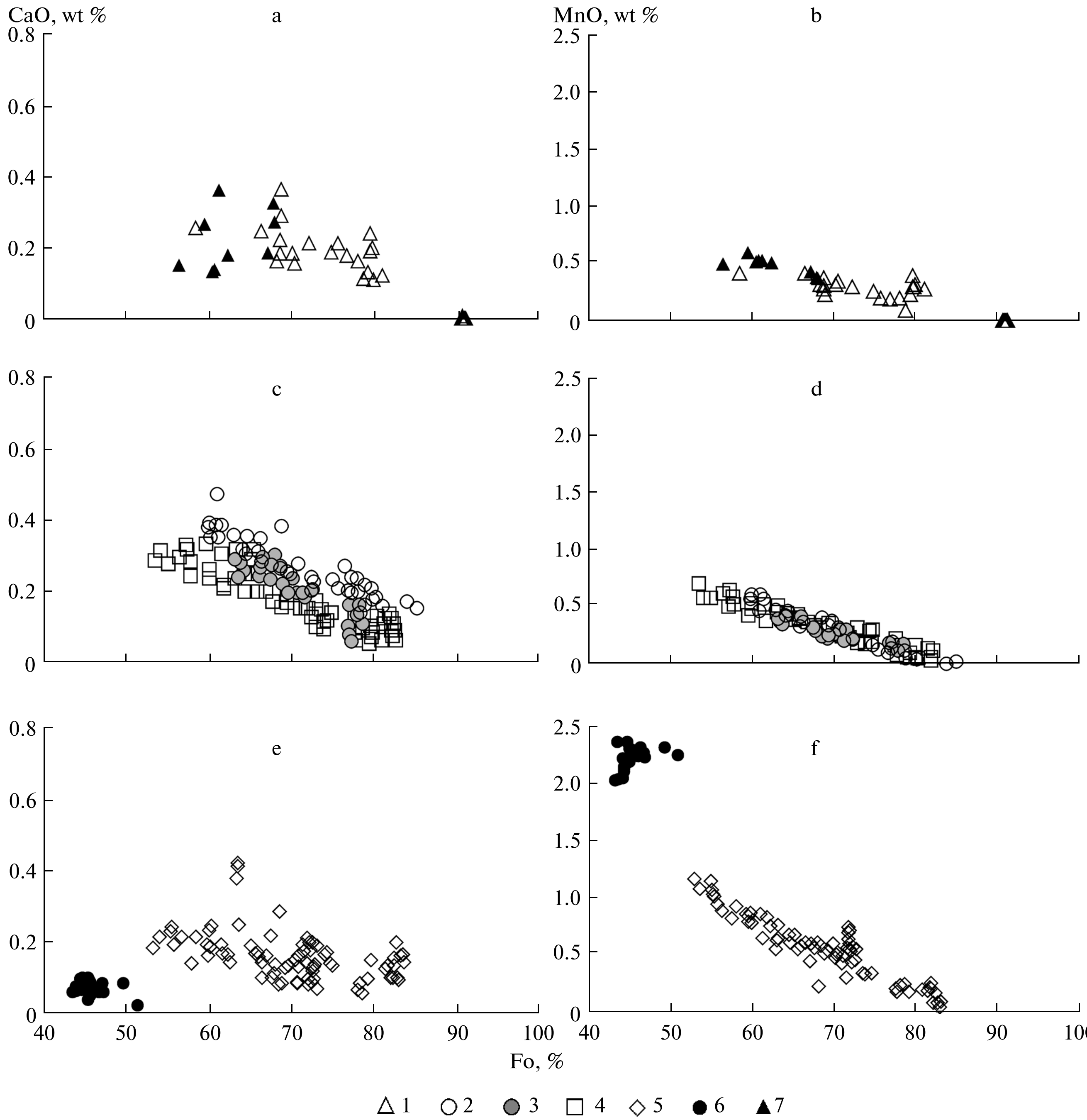

Fig. 3. Variational diagrams showing the relationship of Fo versus CaO and MnO (% wt) in olivines from Belogolovskii rocks. a, b association I; c, d association II; e, f association III. (1–6) Belogolovskii complex: (1) andesites and basaltic andesites in this association; (2–4) Na-K trachybasalts (2) and K-Na trachybasalts (3), basaltic trachyandesites (4); (5) trachyandesites; (6) trachytes; (7) Rassoshina andesites and basaltic andesites.

tals 0.2 and 0.05 mm across in basalt, as well as in the form of corroded relicts and "fritted" inclusions in Opx from basaltic andesites and andesites. Overall, even though the concentrations of CaO and MnO are largely variable in the crystallization series of rocks from basalt to andesite, these concentrations are related with a linear correlation, with the compositional trend proceeding from $Fo_{80.6}$ to $Fo_{58.1}$ (Figs. 3a, 3b). The olivine in intermediate rocks seems to be an earlier metastable phase that has been subjected to pyromorphism as a result of a sharp change in the PT crystallization conditions. One crushed andesite sample was found to contain olivine grains with abnormally high concentrations of Fo_{90} and NiO (0.3–0.4 wt %), obviously a xenogenic phase. The olivines from the

Rassoshina andesite contain $Fo_{67.6-56.1}$ and correspond to those of the Belogolovskii complex, continuing the overall trend of evolution.

The intervals of concentrations of Fo (%) in the olivines from moderately alkaline rocks lie in the ranges 85.3–60.2 for trachybasalts and 82.5–53.2 for basaltic trachyandesites and trachyandesites (see Figs. 3c, 3d, 3e, 3f). While the data points for olivine compositions of association II form continuous evolutionary series in the diagrams, one notes a bimodal distribution for olivines from the trachyandesites of association III: there are two discrete sets with the intervals $Fo_{71.9-53.2}$ and $Fo_{83.5-79.0}$. The first set is typomorphic for this rock association with a silicic content $SiO_2 = 54.9-60.8\%$, the second set corresponds to olivines of association II, which seem to be minerals that have been inherited from the earlier phases of crystallization for magmas of this association. The concentration of CaO in olivines is in overall direct correlation with their iron content, while an increasing silica/alkali ratio from trachybasalts to basaltic trachyandesites and further to trachyandesites is concurrent with a definitely decreasing concentration of calcium in the mineral.

A sharply discrete position is occupied by olivines from trachytes; their compositional intervals are 0.02–0.10 wt % for CaO, $Fo_{52-43.5}$, and 2.03–2.37 wt % for MnO (see Figs. 3e, 3f). They were found in grains up to 0.15 mm across in the form of relict inclusions in Opx and in microlites. This provides evidence that these olivines crystallized in a trachyte melt with high water content and fugacity.

Among the ***spinelides*** of the Belogolovskii complex we clearly discern sets that correspond to picotites and titanomagnetites with transitional varieties (Fig. 4). Picotite is a common mineral in inclusions in olivines from rocks of association II. Titanomagnetite is characteristic for later phases of crystallization for these rocks and is typical of association III trachyandesites, association I trachytes, and normal alkaline rocks. It was noted as an independent phase and in inclusions in minerals. The titanomagnetites from normal alkalinity rocks contain significantly greater amounts of titanium. Ilmenite was found in growths with Ol + Opx in trachyandesite, as an inclusion in Opx from trachyandesite, trachydacite, and andesite, as well as in olivine $Fo_{61.5}$ and $Fo_{72.3}$ from trachybasalt and basaltic trachyandesite, respectively.

Clinopyroxenes from the rock series basalt–normal alkalinity andesite in association I are evolving in a wide compositional range from augite $Wo_{44.7-42.1}$ $En_{43.0-45.3}$ $Fs_{12.3-12.6}$ in impregnations and subphenocrysts to pigeonite in the groundmass (Fig. 5a). When in moderately alkaline volcanic rocks, they occur as the salite–augite series, but the trends of their compositional evolution in rocks of associations II and III are somewhat different (see Figs. 5b, 5c). In the former the trend is parallel to the Wo–En side in the interval $Wo_{48.2-47.4}En_{37-34.1}$ $Fs_{14.8-18.5}$ to $-Wo_{35.8-35.4}En_{45.1-50.3}Fs_{19.1-14.3}$, while in the latter the vector is displaced toward the Fs component in the interval $Wo_{46.5-45.6}En_{40.2-39.1}Fs_{13.3-15.3}$ to $-Wo_{38.2-40.3}En_{43.5-41.8}$ $Fs_{18.3-17.9}$. Clinopyroxene in trachytes is augite $Wo_{43.0-32.3}En_{40.5-45.6}Fs_{16.5-22.1}$ with occasional pigeonite rims (see Fig. 5d).

The diagrams in Fig. 6 show substantial differences in the abundances of Ti and Al relative to the iron content of clinopyroxenes from volcanic rocks of varying alkalinity. The calcic pyroxenes of rocks of normal alkalinity in association I and in the Rassoshina complex are characterized by an extended (as to iron content) trend with the interval F/Fm = 21.0–48.8, the regression lines of their compositions are gently dipping, and show a direct correlative relationship of F/Fm to Ti and a poorly expressed negative relationship to Al, while the concentration of Ti in them is low (see Figs. 6a, 6b). The iron content of clinopyroxenes from moderately alkaline rocks of associations II and II is generally defined by the interval F/Fm = 21.2–34.9 and they typically show steep trends of direct correlation in each rock set for F/Fm to Ti and Al (see Figs. 6c, 6d, 6e, 6f). There is a well-defined tendency of decreasing concentrations of Ti and Al in clinopyroxenes of the rock sets with increasing silica/alkali ratio, respectively, from minerals in trachybasalts to those in basaltic trachyandesites of association II and further to those in association III rocks. The clinopyroxene compositions from association II trachyandesites are characterized by a wide variability in the compositions of these elements. However, one notes two crystallization trends with different directions. In one case, the regression lines of element concentrations in each rock set are in agreement with the overall pattern of successive crystallization with a linear direct correlation of these with the concentration of iron; in the other case one notes an orthogonal trend with a negative correlative relationship from trachyandesites toward trachydacites and trachytes (see Figs. 6e, 6f). Some pyroxenes from trachyandesites that occupy a discrete position in the diagram are consistent with the Cpx compositions from basaltic trachyandesites, which implies the inheritance of mineral phases in the evolution of this rock series. The clinopyroxene compositions (according to the concentrations of Ti and Al) from trachytes mostly overlie those due to later phases of crystallization for trachyandesites and trachydacites. Pyroxene in association V trachyrhyolites and comendites is magnanoferroaugite; in addition, the groundmass was found to contain manganese aegirite–augite in the marginal zone of clinopyroxene and magnesian alkaline amphibole [Volynets et al., 1983].

The ***orthopyroxenes*** are represented by a continuous bronzite–hypersthene series in the ferruginity interval 21.7–39.2 in the rocks of the normal alkalinity series and

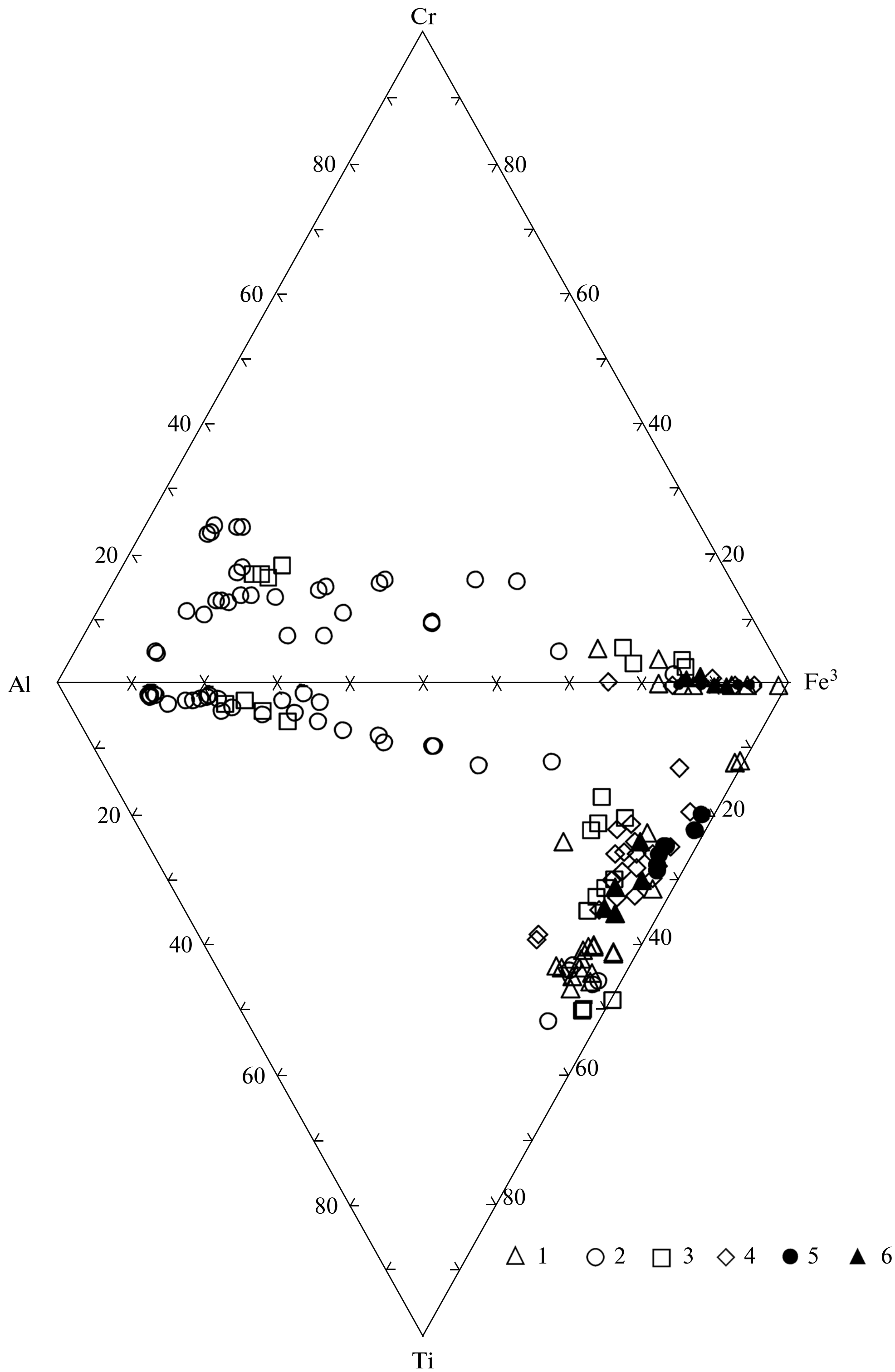

Fig. 4. Cr–Al–Fe3–Ti (cations) compositional diagram for Belogolovskii spinelides.

(1–6) Belogolovskii complex: (1) basaltic andesites and andesites of association I; (2–3) association II: trachybasalts (2) and basaltic trachyandesites (3); (4) association II trachyandesites; (5) association IV trachytes; (6) Rassoshina andesites and basaltic andesites.

The concentration of cations in the crystallochemical formula of the mineral is per 32% oxygen.

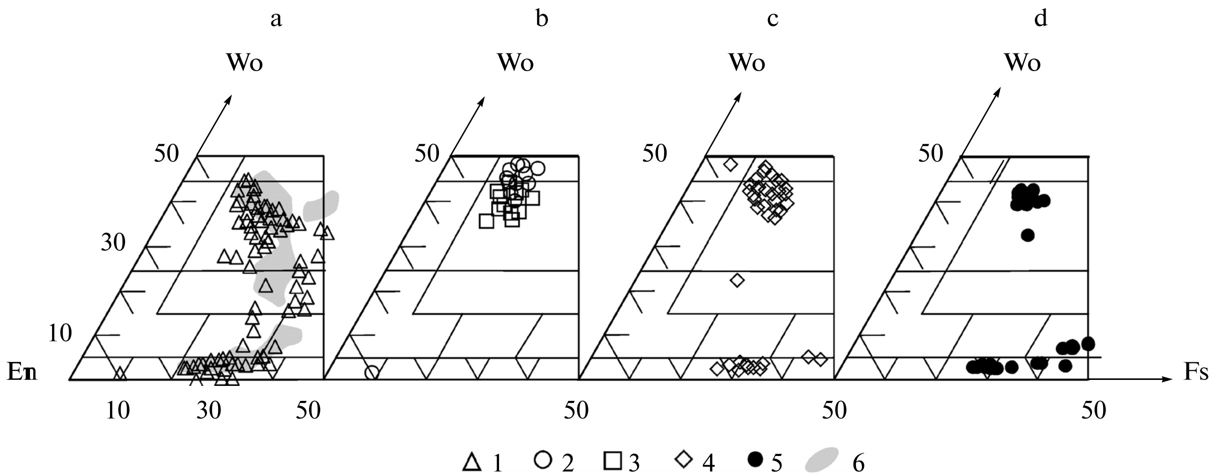

Fig. 5. Wo–En–Fs (at. %) compositional diagram for Belogolovskii clinopyroxenes.
For legends 1 through 5 see Fig. 4; (6) Rassoshina andesites and basaltic andesites.

27.0–35.0 in trachyandesite and olivine-bearing trachytes; by hypersthene in olivine-less trachyte varieties (F/Fm = 40.5–50.2). Some individual enstatite grains with F/Fm = 9 that were found in andesite and trachybasalt are evidently exogenous material (see Fig. 5).

The ***feldspar*** from the basalt–andesite rock series, association I of the Belogolovskii complex, consists of plagioclase ranging in composition from bytownite $An_{77.8}$ to andesine $An_{38.6}$, as well as consists of occasional alkaline feldspar $An_{7.8}Ort_{41.7}$–$An_{2.9}Ort_{52.8}$, in the groundmass metastasis. The single An_{95} grain encountered in the basalt is more likely a xenogenic phase (Fig. 7a). The feldspar from moderately alkaline rocks makes a discontinuous series $An_{77.8-29.1}$ and $An_{22.2}Ort_{17.6}$–$An_{1.4}Ort_{67.6}$ in association II rocks and a continuous series from labradorite $An_{67.8}$ to orthoclase $An_{1.9}Ort_{56.6}$ in association III rocks (see Figs. 7b, 7c). The compositional range of feldspar from trachytes is andesine $An_{36.7}$–$An_{1.2}$ $Ort_{51.0}$. Trachyrhyolites contain impregnations and microlites of calcic feldspar (orthoclase), sanidine, and albite (see Fig. 7d). The feldspars from the Rassoshina complex consist of $An_{63.2-38.4}$ plagioclase, calcic oligoclase, and orthoclase in microlites.

PETROCHEMICAL FEATURES OF ROCKS

According to the classification of types of volcanic series by the concentration of K_2O [Poccerillo and Taylor, 1976; Volynets et al., 1987], normal alkalinity rocks of association I are of the moderately potassic calc-alkaline type. Associations II, III, and V in the moderately alkaline series correspond to the high-potassic calc-alkaline type, while trachytes and some trachyandesites are shifted into the subalkaline region, which provides evidence of increasing role of potassium in the alkali balance in rock evolution (see Fig. 2b). According to the ratio of alkaline elements to SiO_2, for moderately alkaline volcanic rocks of associations II–IV, we have a typical trend of increasing alkalinity in the series of increasing silica content, while the rocks in the basaltic andesite–Belogolovskii dacite series make a nearly horizontal trend.

According to the classification of Kamchatka's petrochemical series types proposed in [Volynets et al., 1987, 1990b], the volcanic rocks in the moderately alkaline series belong to the alkaline olivine basalt–trachyte–comendite series. Remarkably, the evolutionary trend in the region of moderately acidic compositions branches out from trachyandesites toward, in one case, trachytes and in the other toward trachydacites and trachyrhyolites. One notes a compositional shift of basaltic andesites and andesites of association I in the interval SiO_2 = 54–59.6 wt % toward a region of higher total and potassic alkalinity, thus providing evidence that there are rocks whose composition is intermediate between normal and moderately alkaline ones. These rocks are completely in the Rassoshina field (see Fig. 2).

It can be seen in the SiO_2versus oxide diagrams (Fig. 8) that the rocks in each association form rather compact discrete sets that compose linearly related, individual correlation series with somewhat different trends. Comparison of rock compositions with specific silica values shows higher concentrations of TiO_2 and P_2O_5 and lower concentrations of MgO and CaO in the higher alkalinity series volcanic rocks relative to those in the Belogolovskii and Rassoshina normal alkalinity series. The position of the Rassoshina points corresponds to that for normal alkalinity rocks. However, according to the concentrations of CaO and TiO_2, the rocks of the latter series are observed to show a significant shift of several points toward the trachyandesite region.

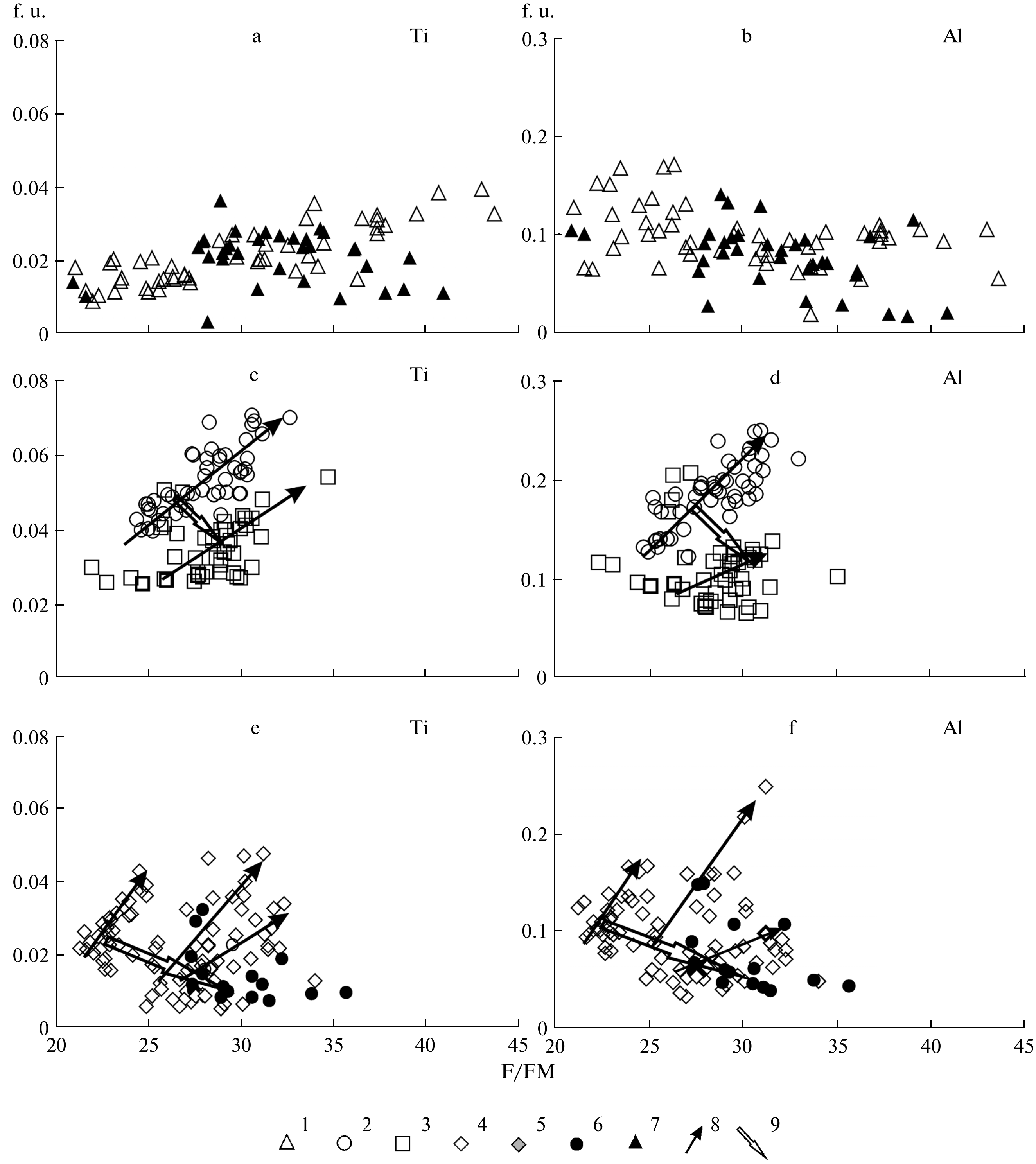

Fig. 6. F/FM–Ti, Al (cations) variational diagrams for Belogolovskii clinopyroxenes.

(1–6) Belogolovskii complex: (1) association I andesites and basaltic andesites; (2–3) association II: trachybasalts (2), basaltic trachyandesites (3); (4–5) association III: trachyandesites (4), trachydacites (5); (6) association IV trachytes; (7) Rassoshina andesites and basaltic andesites; (8) evolutionary compositional trends for individual rocks; (9) trend of compositional evolution for clinopyroxenes in the increasing silica–alkali series. F. units is atomic concentration of an associated element in the crystallochemical formula of the mineral per 6% oxygen. f.u. is the short for formula unit.

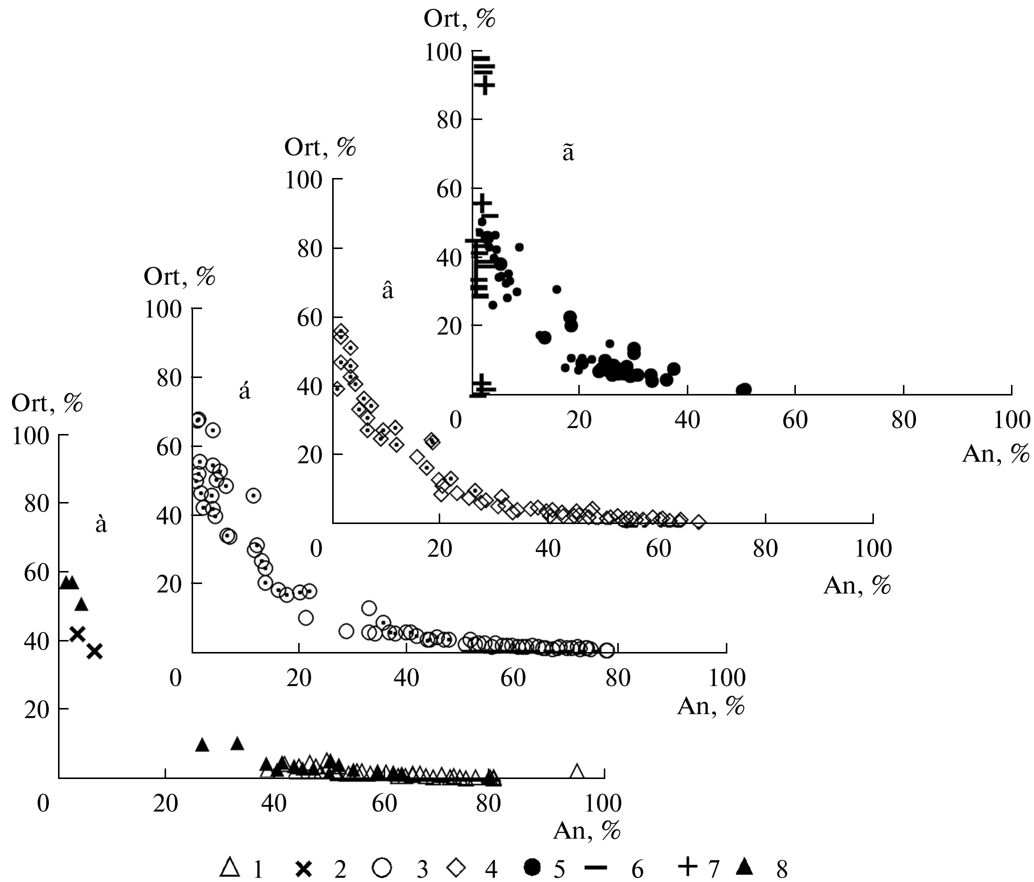

Fig. 7. An–Ort (at. %) variational diagrams in Belogolovskii feldspars. (1–6) Belogolovskii complex: (1–2) association I andesites and basaltic andesites: phenocrysts (1), andesite groundmass mesostasis (2); (3–5) phenocrysts from association II trachybasalts and basaltic trachyandesites (3), association III trachyandesites (4), association IV trachytes (5); (6–7) trachyrhyolites and comendites: phenocrysts (6), microlites (7); (8) Rassoshina andesites and basaltic andesites. A symbol centered around a dot denotes the microlite of the associated rock.

The differences in the evolutionary tendencies for the chief types of rocks of varying alkalinity are also visible in the compositional series of rock to groundmass (scanning analyses) to matrix glass. The compositions of their glasses significantly differ among themselves and when plotted in the diagram of Fig. 9 they are situated in the regions that correspond to the petrochemical types of volcanic rocks with normal and moderate alkalinity. At the same time, both types of glass were found in the groundmass of the Rassoshina basaltic andesites and andesites, in addition to alkaline glass being found in a pyroxene inclusion from andesite (see Fig. 9). Moreover, acidic glass was encountered in orthopyroxene from andesite, with the glass composition being similar to that for the bulk of normal alkalinity rocks (see Figs. 9 and 10, and Table 6). These facts can be regarded as signs of interaction between melts of different alkalinities.

A special position is occupied by a discrete set of acidic alkaline and subalkaline varieties (comendites and trachyrhyolites) whose compositional regression line shows a negative correlative SiO_2 v. alkali relationship. Some information on these rocks and their generation can be found in [Volynets et al., 1990b].

RESULTS AND DISCUSSION

The results of our studies showed significant differences in petrographic and mineral compositions and petrochemistry for the normal and higher alkalinity rock series. The normal alkalinity rocks typically contain orthopyroxene in mineral parageneses both in impregnations and in the groundmass; the impregnations are practically devoid of titanomagnetite. The concentration of pyroxene is less prominent, the groundmass contains pigeonite; olivine is merely occasional in basalts, while the intermediate rocks are mostly in relict form. Titanomagnetite inclusions in impregnations occur sporadically. At the same time, olivine in high alkalinity rocks is a typomorphic mineral, it usually contains spinel inclusions in impregnations from basic varieties and titanomagnetite inclusions from intermediate rocks. There is no orthopyroxene; the feldspar invariably contains potassic oligo-

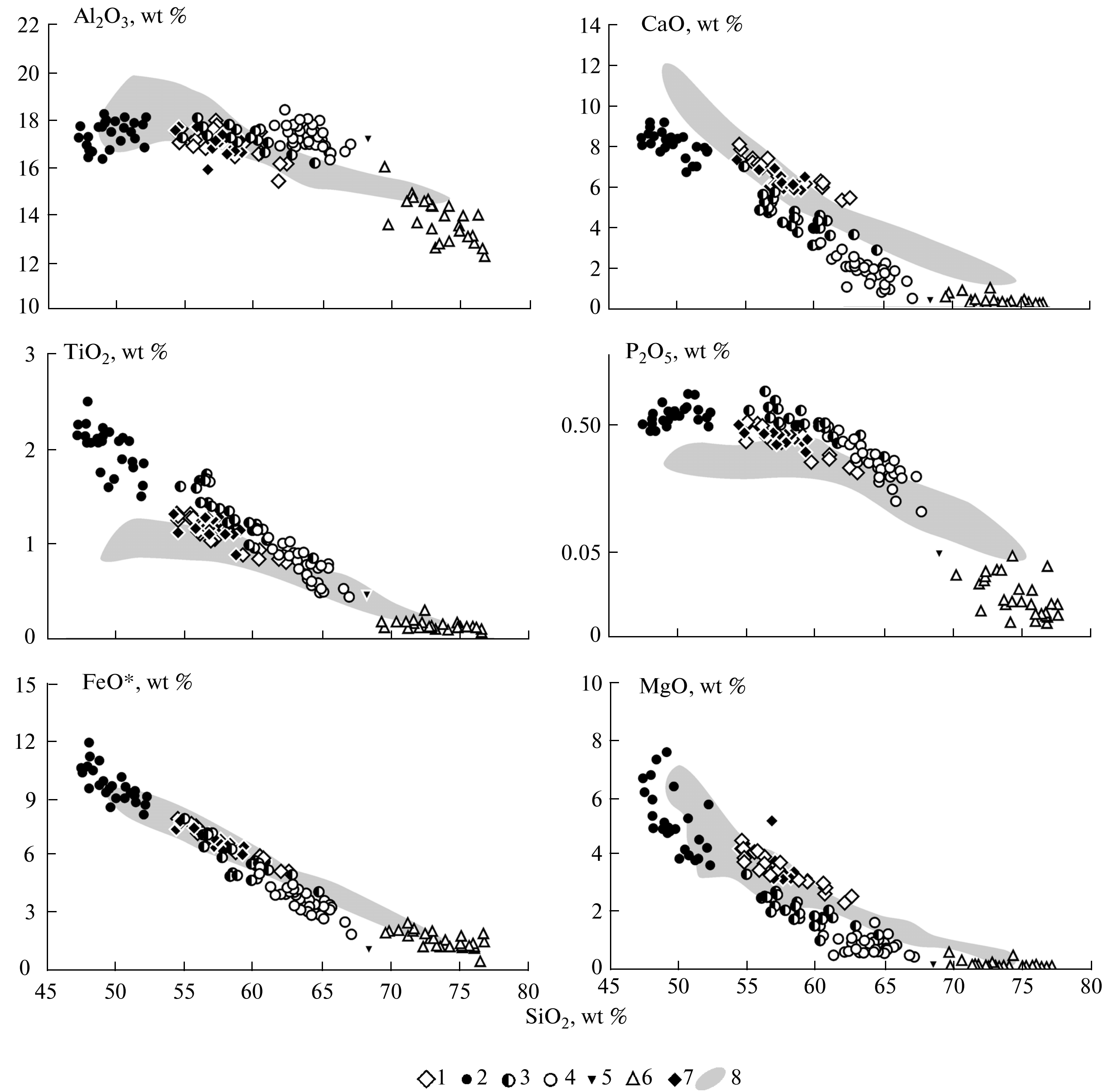

Fig. 8. Diagrams showing the distribution of major oxides for Belogolovskii rocks.
For legend see Fig. 2.

clase and alkaline feldspar in the groundmass, in addition to plagioclase, and apatite as an accessory mineral. Each series has its own tendency in the compositional evolution of rocks (as well as bulk-to-groundmass) and minerals.

The presence of the Ol + AlSp mineral paragenesis in the association II volcanic rocks, which became Ol + TiMt in trachyandesite compositions and Px + TiMt in basaltic andesite, respectively (Fig. 11), provides evidence of significantly higher PT parameters during the crystallization of association II rocks, accordingly, of a deeper source of alkaline basaltic magma that produced them.

The linear correlative relationship of bulk compositions in the trachyandesite → trachyte series, as well as of clinopyroxene compositions in these, as expressed in a common trend (see Figs. 6e, 6f) implies a genetic affinity. However, the discrete position of the trachytes in the diagrams in Fig. 2, of the olivines and plagioclases from these (see Figs. 3, 7), as well as the constant presence of hydroxyl-containing minerals, which shows that crystallization occurred under the conditions of high fluid and water saturation, are all evidence that points to trachyte magma as a comparatively independent material resulting

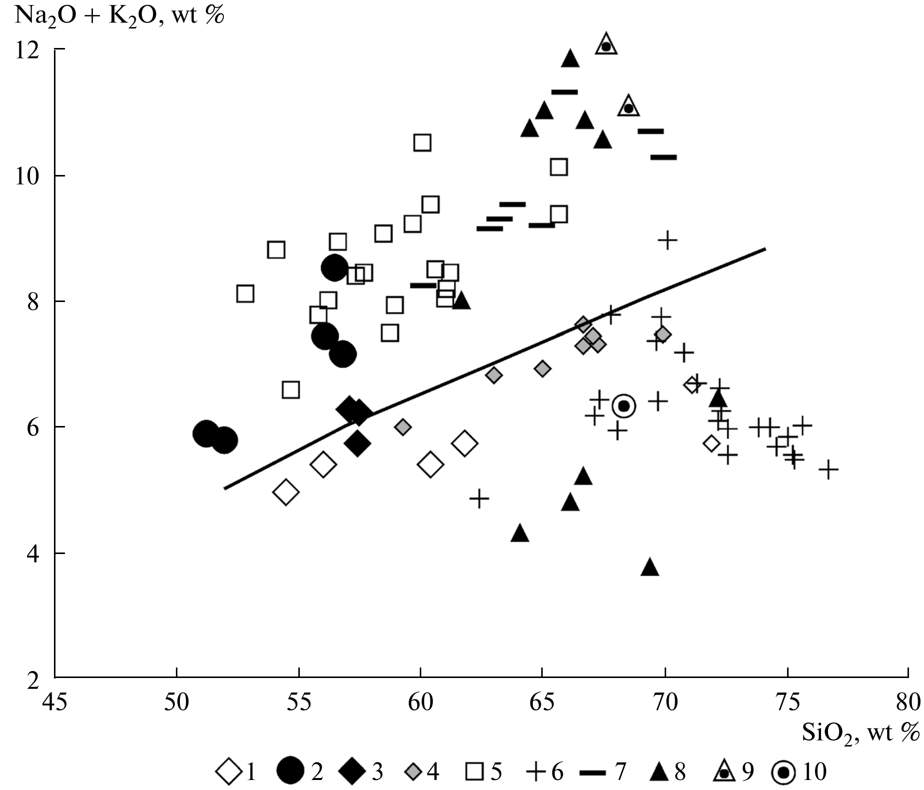

Fig. 9. $Na_2O + K_2O$–SiO_2 variational diagram for Belogolovskii groundmass (raster) and matrix glass.
(1–3) rock: association I andesites and basaltic andesites (1), association II, III trachyandesites and basaltic trachyandesites (2), Rassoshina andesites (3); (4–5) groundmass from: association I andesites and basaltic andesites (4), association II, III trachyandesites and basaltic trachyandesites (5); (6–7) matrix glasses from: association I andesites and basaltic andesites (6), association II, III trachyandesites and basaltic trachyandesites (7), Rassoshina andesites (8); (9–10) glass inclusion in Cpx from Rassoshina andesite (9) and in Opx from trachyandesite (10). Solid line marks the interface between normal and moderately alkaline rocks.

from crystallization differentiation of trachyandesite magma in a shallow chamber. Volynets et al. [1990b] wrote in great detail about the two directions of evolution for trachyandesite magma, viz., toward trachyte and trachyrhyolite and toward comendites; these authors showed that these two directions are related to orthopyroxene fractionation in the former case and to potassic feldspar fractionation in the latter. One notes that holocrystalline mineral growths (with small amounts of residual glass) in the association II basaltoids, basaltic andesites, and trachytes are composed of a paragenesis of minerals that are respective typomorphic ones specifically for these rock sets. Note that the size of their minerals is considerably in excess of that of the impregnations. The growths may be completely crystallized rocks at the marginal parts of a chamber or conduit that were captured during an eruption.

To sum up, the entire data set provides evidence (recalling that all the rocks typically have serial–porphyric textures) of the generation of the trachybasalt–trachyandesite–trachyte and basalt–basaltic andesite–andesite–dacite rock series by crystallization differentiation of the associated magmas in spatially separated chambers, which corroborates an earlier inference [Volynets et al., 1990b]. At the same time, the discrete distribution of basaltic rock sets (association II), intermediate (association III), and acidic sets (associations IV and V) in the diagrams of Fig. 2 reflects their discreteness over time, which determined the phase-like character of volcanic activity in the generation of the Belogolovskii complex. It seems that the associated volcanic activity was due to transitional supply of magma via a system of intermediate chambers residing at different depths where stepwise differentiation of these favored the rock diversity and combined them into a single series. The isotope composition of strontium in the subalkaline rock series provides evidence of a mantle origin of trachybasalts and trachyandesites. At the same time, the direct linear correlation SiO_2–$^{87}Sr/^{86}Sr$ from trachyandesite toward trachyte and trachyrhyolite provides evidence of a crustal contamination of the magmas of rock associations IV and V, hence of spatial independence of the intermediate chambers that were localized within the crust (Table 7, Fig. 12).

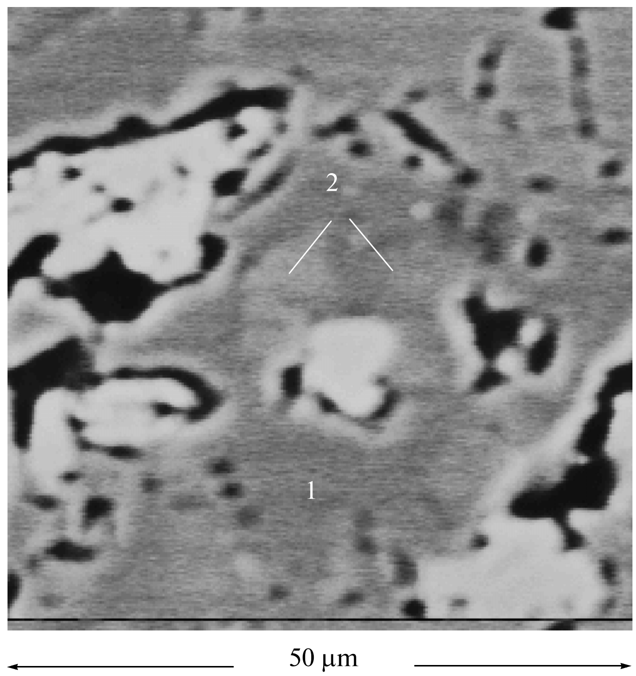

Fig. 10. Matrix glass in Rassoshina andesite groundmass (micropattern). (1) normal alkalinity glass, (2) alkaline glass.

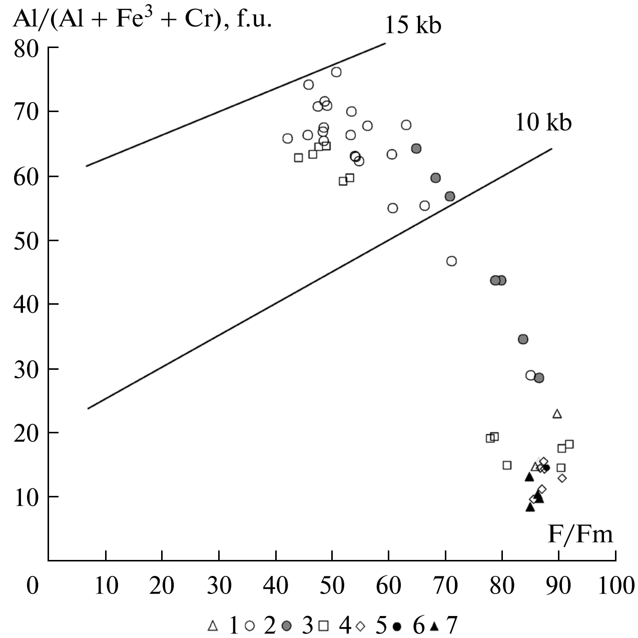

Fig. 11. Al/(Al + Fe3 + Cr)–F/FM (cations) diagram for spinelide inclusions in Belogolovskii minerals.

(1–6) inclusions in minerals from the Belogolovskii rocks: orthopyroxenes from potassium trachybasalts (2) and from sodic trachybasalts (3), from basaltic trachybasalts (4), from trachyandesites (5), and from trachyte (6); (7) inclusions in Opx and Cpx from the Rassoshino rocks. Lines in this diagram are boundaries between fields after [Koloskov, 2001].

The occurrence of K–Na and Na–K trachybasalt varieties in a common association (see Table 1) implies that the alkaline elements were rearranged in the parent melt, resulting in considerable amounts of melts with potassic and sodic specifics. The potassic melts are lower at the magma source, as shown by the succession of trachybasalts from sodic to potassic ones and observed in the exposure section. Accordingly, this had the effect of producing differences in the thermobaric parameters of the Ol + Sp paragenesis and the high magnesium numbers of earlier olivines from these varieties with higher values for the Na–K trachybasalts (see Figs. 3, 11, Tables 2, 3). This difference can be explained by invoking a model of fluidal

Table 3. Representative compositions (% wt) of spinelides from Belogolovskii rocks

Components	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	0.00	0.36	0.00	0.06	0.01	0.03	0.83	0.03	0.00	1.36	0.00	0.00	0.00
TiO_2	15.34	4.84	11.44	0.67	2.14	7.53	1.72	6.13	2.00	2.49	14.96	14.97	15.64
Al_2O_3	4.08	26.39	9.86	38.52	42.94	11.18	34.59	19.22	35.37	29.94	4.30	2.47	1.36
Fe_2O_3	36.16	25.43	29.43	8.80	10.91	40.66	23.6	31.95	15.73	17.37	36.29	37.83	37.75
FeO	39.8	26.1	37.5	17.79	21.92	35.39	27.6	33.26	19.85	22.33	39.74	43.16	43.51
Cr_2O_3	0.40	7.93	8.03	21.34	9.56	2.93	6.08	6.39	13.99	14.19	0.00	0.36	0.00
MgO	3.78	9.57	3.77	13.77	12.02	3.15	8.49	4.81	12.35	11.65	3.34	1.22	0.65
MnO	0.35	0.17	0.29	0.17	0.12	0.18	0.20	0.18	0.17	0.16	0.46	0.47	1.18
Total	99.97	100.80	100.36	101.13	99.71	101.05	103.13	101.98	99.66	99.63	99.17	100.54	100.34
F/FM, at. %	85.53	60.48	84.81	42.03	50.57	86.31	64.58	79.51	47.42	51.82	86.96	95.22	97.41
Fo, at. %	â	67.68	68.92	84.13	78.07	67.68	69.73	71.35	81.75	77.87	71.24	Ph	Ph

(1) association I basaltic andesite; (2–8) association II: potassic trachybasalt (2–5), sodic trachybasalt (6–8); (11, 12) association III trachyandesites; (13) association IV trachyte. Inclusions in Opx (1) and in Ol (2–11); Fo denotes magnesium number of olivine, Fe_2O_3 was found by stoichiometry.

Table 4. Representative compositions (% wt) of clinopyroxenes from Belogolovskii rocks

Components	1	2	3	4	5	6	7	8	9	10	11	12	13
	Ph	mlt	mlt	Ph	mlt	mlt	mlt	mlt	Ph	Ph	mlt	mlt	mlt
SiO_2	51.20	48.61	47.64	52.36	49.82	48.72	48.53	48.01	52.87	52.61	51.99	51.19	50.60
TiO_2	1.52	2.11	2.40	1.35	1.60	1.74	1.87	2.04	0.94	0.97	0.99	1.34	1.48
Al_2O_3	2.99	4.25	4.64	2.31	3.10	4.31	4.06	4.10	2.62	2.19	1.76	2.64	2.94
FeO	8.17	8.83	9.65	8.20	8.17	8.73	9.35	9.69	8.19	8.85	10.03	10.18	10.07
MgO	14.11	13.05	12.13	13.94	13.62	12.84	12.63	12.38	15.47	15.52	14.59	14.54	13.63
CaO	21.42	21.03	21.41	21.98	21.95	22.18	21.32	21.09	20.31	19.77	18.82	19.31	19.24
Na_2O	0.21	0.34	0.42	0.68	0.27	0.43	0.64	0.67	0.47	0.21	1.65	0.15	0.48
MnO	0.00	0.04	0.01	0.00	0.00	0.00	0.07	0.07	0.04	0.04	0.16	0.08	0.18
Total	99.66	98.30	98.33	100.82	98.55	98.96	98.82	98.13	100.92	100.16	99.99	99.44	98.64
WOLL	45.16	45.65	46.73	46.01	46.42	47.35	46.16	45.97	42.11	40.95	40.08	40.67	41.77
EN	41.38	39.40	36.83	40.58	40.08	38.11	38.04	37.54	44.63	44.74	43.24	42.59	41.17
FS	13.45	14.96	16.44	13.40	13.49	14.54	15.80	16.49	13.26	14.31	16.67	16.74	17.06
F/FM, at. %	24.53	27.51	30.86	24.83	25.19	27.61	29.34	30.52	22.91	24.23	27.83	28.21	29.30
Components	14	15	16	17	18	19	20	21	22	23	24	25	26
	Ph	Ph	mlt	Ph	mlt	Ph	Ph	Ph	Ph	Ph	Ph	Ph	mlt
SiO_2	52.15	50.61	47.79	51.83	51.91	52.51	51.27	53.63	51.74	53.65	51.36	50.88	50.29
TiO_2	0.78	1.11	1.58	0.71	1.17	0.32	0.79	0.28	1.05	0.35	0.38	0.85	1.40
Al_2O_3	2.12	2.96	4.23	2.40	1.79	1.12	2.12	0.70	3.36	0.96	3.47	2.12	1.62
FeO	7.86	8.37	9.26	8.85	11.02	9.92	11.18	9.68	9.64	12.93	7.59	13.16	19.95
MgO	15.97	14.83	14.08	14.60	13.33	14.42	13.72	14.77	14.25	13.12	14.82	15.32	14.38
CaO	20.78	20.68	21.13	20.31	19.82	20.89	19.42	19.07	19.54	18.87	21.45	16.32	11.62
Na_2O	0.36	0.46	0.62	0.00	0.40	0.06	0.39	0.31	0.69	0.58	0.45	0.23	0.47
MnO	0.11	0.39	0.21	0.26	0.35	0.30	0.13	0.54	0.51	1.04	0.03	0.28	0.46
Total	100.15	99.41	98.91	98.97	99.78	99.57	99.04	99.02	100.79	101.49	99.67	99.19	100.31
WOLL	42.30	43.22	43.68	42.74	42.21	42.91	41.12	40.43	41.68	39.96	44.69	34.07	24.62
EN	45.22	43.13	44.13	42.73	39.48	41.19	40.41	43.55	42.27	38.66	42.96	44.49	42.39
FS	12.48	13.65	12.20	14.53	18.31	15.90	18.47	16.02	16.05	21.38	12.34	21.44	32.99
F/FM, at. %	21.63	24.05	26.96	25.37	31.68	27.86	31.37	26.90	27.52	35.61	22.32	32.52	43.77

(1–13) association II: potassic trachybasalt (1–3), sodic trachybasalt (4--8), basaltic trachyandesite (9–13); (14–21) association III: trachyandesites (14–20), (21) trachydacite; (22–23) association IV trachyte; (24–26) association I: basalt (24), basaltic andesite (25), andesite (26). F/FM denotes the magnesium number.

magmatic differentiation controlled by the potassic fluid, as envisaged for the Kekuknai massif [Koloskov et al., 2013].

Potassium-dominated alkaline fluids are supplied into the magmatic system during its evolution as shown by progressively increasing alkaline components (a steep trend) in the evolution of trachyandesites toward trachytes. Intermediate varieties with higher concentrations of alkalies, titanium, and calcium appeared among the association I intermediate rocks (see Figs. 2, 8), as well as alkali feldspar that occurred in the groundmass metastasis; this serves as additional evidence in favor of increasing alkalinity in the earth during the crystallization of these intermediate varieties. This deviation can be explained by fluidal magmatic interaction between trachyandesite and basaltic andesite magmas during their subsynchronous eruptions. Such an interaction on a substantially greater scale probably occurred as well during the pre-crystallization period in the source chamber itself, resulting in the Rassoshina intermediate magmas.

Table 5. Representative compositions (% wt) of feldspars from Belogolovskii rocks

Components	1	2	3	4	5	6	7	8	9	10	11	12
	Ph	Ph	mlt	Ph	Ph	mlt	Ph	Ph	mlt	Ph	mlt	mlt
SiO_2	50.09	61.20	64.01	50.77	60.70	65.45	61.42	47.88	64.73	53.26	60.27	66.08
TiO_2	0.01	0.04	0.19	0.00	0.04	0.12	0.00	0.00	0.29	0.01	0.24	0.14
Al_2O_3	31.35	25.47	20.65	31.32	25.12	19.29	22.92	33.51	19.21	28.86	23.93	20.40
FeO	0.72	0.47	0.46	0.63	0.48	0.48	0.24	0.56	0.62	0.48	1.39	0.50
CaO	14.32	6.82	1.09	14.27	6.15	0.50	4.98	15.70	0.30	12.51	5.57	1.30
Na_2O	2.68	6.53	4.57	2.63	7.60	6.54	8.13	2.42	5.17	3.61	7.30	7.04
K_2O	0.15	0.89	8.72	0.20	1.04	7.53	1.24	0.09	8.73	0.34	1.82	4.60
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.34	101.43	99.70	99.83	101.32	100.00	98.94	100.28	99.04	99.08	100.55	100.06
ORT	0.93	5.39	52.59	1.21	5.87	42.09	6.99	0.53	51.85	2.11	10.34	28.06
AB	25.03	59.99	41.88	24.72	65.03	55.54	69.47	21.68	46.66	33.61	63.09	65.29
AN	74.04	34.62	5.53	74.07	29.10	2.37	23.53	77.79	1.49	64.28	26.57	6.65
Components	13	14	15	16	78	18	19	20	21	22	23	24
	Ph	Ph	mlt	Ph	Ph	mlt	Ph	Ph	mlt	Ph	Ph	Ph
SiO_2	51.31	60.25	66.51	60.13	63.21	67.06	51.14	54.52	56.20	63.73	68.03	69.18
TiO_2	0.04	0.00	0.05	0.00	0.06	0.06	0.00	0.00	0.00	0.00	0.04	0.03
Al_2O_3	30.55	23.54	21.74	25.67	22.14	19.43	30.64	27.77	26.24	17.95	18.33	19.53
FeO	0.75	0.28	0.49	0.58	0.37	0.54	1.03	0.82	1.02	0.04	0.57	0.16
CaO	13.00	5.51	2.99	6.76	3.67	0.70	14.81	11.41	9.07	0.38	0.43	0.39
Na_2O	3.87	7.94	5.00	6.29	7.03	5.04	2.94	4.68	5.27	0.20	5.43	10.55
K_2O	0.26	1.52	3.29	0.82	3.62	7.11	0.19	0.44	0.79	17.36	6.79	0.34
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.85	99.08	100.08	100.27	100.21	99.95	100.74	99.70	98.62	99.67	99.65	100.18
ORT	1.53	8.33	24.57	5.08	20.79	46.26	1.09	2.57	4.81	96.55	44.09	2.06
AB	34.48	66.28	56.72	59.57	61.47	49.90	26.15	41.49	48.79	1.68	53.58	95.99
AN	63.99	25.39	18.72	35.35	17.74	3.85	72.76	55.94	46.40	1.77	2.33	1.95

(1–9) association II: potassic trachybasalt (1–3), sodic trachybasalt (4–6), basaltic trachyandesite (7–9); (10–15) association III trachyandesites; (16–18) association IV trachyte; (19–21) association I: basalt (19), basaltic andesite (20, 21); (22–24) association V trachyrhyolite.

The above considerations suggest the following conceptual model for the generation of the Belogolovskii massif:

(1) The magmatic activity that formed the Belogolovskii massif began with eruptions of normal alkalinity basaltic magma in a geodynamic compression setting, which the island-arc type of volcanism shows [Volynets et al., 1990a]. The crystallization differentiation of this magma that seems to have been occurring in the intermediate chamber supplied periodic portions of melt to the

Table 6. Average compositions (% wt) of glasses from Belogolovskii rocks

Component	1	2	3	4	5	6	7
SiO_2	71.57	68.44	63.01	68.36	67.31	65.26	66.53
TiO_2	0.77	1.14	0.66	0.59	0.23	0.37	0.22
Al_2O_3	14.89	14.50	18.01	16.52	17.28	17.34	18.03
FeO	1.34	2.27	2.22	1.08	2.69	1.22	1.05
MnO	0.00	0.00	0.00	0.00	0.02	0.00	0.00
MgO	0.00	0.17	0.55	0.00	2.92	0.14	0.00
CaO	1.72	0.19	3.16	3.31	0.49	0.73	0.78
Na_2O	2.28	3.83	5.08	3.28	0.91	3.39	4.99
K_2O	4.04	6.90	3.97	3.04	4.28	7.79	6.49
n	24	3	5	1	4	7	2

(1–4) Belogolovskii complex: matrix glasses from: andesites and basaltic andesites of association I (1), basaltic trachyandesite of association II (2), trachyandesite of association III (3); inclusion in Opx from trachyandesite (4); (5–7) Rassoshina complex (andesite): matrix glasses (5, 6), inclusion in Cpx (7); *n* denotes the number of analyses.

Table 7. Isotope composition of strontium in Belogolovskii rocks

Associations	Sample #	Rock	SiO_2	Na_2O	K_2O	$^{87}Sr^{86}Sr$	Analysis year
II	PP-3064	Trachybasalt	49.59	3.85	1.88	0.703380	2011
	PP-2601	Trachybasalt	50.31	4.22	1.51	0.703553	2008
	PP-2500	Trachybasalt	49.04	4.03	1.72	0.703677	2008
	PP-2706	Trachybasalt	47.99	4.22	1.84	0.703506	2008
	6257*	Trachybasalt	50.75	–	2.4	0.70329	–
	6254*	Trachybasalt	48.78	–	1.73	0.70328	–
III	6267*	Trachyandesite	60.22	–	2.98	0.70328	–
IV	6353*	Trachyte	61.66	–	4.8	0.70348	–
	6297*	Trachyte	63.80	–	5.18	0.70416	–
	523*	Trachyte	66.6	–	–	0.70461	–
V	6296*	Trachyrhyolite	70.99	–	–	0.70619	–
	4001/11*	Trachyrhyolite	71.50	–	–	0.70510	–

* Denotes data from [Pokrovskii, 2000].

surface, ranging in composition from basalt to dacite (the association I differentiated rock series).

(2) The high alkali series was generated in a rifting setting, resulting in intraplate volcanism [Volynets et al., 1990a]. Changes in the geodynamic regime produced deep-reaching faults that penetrate down to the mantle source of alkaline basaltic magma. The magma goes upward to the surface to form an intermediate chamber (or a system of intermediate chambers) in the upper lithosphere layers where decompression due to decreasing partial pressure causes the magma to differentiate and to produce the range of rocks that belong to association II. The continuing process of crystallization differentiation with accompanying supply of alkaline fluids produced trachyandesite magma of association III, and then trachyte magmas. The trachyte magma formed a shallow, spatially isolated intermediate chamber in the crust where the magma is contaminated with crustal material. The magma was erupted in the form of effusions and extrusions. This phase terminated in the emplacement of trachyrhyolite and comendite subvolcanic bodies.

During periods of changing geodynamic settings the eruptions of normal and increased alkalinity magmas were concurrent in time, so that they were prone to interact; the result was to alkalize the normal alkalinity magma at the source and during rock crystallization; this caused intermediate rock varieties to be generated.

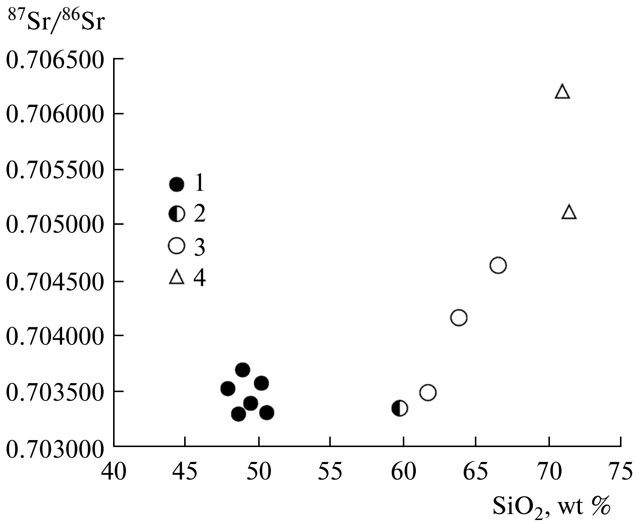

Fig. 12. SiO_2–$^{87}Sr/^{86}Sr$ relationship in Belogolovskii rocks.
(1) trachybasalts, (2) trachyandesite, (3) trachytes, (4) trachyrhyolites. For the numeric values of the data points see Table 7.

(3) The alkaline magmatic activity in the area of the Belogolovskii massif decayed during Late Pliocene time. The upper chamber of basaltic magma again increased in activity and began to function. Differentiates that consisted of basaltic andesites and andesites of normal and higher alkalinity belonging to the Rassoshina Eopleistocene complex came to the surface.

CONCLUSIONS

(1) Two rock series of different alkalinities were identified within the Belogolovskii massif: the normal alkalinity basalt–basaltic-andesite–andesite–dacite series and the high-alkalinity trachybasalt–trachyandesite–trachyte (trachydiorite, comendite) series. The leading process that was responsible for the generation of the melts that were initial for the range of rocks within each series was crystallization differentiation.

(2) The evolution of rocks of different alkalinities provides evidence that the two series followed different tendencies of their generation; thus, the parent magmas were spatially independent and resided at different depths. Their differentiation and subsequent arrival at the surface occurred via a system of intermediate chambers.

(3) The generation of rocks of intermediate composition was due to interaction among coexisting magmas of different compositions in the system of intermediate chambers.

REFERENCES

Antipin, V.S., Volynets, O.N., Perepelov, A.B., et al., Geological relationships and geochemical evolution of the Pliocene–Quaternary calc–alkaline and subalkaline volcanism of Uksichan Caldera, Kamchatka, in *Geokhimiya magmaticheskikh porod sovremennykh i drevnikh aktivnykh zon* (Geochemistry of Magmatic Rocks of the Present-Day and Ancient Active Zones), Tauson, L.V., Ed., Novosibirsk: Nauka, 1987, pp. 73–90.

Flerov, G.B., Filosofova, T.G., and Puzankov, M.Yu., Rock series of Belogolovskii paleovolcano as reflecting the magma generation of the sources at Sredinnyi Range, Kamchatka, in *Materialy IV Vserossiiskogo simpoziuma po vulkanologii i paleovulkanologii. Vulkanizm i geodinamika* (Proc. IV All-union symposium on volcanology and paleovolcanology. Volcanism and Geodynamics), Petropavlovsk-Kamchatskii: 2009, vol. 1, pp. 208–211.

Koloskov, A.V., *Ul'traosnovnye vklyucheniya i vulkanity kak samoreguliruyushchayasya geologicheskaya sistema* (Ultrabasic Inclusions and Volcanic Rocks as a Self-Regulated Geological System), Moscow: Nauchnyi Mir, 1999.

Koloskov, A.V., The Koryak–Kamchatka volcanic zone, in *Geodinamika, magmatizm i metallogeniya Vostoka Rossii* (Geodynamics, Magmatism, and Metallogeny in Eastern Russia), Book 1, Khanchuk, A.I., Ed., Vladivostok: Dal'nauka, 2006, pp. 398–417.

Koloskov, A.V., Puzankov, M.Yu., and Pirozhkova, E.S., Ultramafic inclusions in island arc basaltoids: The problem of the composition and genesis of the transitional "crust–mantle mixture" layer in island arc systems, in *Geodinamika i vulkanizm Kurilo-Kamchatskoi ostrovoduzhnoi sistemy* (The Geodynamics and Volcanism of the Kuril–Kamchatka Island Arc System), Petropavlovsk-Kamchatskii: IVGiG DVO RAN, 2001, pp. 123–152.

Koloskov, A.V., Flerov, G.B., Perepelov, A.B., Melekestsev, I.V., Puzankov, M.Yu., and Filosofova, T.M., Evolution stages and petrology of the Kekuknai volcanic massif as reflecting the magmatism in backarc zone of Kuril–Kamchatka island arc system. Part 1. Geological position and geochemistry of volcanic rocks, *J. Volcanol. Seismol.*, 2011, vol. 5, no. 5, pp. 312–334.

Koloskov, A.V., Flerov, G.B., Perepelov, A.B., Melekestsev, I.V., Puzankov, M.Yu., and Filosofova, T.M., Evolution stages and petrology of the Kekuknai volcanic massif reflecting the magmatism in the backarc zone of the Kuril–Kamchatka island arc system. Part II. Petrologic and mineralogical features, petrogenesis model, *J. Volcanol. Seismol.*, 2013, vol. 7, no. 2, pp. 145–169.

LeBas, M.J., LeMaitre, R.W., Streckeisen, A., and Zanettin, B.A., Chemical classification of volcanic rocks based on the total alkali-silica diagram, *J. Petrology*, 1986, vol. 27, pp. 745–750.

Perepelov, A.B., *Geochemistry of Late Cenozoic High Potassic Volcanic Series in the Kamchatka Island Arc System*, Extended Abstract of Dr. Sci. (Geol.–Mineral.) Dissertation, Irkutsk, 1989, 26 p.

Perepelov, A.B., Puzankov, M.Yu., Ivanov, A.V., et al., Neogene basanites of western Kamchatka: Mineralogic and geochemical features and the geodynamic setting, *Petrologiya*, 2007, vol. 15, no. 5, pp. 524–546.

Petrograficheskii kodeks (Petrographic Code), St. Petersburg, 2009.

Poccerillo, A. and Taylor, S.R., Geochemistry of Eocene calc-alkaline volcanic rock from the Kastamonu area, Northern Turkey, *Contrib. Mineral. Petrol.*, 1976, vol. 58, no. 1, pp. 63–81.

Pokrovskii, B.G., *Korovaya kontaminatsiya mantiinykh magm po dannym izotopnoi geokhimii* (Crustal Contamination of Mantle Magmas from Data of Isotope Geochemistry), Moscow: MAIK Nauka, Interperiodika, 2000.

Volynets, O.N., *Petrologic and Geochemical Classification of Volcanic Series in a Present-Day Island-Arc System*, Extended Abstract of Dr. Sci. (Geol.–Mineral.) Dissertation, Moscow State University, Moscow, 1993, p. 67.

Volynets, O.N., Patoka, M.G., Filosofova, T.M., and Chubarov, V.M., A first finding of alkaline mafic minerals in Late Cenozoic lavas of Kamchatka, *Dokl. AN SSSR*, 1983, vol. 269, no. 5, pp. 1182–1185.

Volynets, O.N., Anoshin, G.N., and Antipin, V.S., The petrology and geochemistry of alkaline and subalkaline lavas as an indicator of the geodynamic setting at island arcs, *Geol. Geofiz.*, 1986, no. 8, pp. 10–16.

Volynets, O.N., Flerov, G.B., Shantser, A.E., and Melekestsev, I.V., The Kuril–Kamchatka arc. The Kamchatka segment, in *Petrologiya i geokhimiya ostrovnykh dug i okrainnykh morei* (Petrology and Geochemistry of Island Arcs and Marginal Seas), Moscow: Nauka, 1987, pp. 56–85.

Volynets, O.N., Antipin, V.S., Perepelov, A.B., and Anoshin, G.N., Geochemistry of volcanic series of island arc systems applied to geodynamics (Kamchatka), *Geol. Geofiz.*, 1990a, no. 5, pp. 3–13.

Volynets, O.N., Asavin, A.M., and Kogarko, L.N., The origin of alkaline and subalkaline lavas in Kamchatka, *Geokhimiya*, 1990b, no. 4, pp. 506–525.

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