ISSN 0016-7029, Geochemistry International, 2012, Vol. 50, No. 6, pp. 522–550. © Pleiades Publishing, Ltd., 2012.
Original Russian Text © M.L. Tolstykh, V.B. Naumov, M.G. Gavrilenko, A.Yu. Ozerov, N.N. Kononkova, 2012, published in Geokhimiya, 2012, Vol. 50, No. 6, pp. 576–606.

Chemical Composition, Volatile Components, and Trace Elements in the Melts of the Gorely Volcanic Center, Southern Kamchatka: Evidence from Inclusions in Minerals

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Received November 17, 2010; in final form, May 24, 2011

Abstract—Melt inclusions in olivine and plagioclase phenocrysts from rocks (magnesian basalt, basaltic andesite, andesite, ignimbrite, and dacite) of various age from the Gorely volcanic center, southern Kamchatka, were studying by means of their homogenization and by analyzing the glasses in 100 melt inclusions on an electron microprobe and 24 inclusions on an ion probe. The SiO_2 concentrations of the melts vary within a broad range of 45–74 wt %, as also are the concentrations of other major components. According to their SiO_2, Na_2O, K_2O, TiO_2, and P_2O_5 concentrations, the melts are classified into seven groups. The mafic melts (45–53 wt % SiO_2) comprise the following varieties: potassic (on average 4.2 wt % K_2O, 1.7 wt % Na_2O, 1.0 wt % TiO_2, and 0.20 wt % P_2O_5), sodic (3.2% Na_2O, 1.1% K_2O, 1.1% TiO_2, and 0.40% P_2O_5), and titaniferous with high P_2O_5 concentrations (2.2% TiO_2, 1.1% P_2O_5, 3.8% Na_2O, and 3.0% K_2O). The melts of intermediate composition (53–64% SiO_2) also include potassic (5.6% K_2O, 3.4% Na_2O, 1.0% TiO_2, and 0.4% P_2O_5) and sodic (4.3% Na_2O, 2.8% K_2O, 1.3% TiO_2, and 0.4% P_2O_5) varieties. The acid melts (64–74% SiO_2) are either potassic (4.5% K_2O, 3.6% Na_2O, 0.7% TiO_2, and 0.15% P_2O_5) or sodic (4.5% Na_2O, 3.1% K_2O, 0.7% TiO_2, and 0.13% P_2O_5). A distinctive feature of the Gorely volcanic center is the pervasive occurrence of K-rich compositions throughout the whole compositional range (silicity) of the melts. Melt inclusions of various types were sometimes found not only in a single sample but also in the same phenocrysts. The sodic and potassic types of the melts contain different Cl and F concentrations: the sodic melts are richer in Cl, whereas the potassic melts are enriched in F. We are the first to discover potassic melts with very high F concentrations (up to 2.7 wt %, 1.19 wt % on average, 17 analyses) in the Kuriles and Kamchatka. The average F concentration in the sodic melts is 0.16 wt % (37 analyses). The melts are distinguished for their richness in various groups of trace elements: LILE, REE (particularly HREE), and HFSE (except Nb). All of the melts share certain geochemical features. The concentrations of elements systematically increase from the mafic to acid melts (except only for the Sr and Eu concentrations, because of active plagioclase fractionation, and Ti, an element contained in ore minerals). The paper presents a review of literature data on volcanic rocks in the Kurile–Kamchatka area in which melt inclusions with high K_2O concentrations ($K_2O/Na_2O > 1$) were found. K-rich melts are proved to be extremely widespread in the area and were found on such volcanoes as Avachinskii, Bezymyannyi, Bol'shoi Semyachek, Dikii Greben', Karymskii, Kekuknaiskii, Kudryavyi, and Shiveluch and in the Valaginskii and Tumrok Ranges.

Keywords: Kamchatka, Gorely volcano, melt inclusions, volatile components, trace elements.

DOI: 10.1134/S0016702912060079

INTRODUCTION

Gorely volcano is a large long-lived volcanic center in southern Kamchatka, whose eruptive activity continues until nowadays. The complicated structure of this volcano comprises two edifices: an ancient and modern ones. The ancient edifice, which is also referred to as Pra-Gorely, is shield-shaped with a caldera 13 × 12 km at its center. The modern edifice or Young Gorely occupies the central part of the caldera and consists of three merged cones. The central cone raises for 1829 m, its summit carries eleven mutually overlapping craters, and about forty more craters and side fissures with lava flows occur on the slopes. The geological evolution of the Gorely volcanic center is currently seen as follows [1–3].

Precaldera development. The ancient volcano Pra-Gorely started to develop in the Miocene as an extensive multivent extrusion–lava complex over an area of 12 × 15 km. The eruption products of this complex span a broad range of compositions from dacite and rhyolite

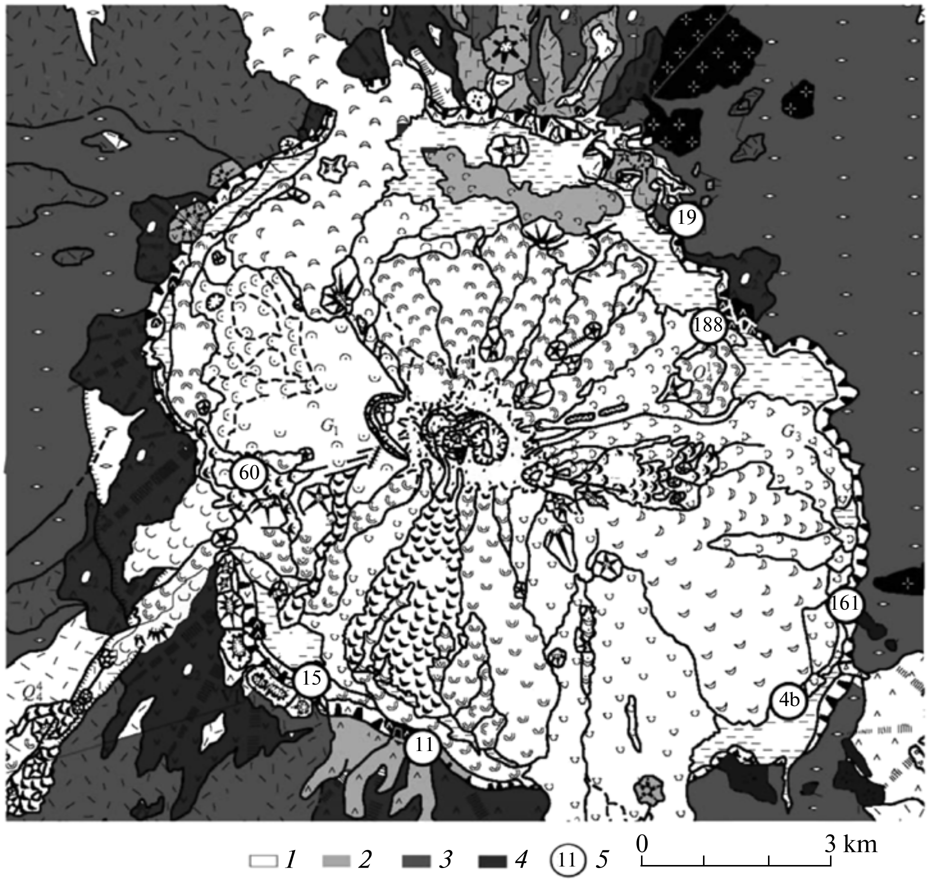

Fig. 1. Schematic geomorphological map of Gorely volcano [2].
(*1*) Modern (late Pleistocene–late Holocene) rocks; (*2*) rocks of the early postcaldera stage (late Pleistocene); (*3*) rocks of the caldera development stage (late Pleistocene); (*4*) rocks of the precaldera stage (late Miocene–mid-Pleistocene); (*5*) sampling sites.

extrusions and dikes to andesites and dacites of the main edifice and the basaltic andesites of adventive cones (Fig. 1).

Caldera development. A number of grandiose eruptions of intermediate–acid magma that have formed the multilayer pumice tuff and ignimbrite blanket emptied the chamber and triggered the collapse of its roof and thus the origin of the caldera. The origin of the latter is dated at approximately 38–40 ka based on relations between the so-called Gorely ignimbrite with analogous and roughly coeval rocks in the caldera of Opala volcano west of it. The caldera of Gorely volcano is a typical collapse structure of the Krakatau type and is bounded by steep arc normal faults.

Early postcaldera development. The next evolutionary stage of Gorely was marked by volcanic activity at several vents at the caldera crest and outer flanks. The early postcaldera complex comprises numerous volcanic apparatuses: basalt–andesite cinder cones, dacite extrusions, and necks.

Modern Gorely volcano. The initial activity of Gorely volcano began under a glacier during glaciation. This likely explains the fairly unusual shapes of the two early cones: western (Gorely 1) and central (Gorely 2), whose slopes are steep up to heights of 80–100 m above the bottoms and are partly covered by younger lavas. *Gorely 1* volcano is made up of basalt and andesite, and its edifice is approximately 14 km^3 in volume. Its activity ended with a significant pyroclastic eruption, which covered its slopes with a bumpy blanket of andesite agglomerate–agglutinate material of bombs and rock blocks. This eruption was likely responsible for the origin of a large (0.7 × 1.4 km) oval crater at the very top of the cone. The neck of *Gorely 2 volcano* started to develop near the low eastern part of the crater of Gorely 1 in the earliest Holocene. The activity center of this edifice shifted in a reciprocative manner with time and left a track of numerous excentrical and side fissures. *Gorely 2 volcano* remains active until now, and its products range from basalt to andesite, with the strong predominance of intermediate basaltic andesite varieties. The onset of the development of Gorely 2 volcano was associated with a change in the petrographic and genetic types of its rocks, likely in response to changes in the structure and mechanisms forming its plumbing

Table 1. Chemical composition (wt %) of the examined rocks from the Gorely volcanic center

Component	Sample no.						
	Gor-161	Gor-46	Gor-188	Gor-15	Gor-60	Gor-11	Gor-19
SiO_2	51.27	53.51	53.81	55.65	57.17	64.83	66.48
TiO_2	1.14	1.15	1.11	1.21	1.38	0.84	0.95
Al_2O_3	16.49	16.51	16.90	16.28	15.71	15.69	15.26
FeO	10.04	9.57	9.58	9.39	9.13	4.92	4.37
MnO	0.17	0.17	0.17	0.17	0.17	0.12	0.14
MgO	7.29	5.92	5.05	4.38	2.88	1.55	1.11
CaO	9.29	8.02	8.19	7.19	6.18	3.50	2.55
Na_2O	2.94	3.29	3.14	3.49	3.69	4.81	5.09
K_2O	1.06	1.59	1.36	2.05	2.62	2.95	3.09
P_2O_5	0.32	0.40	0.39	0.42	0.54	0.27	0.19
Total	100.01	100.13	99.70	100.23	99.47	99.48	99.23

system. Gorely 3 volcano started to grow at the southeastern flank of Gorely 2. This is the lowest (1698 m) and the overall smallest (approximately 2 km^3) cone of the edifice, which is made up of pyroclastic material and andesite–basalt lavas.

Side fissures and the rift zone of Gorely volcano. The Gorely center showed a complicated volcanic activity, with a combination of central and fissure eruptions. The feeding structure of the volcano likely consists of a pipe-shaped conduit with a number of swells (chambers) and an array of subcircular fissures, which fed adventive volcanic apparatuses. The fissure zone started to develop in pre-Holocene time, and its role as a feeder became more significant with time, so that the two latest episodes of basaltic andesite eruptions were controlled by this zone alone.

Although various aspects of Gorely volcano were discussed in a great number of publications [1–9 and others], melt inclusion in its minerals are studied still inadequately poorly [4, 5]. Our studies were aimed on bridging this gap by obtaining representative information on the major-component and trace-element composition of the melts that produced various rocks of this volcano and on concentrations of volatiles in these melts. The main technique applied in solving these problems was studying melt inclusions in phenocryst minerals.

ROCKS AND MINERALS OF GORELY VOLCANO

We examined rock samples represent various activity stages of the volcano. *Precaldera evolution*: magnesian basalts of the side fissure (sample Gor-161). *Caldera development*: ignimbrite (sample Gor-19). *Early post-caldera evolution*: dacite (sample Gor-11). *Modern Gorely volcano*: basaltic andesite of early and late Holocene age (sample Gor-60). Analyses of the rocks are given in Table 1. Along with their SiO_2 concentrations (51–66 wt %), the rocks also differ from one another in alkalinity: the basalt and basaltic andesite plot within the field of rocks of normal alkalinity, and the andesite, dacite, and ignimbrite are subalkaline rocks (Fig. 2). The MgO concentrations also broadly vary (from 1.1 to 7.3%), as also are the CaO concentrations (2.6–9.3%), with the minimum concentrations of these components detected in the ignimbrite. The Fe, Mg, and Ca concentrations of the rocks generally systematically decrease, and the concentrations of alkalis increase, from mafic to acid rocks.

Our rock samples differ in both bulk chemical and mineralogical composition and also in their textures. Sample Gor-161 is massive olivine basalt with an insignificant amount of plagioclase and pyroxene phenocrysts. All of the phenocrysts are of roughly equal size and are submerged in a pilotaxitic groundmass. The basaltic andesite (samples Gor-46, Gor 188, and Gor-15) contains plagioclase, pyroxene, and olivine phenocrysts, and the groundmass of the rocks has a pilotaxitic or microlitic texture. The andesite (sample Gor-60) is a porous predominantly plagioclase rock with subordinate amounts of clinopyroxene and orthopyroxene phenocrysts and olivine relics in a vitreous groundmass. The ignimbrite (sample Gor-19) is a black–red banded rocks with rare plagioclase and pyroxene phenocrysts in a vitreous groundmass. The dacite (sample Gor-11) is richer in phenocrysts of the same composition, the rock is porous, and its groundmass is vitreous.

The compositional ranges of minerals in rocks from the volcano are fairly wide. *Olivine.* The most magnesian varieties (Fo_{85}) were found in the basalts and in the cores of olivine phenocrysts from the basaltic andesites. The marginal zones of the phenocrysts and microlites in the basalts, basaltic andesites, and andesites consist of $Fo_{70–60}$. The most ferrous olivine (Fo_{46}) composes microlites in the andesite (Table 2). *Plagioclase* composi-

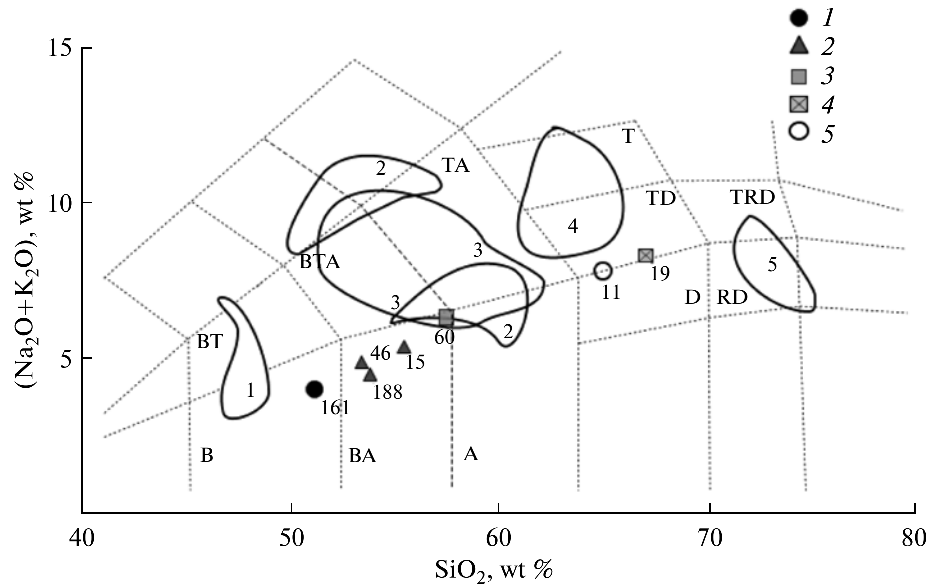

Fig. 2. TAS diagram [10] for rocks and melts at the Gorely volcanic center.
(*1*) Basalt (sample Gor-16); (*2*) basaltic andesite (samples Gor-46, Gor-188, and Gor-15); (*3*) andesite (sample Gor-60); (*5*) dacite (sample Gor-11). Fields correspond to the compositions of melt inclusions in these samples. Rock symbols: B—basalt, BA—basaltic andesite, A—andesite, D—dacite, RD—rhyodacite, BT—basaltic trachyte, BTA—basaltic trachyandesite, TA—trachyandesite, TD—trachydacite, TRD—trachyrhyodacite, T—trachyte.

tions define a continuous series (practically without compositional gaps) from the most calcic varieties (An_{87}) in the basalt to the most sodic ones (An_{35}) in the ignimbrites; the most common compositions are An_{40-55} (Table 3). *Pyroxenes.* Pyroxenes are contained in the rocks as large and small phenocrysts, microlites, and overgrowth rims on olivine. The Mg mole fraction of orthopyroxene in the rocks of various types fluctuates insignificantly around En_{70}, whereas the composition of the clinopyroxene varies much more significantly (En_{43-52}, Wo_{21-40}), with the least calcic clinopyroxene found in the form of microlites in the andesite (Table 4). *Ore minerals* of phenocrysts and microlites are mostly titanomagnetite (Table 5); another ore mineral is Cr-spinel, which occurs as inclusions in magnesian olivine phenocrysts.

MELT INCLUSIONS

Melt inclusions were examined in doubly polished thin sections 0.3 mm thick. The sections were preparatorily examined under an optical microscope to handpick phenocrysts with melt inclusions. Melt inclusions in olivine and plagioclase from various rocks of Gorely volcano contain microcrystalline daughter phases, a gas phase, and residual glass. The inclusions were partly homogenized in a muffle heater [11], with olivine grains heated with the application of graphite rods to preclude oxidation [12]. Olivine grains were heated to a temper-

Table 2. Representative analyses (wt %) of olivine (phenocrysts and microlites) in rocks from the Gorely volcanic center

Component	Sample no.							
	Gor-161	Gor-161	Gor-161*	Gor-46	Gor-46	Gor-46	Gor-60	Gor-60*
SiO_2	40.67	38.39	37.24	39.07	36.21	37.44	37.53	34.58
MgO	44.21	34.70	29.92	44.95	30.35	36.37	34.14	20.32
FeO	13.94	25.84	31.22	16.07	32.50	25.63	27.72	43.12
TiO_2	0.03	0.00	0.03	0.01	0.02	0.02	0.02	0.15
Al_2O_3	0.09	0.02	0.05	0.06	0.06	0.03	0.03	0.25
MnO	0.20	0.50	0.62	0.27	0.58	0.51	0.53	0.76
CaO	0.23	0.26	0.28	0.19	0.29	0.24	0.23	0.42
Total	99.37	99.70	99.36	100.62	100.01	100.24	100.20	99.60
Fo	85	71	63	83	62	72	69	46

Note: asterisks mark microlites, others are phenocrysts.

Table 3. Representative analyses (wt %) of plagioclase in rocks from the Gorely volcanic center

Component	Sample no.								
	161	161	161	161*	161*	60	60	60	60*
SiO_2	45.98	46.59	46.70	50.43	54.34	48.49	52.30	54.05	55.90
TiO_2	0.03	0.03	0.04	0.03	0.07	0.03	0.09	0.06	0.12
Al_2O_3	33.35	33.19	32.53	30.37	28.06	32.07	29.83	28.53	27.04
FeO	0.52	0.49	0.26	0.81	0.71	0.77	0.93	0.72	1.10
MnO	0.01	0.02	0.01	0.04	0.00	0.00	0.02	0.00	0.03
MgO	0.09	0.15	0.15	0.09	0.15	0.09	0.12	0.13	0.20
CaO	17.58	17.06	16.86	14.10	11.24	15.48	13.15	11.74	10.15
Na_2O	1.43	1.79	1.85	3.35	4.93	2.59	3.96	4.83	5.57
K_2O	0.05	0.05	0.04	0.20	0.34	0.15	0.26	0.41	0.55
Total	99.04	99.37	98.44	99.42	99.83	99.67	100.66	100.45	100.68
An	87	84	83	69	55	76	64	56	49
Ab	13	16	17	30	43	23	35	42	48
Or	0	0	0	1	2	1	1	2	3
Component	Sample no.								
	60	46	46*	46	46	19	19	15	11
SiO_2	57.75	53.16	53.53	54.30	55.35	56.64	57.77	54.45	57.32
TiO_2	0.10	0.07	0.10	0.05	0.12	0.05	0.04	0.10	0.07
Al_2O_3	26.20	28.53	28.25	27.85	27.30	26.60	25.58	27.37	25.70
FeO	0.92	0.80	1.08	0.81	1.22	0.57	0.46	0.73	0.52
MnO	0.01	0.05	0.00	0.03	0.03	0.03	0.02	0.01	0.00
MgO	0.15	0.15	0.17	0.15	0.14	0.04	0.06	0.11	0.06
CaO	8.70	11.50	11.69	11.09	10.24	8.91	7.82	10.78	8.72
Na_2O	6.34	4.63	4.59	4.87	5.69	6.19	6.60	5.22	6.12
K_2O	0.74	0.39	0.41	0.46	0.55	0.49	0.51	0.56	0.44
Total	100.91	99.28	99.82	99.61	100.64	99.52	98.86	99.33	98.95
An	41	57	57	54	48	43	38	52	43
Ab	55	41	41	43	49	54	59	45	55
Or	4	2	2	3	3	3	3	3	3

Note: asterisks mark microlites, others are phenocrysts.

ature of 1200–1220°C and held for 10–20 min. Plagioclase grains from more acid rocks were heated to 1140 (dacite) and 1180°C (basaltic andesite and andesite) and held for 2–5 h. After being held at a certain temperature during a specified time, the phenocrysts were quenched.

Our thermal experiments yielded inclusions (colorless glass in intermediate–acid rocks and brown glass in basalts) suitable for examination under an electron microscope and analyzing on an ion microprobe. A number of microprobe profiles (with analytical spots spaced 1 μm apart) across inclusions thus prepared indicate the absence of host-mineral rims on inclusion walls.

Silicate glass in daughter phases in the inclusions was analyzed on a Cameca SX-100 electron microprobe at an accelerating voltage of 15 kV, 30 nA current, and rastering over areas of 12 × 12 and 5 × 5 μm for glasses and 2 × 2 μm for crystalline phases; elements were analyzed accurate to 2% at concentrations of >10 wt %, 5% at concentrations of 5–10 wt %, and 10% at concentrations of <5 wt %. The composition of the glasses (including their Na_2O concentrations) are not correlated with the size f the inclusions. The inclusions were analyzed for F using a TAP (2d = 25.745 A) analyzer crystal and the FK_α line in integral mode, because the analytical line of F is not superposed by any line of other elements identified in the analysis. The standard reference sample was MgF_2 as the most stable and composi-

Table 4. Representative analyses (wt %) of pyroxene (phenocrysts and microlites) in rocks from the Gorely volcanic center

Component	Sample no.								
	161	161	46	60	46	60	60*	19*	19
SiO_2	51.7	37.55	53.04	53.17	49.06	51.27	49.47	53.84	50.96
TiO_2	0.58	0.02	0.31	0.34	1.35	0.78	1.29	0.30	0.70
Al_2O_3	2.02	0.03	1.00	1.07	3.25	2.28	3.76	0.67	1.77
FeO	9.02	25.71	15.91	17.92	10.34	11.01	16.08	15.64	9.43
MnO	0.31	0.51	0.45	0.53	0.31	0.41	0.52	1.35	0.96
MgO	15.81	33.46	25.7	24.42	14.22	15.45	17.82	25.74	14.79
CaO	18.76	0.23	1.92	2.02	18.37	18.45	9.95	1.54	18.29
Na_2O	0.33	0.00	0.02	0.03	0.35	0.34	0.24	0.02	0.45
K_2O	0.01	0.01	0.02	0.01	0.01	0.02	0.05	0.02	0.01
P_2O_5	0.00	0.01	0.19	0.16	0.01	0.19	0.32	0.01	0.00
Total	98.54	97.53	98.56	99.67	97.27	100.16	99.5	99.13	97.36
Fs	15	30	25	28	17	18	27	25	16
En	46	70	71	68	43	44	52	72	45
Wo	39	0	4	4	40	38	21	3	40

Note: asterisks mark microlites, others are phenocrysts.

Table 5. Representative analyses (wt %) of ore minerals in various rocks from the Gorely volcanic center

Component	Sample no.								
	Gor-161	Gor-161	Gor-161	Gor-46	Gor-46	Gor-60	Gor-19	Gor-19	Gor-11
SiO_2	0.09	0.11	0.11	0.36	0.22	0.22	0.04	0.19	0.19
FeO	35.39	33.83	61.20	64.85	69.43	71.65	45.23	71.46	74.74
TiO_2	1.40	1.07	14.23	18.29	17.46	12.27	45.23	13.12	11.91
Al_2O_3	24.97	26.77	2.89	2.46	2.29	3.84	0.09	1.52	1.53
Cr_2O_3	26.13	26.18	6.42	0.94	0.47	1.07	0.04	0.33	0.10
MnO	0.32	0.29	0.48	0.45	0.50	0.39	1.21	1.16	0.72
MgO	11.24	11.43	2.48	2.50	2.00	3.30	1.82	0.98	1.62
CaO	–	–	0.03	0.18	0.32	0.14	0.01	0.05	–
Total	99.54	99.68	87.84	90.03	92.69	92.88	93.67	88.81	90.81

tionally suitable. The detection limit was 0.1 wt %, and the mean square deviation within the concentration range in question did not exceed 10%.

Melt inclusions larger than 25 μm were analyzed for H_2O, F, and trace elements by SIMS on an IMS-4f probe at the Yaroslavl Branch of the Physical Technical Institute. These analytical techniques were described in detail in [13–15].

Chemical Composition of Inclusions

Major components. Melt inclusions from Gorely volcano exhibit a fairly broad range of silica concentrations, from 45 to 74 wt % (Tables 6–8, Figs. 2, 3), and broad ranges of the concentrations of other major components: 0.3–3.3% TiO_2, 0.2–9.2% MgO, 0.9–12.8% CaO, 1.7–15.7% FeO, 0.6–6.1% Na_2O, and 0.6–8.2% K_2O (Tables 6–8). Positive and negative correlations between the concentrations of these components and SiO_2 are shown in Fig. 3. In describing these diverse melts, it is convenient to subdivide them into mafic, intermediate, and acid according to currently universally adopted classifications.

Basaltic melts. Melt inclusions of mafic composition (45–53 wt % SiO_2) were found in olivine from basalt and in plagioclase from basaltic andesite and andesite, but these melts have principally different compositions. Olivine from sample Gor-161 (Table 6) contains melts corresponding to typical magnesian basalt (in wt %) 45–49% SiO_2, 6.4–9.2% MgO, 7.6–12.8% CaO, and

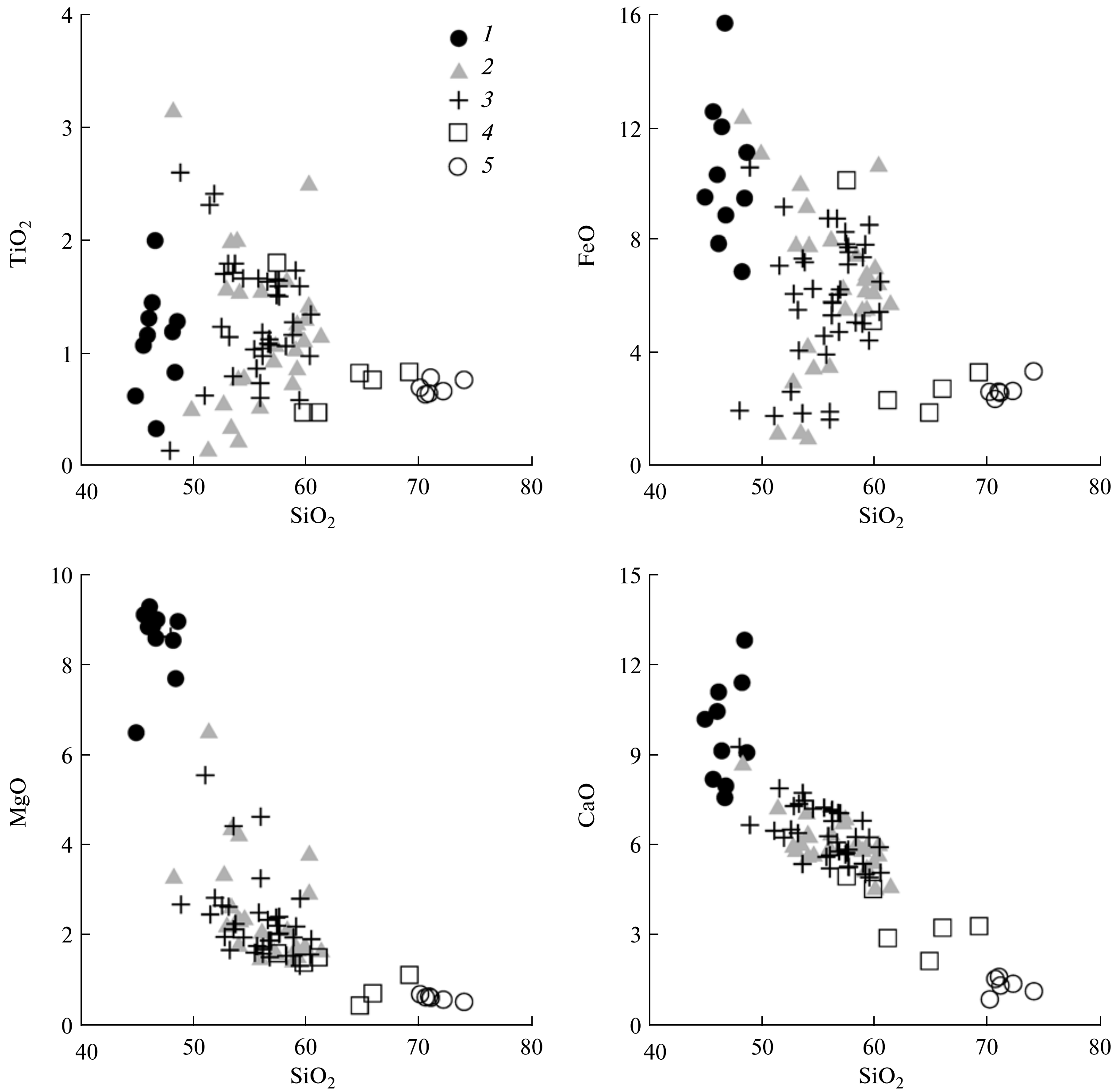

Fig. 3. Variation diagrams for major oxides in melt inclusions in minerals from various rocks of the Gorely volcanic center. (*1*) Basalt; (*2*) basaltic andesite; (*3*) andesite; (*4*) ignimbrite; (*5*) dacite.

6.9–15.7% FeO. The TiO_2 and Al_2O_3 concentrations are relatively low. These magnesian basalts can be classified into two groups based on their alkali concentrations. The melts *of the potassic group* with $K_2O > Na_2O$ (six inclusions, Table 6) contain 2.4–5.6% K_2O and 0.6–1.1% Na_2O. The melts of *the sodic group* (four inclusions, Table 6) contain 2.9–3.5% Na_2O and 0.6–2.1% K_2O. The SiO_2, TiO_2, Al_2O_3, and MgO concentrations of these two melt types are closely similar, whereas the FeO and CaO concentrations differ: 11.7 versus 8.7 and 8.7 versus 11.4%, respectively. The differences are mirrored by the concentrations of volatiles (Cl and S): their concentrations are at a minimum in the potassic melts (0.00% Cl and 0.02% S on average) and are remarkably higher in the sodic melts (0.05% Cl and 0.06% S on average).

Basaltic *high-Ti* melt in inclusions in plagioclase from basaltic andesite (sample Gor-46) and andesite (sample Gor-60) has a fairly unusual composition (Table 6): bearing 48–52 wt % SiO_2, it contains relatively little MgO (2.6–3.3%) but much TiO_2 (up to 3.2%), FeO (up to 12.5%), and P_2O_5 (up to 2.3%).

The melts of intermediate composition (53–63 wt % SiO_2) can also be subdivided into two groups according

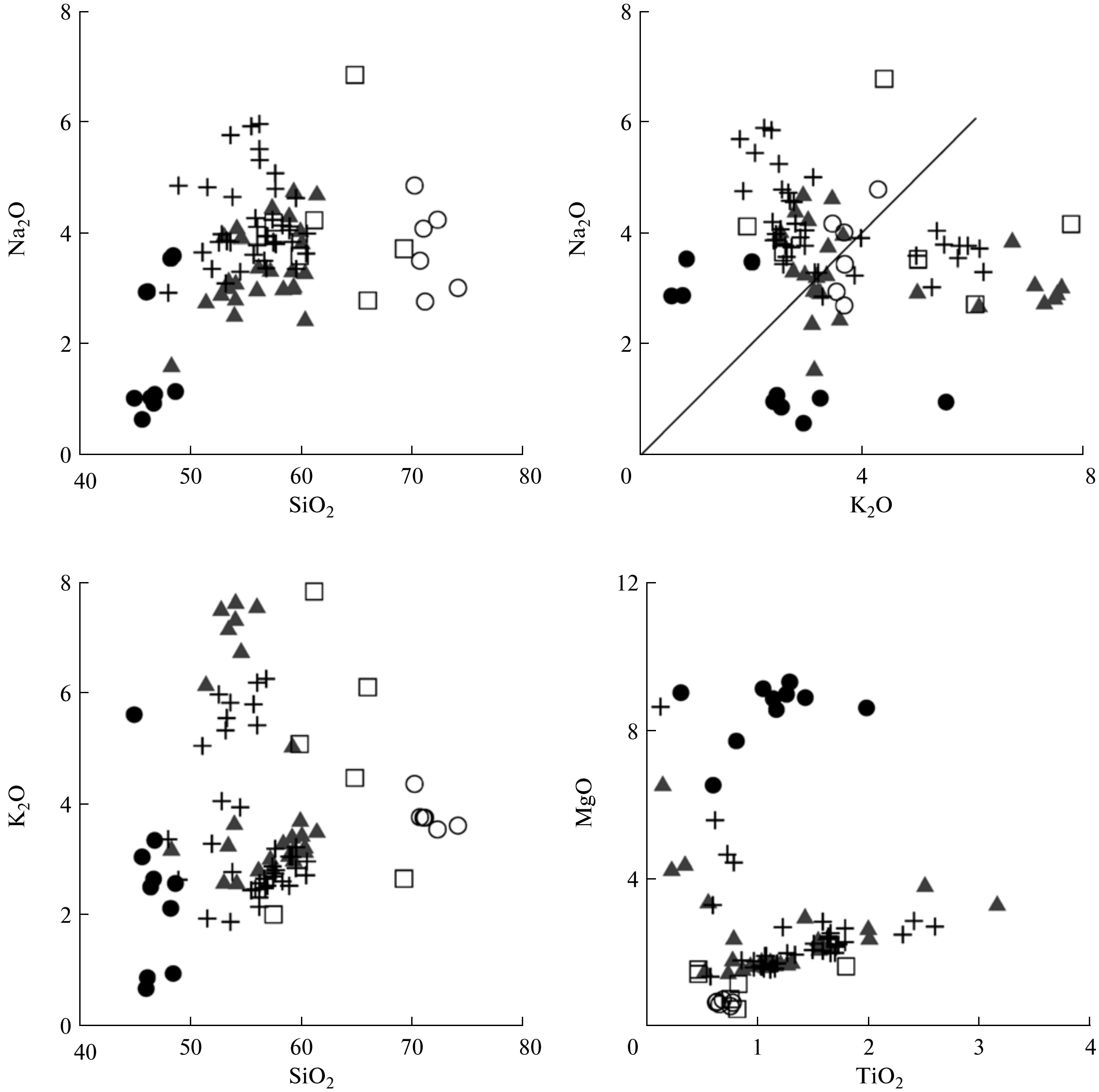

Fig. 3. Contd.

to the concentrations of alkalis. *Potassic melts of intermediate composition* were detected in plagioclase from basaltic andesite Gor-188), andesite (Gor-60), and ignimbrite (Gor-19). The melts are characterized not only by high K_2O concentrations (up to 8.2%) but also by high of Al_2O_3 concentrations (16–23%) and low TiO_2 and FeO concentrations (0.9 and 1.7–5.2%, respectively). The CaO and Na_2O concentrations are as in normal andesite melts, and this rules out the effect of the host plagioclase on the microprobe analysis. Another distinctive feature of the melts of intermediate composition is their high F concentrations (up to 2.7 wt %, Tables 7, 8).

Sodic (basaltic andesite and andesite) melts of intermediate composition were found in plagioclase from basaltic andesite (samples Gor-46, Gor-188, and Gor-15), andesite (Gor-60), and ignimbrite (Gor-19) of various age from Gorely volcano. In spite of the significant ranges of the concentrations of major components in these melts, they define a single field in variation diagrams (Fig. 3) which is hard to differentiate: SiO_2 53–61 wt %, TiO_2 1.3–2.5%, FeO 6.3–10.1%, MgO 1.6–2.9%, Al_2O_3 11–16%, K_2O 2.5–5.0%.

Acid melts (64–74 wt % SiO_2) were detected in inclusions (Table 6) in plagioclase from the ignimbrite (sample Gor-19) and dacite (sample Gor-11). This

Table 6. Chemical composition (wt %) of glasses in melt inclusions in olivine and plagioclase from rocks of Gorely volcano

Inclusion no.	Component												Total	*Ol*, *An**
	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cl	S		
Sample Gor-161														
1	44.93	0.60	17.02	9.54	0.17	6.44	10.18	0.96	5.55	0.09	0.02	0.05	95.55	*Fo* 83
2	45.64	1.05	14.83	12.58	0.22	9.06	8.18	0.58	2.98	0.30	0.00	0.00	95.42	*Fo* 84
3	46.00	1.14	16.30	10.34	0.11	8.79	10.44	2.88	0.60	0.74	0.00	0.05	97.39	*Fo* 84
4	46.12	1.29	17.80	7.90	0.17	9.24	11.09	2.89	0.80	0.35	0.05	0.08	97.78	*Fo* 82
5	46.41	1.43	16.92	12.04	0.19	8.82	9.13	0.97	2.44	0.14	0.00	0.01	98.50	*Fo* 84
6	46.68	1.98	14.67	15.73	0.25	8.54	7.57	0.87	2.58	0.10	0.00	0.01	98.98	*Fo* 84
7	46.77	0.31	20.76	8.90	0.17	8.95	7.96	1.03	3.28	0.12	0.00	0.00	98.25	*Fo* 84
8	48.21	1.17	18.22	6.91	0.10	8.49	11.40	3.49	2.05	0.19	0.04	0.06	100.33	*Fo* 83
9	48.43	0.81	14.16	9.50	0.14	7.64	12.82	3.54	0.87	0.33	0.11	0.06	98.41	*Fo* 83
10	48.63	1.26	16.60	11.13	0.23	8.91	9.07	1.08	2.50	0.05	0.00	0.02	99.48	*Fo* 84
Sample Gor-46														
11	48.21	3.15	14.59	12.45	0.29	3.28	8.76	3.16	1.59	2.31	0.07	0.05	97.91	54**
12	52.93	1.57	15.42	7.93	0.18	2.20	5.88	3.93	2.56	–	0.03	0.01	92.64	59
13	53.87	2.00	15.66	9.28	0.19	2.36	7.13	3.62	2.50	1.13	0.04	0.04	97.82	54
14	54.09	1.54	16.29	7.91	0.17	2.31	6.35	4.07	2.55	–	0.08	0.00	95.36	59
15	56.04	1.55	15.84	8.11	0.17	2.06	6.43	3.37	2.78	–	0.13	0.02	96.50	58
16	58.28	1.64	15.91	7.57	0.16	2.11	6.11	2.98	3.27	0.51	0.10	0.02	98.66	56
17	59.06	1.03	15.99	6.71	0.17	1.73	5.20	3.30	3.38	–	0.07	0.00	96.64	58
18	59.10	1.20	16.62	6.30	0.14	1.67	5.97	5.02	2.99	0.44	0.05	0.05	99.55	59
19	59.79	1.11	15.65	6.24	0.11	1.72	5.48	4.02	3.68	0.33	0.10	0.03	98.26	56
20	60.22	1.42	13.50	6.55	0.20	2.93	5.73	3.27	3.20	0.36	0.06	0.02	97.46	56
21	60.62	1.16	16.25	6.84	0.10	1.70	5.15	3.35	3.22	–	0.08	0.03	98.50	58
Sample Gor-188														
22	53.32	1.99	14.76	10.07	0.21	2.62	6.13	3.00	3.23	0.00	0.03	0.02	95.38	57
23	57.36	1.98	15.85	7.22	0.17	2.19	6.41	3.39	2.80	0.00	0.05	0.04	97.46	57
24	60.24	2.50	10.19	10.75	0.21	3.79	6.08	2.42	3.12	0.00	0.10	0.05	99.45	57
Sample Gor-15														
25	59.74	0.99	16.59	5.18	0.10	1.35	4.55	5.03	3.55	0.49	0.07	0.07	97.71	52
26	59.19	1.26	15.91	6.90	0.10	1.66	5.29	4.74	2.96	–	0.06	0.03	98.10	55

Table 6. (Contd.)

Inclusion no.	Component												Total	*Ol*, *An**
	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cl	S		
27	59.94	1.30	14.73	7.12	0.11	1.71	4.61	3.81	3.41	–	0.07	0.10	96.94	51
28	61.30	1.15	14.90	5.85	0.10	1.64	4.67	4.68	3.48	–	0.06	0.01	97.84	54
Sample Gor-60														
29	48.83	2.59	14.96	10.62	0.19	2.64	6.68	4.81	2.58	1.39	0.10	0.02	95.41	60
30	51.85	2.40	14.26	9.22	0.20	2.79	6.26	3.31	3.23	1.03	0.12	0.05	94.72	60
31	55.60	0.85	18.35	3.98	0.04	1.72	5.62	3.57	5.75	0.37	0.02	0.02	95.89	60
32	55.76	1.65	15.35	8.81	0.14	2.46	6.31	4.22	2.41	-	0.10	0.00	97.21	66
33	55.92	0.72	20.92	1.95	0.04	4.59	5.67	4.06	5.37	0.43	0.01	0.02	97.70	60
34	56.55	1.62	14.99	8.80	0.19	2.30	6.10	3.46	2.60	–	0.08	0.02	96.71	59
35	57.30	1.64	14.96	8.33	0.17	2.35	5.70	4.19	2.82	–	0.09	0.01	97.56	66
36	57.37	1.50	15.38	7.91	0.16	2.17	5.76	3.79	2.64	–	0.09	0.00	96.77	58
37	57.55	1.63	15.17	7.80	0.16	2.37	5.86	4.75	2.69	–	0.11	0.03	98.12	57
38	57.54	1.58	15.84	7.19	0.19	1.98	5.29	5.03	3.14	0.65	0.09	0.00	98.52	64
39	57.59	1.49	14.01	7.63	0.16	2.00	5.28	3.76	2.75	–	0.08	0.00	94.75	59
40	57.63	1.85	15.65	8.07	0.21	2.33	5.40	3.93	3.06	0.85	0.09	0.04	99.11	57
41	58.84	1.26	15.22	7.45	0.14	1.91	5.39	4.07	3.00	–	0.08	0.01	97.37	59
42	59.06	1.72	13.43	7.89	0.14	2.15	5.04	3.79	2.99	–	0.09	0.02	96.32	57
43	59.42	1.58	14.18	8.58	0.19	2.77	4.93	3.31	3.17	–	0.07	0.03	98.23	57
44	60.41	1.33	15.65	6.58	0.13	1.87	5.09	3.94	2.91	–	0.08	0.01	98.00	62
Sample Gor-19														
45	57.39	1.79	15.84	10.17	0.23	1.56	4.97	4.14	1.95	–	0.09	0.08	98.21	46
46	61.05	0.46	16.91	2.36	0.04	1.47	2.91	4.18	7.79	–	0.00	0.00	97.17	40
47	62.31	0.25	17.01	1.91	0.21	0.98	2.35	5.30	4.99	–	0.00	0.02	95.33	50
48	62.59	0.55	17.72	2.79	0.16	0.61	2.35	4.28	8.20	–	0.00	0.00	99.25	50
49	64.72	0.81	17.23	1.92	0.08	0.40	2.15	4.42	6.81	0.21	0.08	0.02	98.85	42
50	65.88	0.75	17.40	2.77	0.09	0.67	3.26	6.06	2.74	0.13	0.10	0.02	99.87	42
51	69.13	0.82	15.24	3.35	0.13	1.08	3.31	3.67	2.60	–	0.08	0.02	99.43	43
Sample Gor-11														
52	70.07	0.68	12.45	2.66	0.10	0.65	0.87	4.31	4.81	0.14	0.27	0.01	97.02	44
53	70.57	0.62	14.77	2.41	0.09	0.58	1.55	3.46	3.71	0.14	0.17	0.02	98.09	43
54	70.88	0.63	13.44	2.67	0.05	0.60	1.62	4.03	3.70	0.17	0.14	0.02	97.95	43
55	71.02	0.77	12.24	2.62	0.10	0.57	1.33	2.72	3.70	0.21	0.14	0.01	95.43	37
56	72.14	0.65	12.48	2.69	0.10	0.53	1.39	4.19	3.49	0.20	0.16	0.01	98.03	37
57	73.98	0.75	11.97	3.39	0.13	0.48	1.14	2.97	3.56	0.06	0.11	0.02	98.56	39

Notes: * —host mineral, *Ol*—olivine, *An*—plagioclase,
** anorthite concentrations in plagioclase.

Table 7. Chemical composition (wt %) of glasses in melt inclusions in a single plagioclase phenocryst from sample Gor-60

Inclusion no.	Component													Total	*An*
	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cl	S	F		
Melts with $K_2O/Na_2O > 1$															
*	47.93	0.12	23.33	1.99	0.10	8.59	9.28	2.88	3.31	0.17	0.00	0.00	1.16	98.86	–
1	50.99	0.61	21.66	1.80	0.02	5.51	6.49	3.61	5.00	0.27	0.01	0.01	1.58	97.56	54
2	52.47	1.22	20.88	2.66	0.07	2.62	6.53	3.79	5.93	0.57	0.04	0.03	1.67	98.48	56
3	53.08	1.78	18.68	5.57	0.08	2.59	6.41	3.05	5.28	0.70	0.07	0.02	0.96	98.27	56
4	53.18	1.13	19.14	4.13	0.13	1.63	7.39	3.81	5.50	0.42	0.04	0.00	1.18	97.68	52
5	53.50	0.78	20.40	1.89	0.03	4.38	5.38	3.79	5.78	0.40	0.02	0.01	1.81	98.17	54
6	53.58	1.68	18.33	6.10	0.14	1.91	5.47	3.35	5.10	0.59	0.03	0.02	–	96.30	51
7	54.40	1.65	18.31	6.32	0.14	1.91	7.22	3.26	3.89	0.54	0.09	0.00	0.46	98.19	56
8	55.56	0.92	18.37	5.31	0.10	1.82	5.76	3.98	4.59	0.31	0.02	0.01	–	96.75	51
9	55.91	0.59	20.89	1.67	0.00	3.22	5.23	3.74	6.14	0.34	0.00	0.00	2.70	99.99	60
10	56.73	1.11	18.96	4.79	0.09	1.47	5.80	3.32	6.21	0.39	0.01	0.00	0.88	99.76	52
11	57.04	0.91	18.88	4.26	0.06	1.33	5.77	3.72	4.71	0.23	0.07	0.00	–	96.98	51
Melts with $K_2O/Na_2O < 1$															
12	51.44	2.30	17.08	7.15	0.20	2.42	7.90	4.78	1.88	0.94	0.08	0.03	0.17	96.37	56
13	51.96	2.02	18.11	6.67	0.15	2.22	7.15	5.23	1.77	0.90	0.08	0.01	–	96.27	51
14	53.51	1.70	19.97	7.40	0.19	2.09	7.75	5.72	1.82	0.73	0.07	0.02	0.13	101.10	54
15	53.69	1.78	18.90	7.27	0.14	2.21	7.49	4.60	2.72	0.70	0.07	0.02	0.37	99.96	54
16	55.24	1.02	19.28	4.65	0.15	1.57	7.26	5.88	2.39	0.48	0.07	0.00	0.30	98.29	54
17	56.10	1.03	21.16	5.38	0.05	1.55	7.13	5.92	2.26	0.60	0.07	0.01	0.00	101.26	56
18	56.11	1.17	20.60	5.86	0.08	1.64	7.19	5.47	2.09	0.67	0.05	0.02	0.12	101.07	56
19	56.14	0.96	20.23	5.82	0.17	1.70	6.81	5.27	2.52	0.63	0.07	0.01	0.35	100.68	52
20	56.36	0.97	19.41	4.76	0.07	1.56	6.31	5.23	2.48	0.42	0.06	0.00	–	97.63	51
21	56.49	1.50	17.92	6.11	0.14	1.87	5.96	4.46	2.36	0.62	0.07	0.03	–	97.53	51
22	56.64	1.07	18.68	6.12	0.09	1.84	7.08	3.89	2.43	0.43	0.04	0.02	0.20	98.53	52
23	56.81	0.91	18.98	5.07	0.12	1.70	6.24	5.04	2.58	0.46	0.04	0.05	–	98.00	51
24	56.83	1.06	18.71	6.30	0.11	1.84	7.07	3.90	2.47	0.35	0.07	0.01	0.28	99.00	56
25	57.07	0.94	19.20	4.94	0.09	1.55	6.26	4.67	2.26	0.22	0.06	0.01	–	97.27	51
26	57.25	0.99	18.99	4.84	0.12	1.43	6.04	4.44	2.54	0.36	0.04	0.00	–	97.04	51
27	57.91	0.81	19.32	4.76	0.10	1.40	6.07	4.20	2.28	0.28	0.05	0.00	–	97.18	51
28	58.20	1.05	19.18	5.13	0.10	1.50	6.28	4.09	2.55	0.41	0.05	0.03	0.33	98.90	54
29	58.80	1.15	19.03	5.09	0.09	1.50	6.82	4.00	2.47	0.59	0.05	0.02	0.15	99.76	54
30	58.84	1.21	17.97	4.85	0.16	1.61	5.22	4.03	2.97	0.24	0.06	0.03	0.60	97.79	52
31	59.39	0.57	20.16	4.48	0.08	1.28	6.27	4.58	2.79	0.21	0.04	0.01	0.39	100.25	52
32	60.31	0.96	19.99	5.50	0.06	1.53	5.94	3.59	2.66	0.52	0.05	0.00	0.00	101.11	52
Melts with $K_2O/Na_2O \sim 1$															
33	52.73	1.69	17.77	6.14	0.08	1.92	7.31	3.93	4.00	0.51	0.04	0.02	0.40	96.54	54

Note: analysis of the groundmass in contact with the phenocryst.

Table 8. Chemical composition (wt %) of glasses in melt inclusions in a single plagioclase phenocryst (*An* 61) from sample Gor -188

Inclusion no.	Component													Total
	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cl	S	F	
	Melts with $K_2O/Na_2O > 1$													
*	51.31	0.14	23.38	1.24	0.00	6.51	7.30	2.74	6.13	0.03	0.00	0.00	1.57	100.35
1	52.67	0.55	22.01	3.07	0.01	3.34	6.02	2.88	7.49	0.16	0.00	0.00	0.99	99.19
2	53.34	0.34	22.11	1.26	0.01	4.36	6.09	3.12	7.14	0.21	0.01	0.00	1.44	99.43
3	53.97	0.77	20.95	4.32	0.03	1.77	6.42	2.79	7.31	0.31	0.06	0.00	0.78	99.48
4	53.99	0.22	22.84	1.07	0.02	4.22	5.69	3.08	7.62	0.11	0.01	0.01	1.52	100.40
5	54.49	0.78	19.97	3.56	0.02	2.36	5.73	3.90	6.73	0.33	0.00	0.01	0.24	98.12
6	55.90	0.52	21.02	3.62	0.07	1.47	5.97	2.96	7.54	0.12	0.04	0.00	0.61	99.84
7	59.19	0.86	17.99	5.65	0.17	1.52	6.02	3.02	3.15	0.19	0.05	0.03	0.69	98.53
	Melts with $K_2O/Na_2O < 1$													
8	57.10	0.93	19.14	6.39	0.16	1.62	6.80	3.31	2.99	0.41	0.06	0.00	0.38	99.29
9	57.28	1.07	19.76	5.65	0.10	1.59	6.94	4.44	2.82	0.34	0.03	0.04	0.55	100.61
10	58.79	0.73	17.66	5.62	0.13	1.42	5.88	4.29	3.05	0.22	0.06	0.03	0.55	98.43

* analysis of the groundmass in contact with the phenocryst.

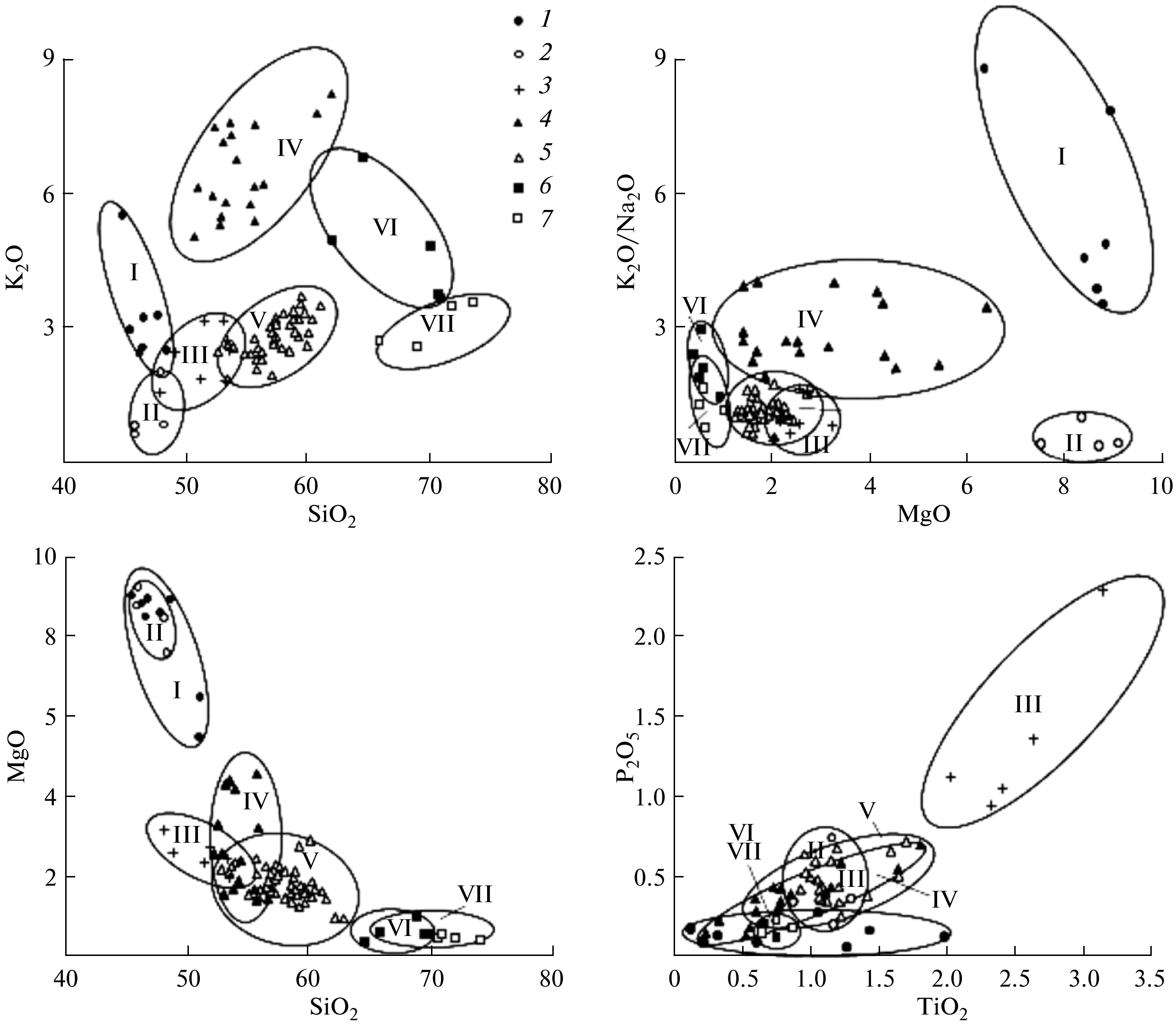

Fig. 4. Variation diagrams for melts of the Gorely volcanic center. Fields show the following melt types: (I) basic potassic melt; (II) basic sodic melt; (III) basic melt with high P and Ti concentrations; (IV) intermediate potassic melt; (V) intermediate sodic melt; (VI) acid potassic melt; (VII) acid sodic melt.

groups comprise K-rich (up to 6.8 wt % K_2O) and Na-rich (up to 6.1 wt % Na_2O) varieties. It is worth mentioning that the acid melts from ignimbrite in the aforementioned sample Gor-19 are slightly less silicic (65–69% SiO_2) and more aluminous (15.2–17.4% Al_2O_3) and calcic (2.2–3.3 wt % CaO). Inclusions in dacite in sample Gor-11 are more usual acid melts (70–74 wt % SiO_2) poor in Al_2O_3 (12.0–14.8%) and CaO (0.9–1.6%).

The diverse melts examined in our samples from the Gorely volcanic center can thus be classified into seven types with different concentrations of SiO_2, Na_2O, K_2O, TiO_2, and P_2O_5. Table 9 and Fig. 4 present their average compositions and data on the numbers of analyses.

It is pertinent to more closely examine analyses of melt inclusions in Tables 7 and 8 and in Figs. 5 and 6. In analyzing melt inclusions on an electron microscope during the same analytical session, we detected melts rich in K and Na in two plagioclase grains from two samples (Gor-60 and Gor-188) (Fig. 5). We failed to detect any correlation between the chemistries of the inclusions and their morphologies or settings in the host mineral grains. The further polishing of the platelets exposed other inclusions, but the situation with them was analogous.

We have analyzed 33 melt inclusions in sample Gor-60 and ten inclusions in sample Gor-188. First of all, it worth noting that these inclusions contain remarkably different SiO_2 concentrations. In sample Gor-60, K_2O-dominated melts contain 51.0–57.0 wt % SiO_2, and Na_2O-dominated melts bear 51.4–60.3 wt %

Table 9. Chemical composition (wt %) of various melt types from Gorely volcanic center

Component	Melt type						
	I	II	III	IV	V	VI	VII
SiO_2	49.25	47.19	51.66	56.22	57.80	70.07	69.51
TiO_2	1.00	1.10	**2.17**	1.00	1.26	0.73	0.71
Al_2O_3	18.37	16.62	16.28	18.58	17.22	13.73	14.64
FeO	8.61	8.66	8.34	4.60	6.46	2.60	2.87
MnO	0.14	0.13	0.17	0.09	0.14	0.10	0.09
MgO	6.91	8.54	**2.50**	2.36	1.83	0.54	0.72
CaO	7.90	11.44	7.05	5.63	5.93	1.41	2.40
Na_2O	1.75	**3.20**	3.98	3.44	**4.32**	3.58	**4.49**
K_2O	**4.19**	1.08	2.83	**5.53**	2.78	**4.52**	3.13
P_2O_5	0.20	0.40	**1.11**	0.35	0.44	0.15	0.13
Cl	0.01	0.05	0.07	0.04	0.07	0.15	0.12
S	0.02	0.06	0.03	0.01	0.02	0.02	0.02
Total	98.35	98.47	96.20	97.85	98.27	97.60	98.83
n	9	4	9	22	47	5	4

Note: (I–III) basaltic melts (I—K_2O-rich, II—Na_2O-rich, III—K_2O- and Na_2O-rich high in TiO_2 and P_2O_5 and low in MgO); (IV, V) andesitic melts (IV—K_2O-rich, V—Na_2O-rich), (VI, II) dacitic melts (VI—K_2O-rich, VII—Na_2O-rich); *n* is the number of analyzed melt inclusions.

SiO_2 (Table 7). The K_2O-dominated melts also show significant variations in their FeO concentrations: these vary from 1.7 to 6.3 wt % in sample Gor-60 and from 1.1 to 5.7 wt % in sample Gor-188 (Tables 7, 8). The most unexpected results were obtained on the F concentrations of the inclusions: these concentrations turned out to be much higher in the K_2O-rich melts than in the Na_2O-rich ones. The F concentrations in sample Gor-60 vary from 0.46 to 2.70 wt % at an average of 1.40 wt % for eight inclusions, whereas these values for the Na_2O-rich melts never exceed 0.60 wt % at an average of 0.24 wt % (14 melt inclusions). The F concentration in sample Gor-188 is also higher in K_2O-rich melts (0.90 wt % on average) than in the Na_2O-rich ones (0.49 wt % on average). It is pertinent to mention that, when analyzing F-rich melt inclusions in sample Gor-60 (inclusions 1, 2, 4, 5, and 16 in Table 7), we analyzed (in the course of the same analytical session) melt inclusions in quartz and plagioclase from volcanic rocks from Baia Mare, Romania. The latter inclusions either did not contain any F at all, or its concentrations were no higher than 0.12 wt %. In the course of the later analysis of two inclusions in the quartz on an ion probe, we determined F concentrations of 173 and 201 ppm in melt inclusions. These data testify that our analytical data obtained on the ion probe are accurate enough.

Trace elements. Tables 10 and 11 present our microprobe analyses of melt inclusions obtained after their analysis on an ion-probe. Melt inclusions from the Gorely volcanic center are generally distinguished for their elevated concentrations of trace elements, first of all, LILE and HFSE (except only for Nb, an element whose elevated concentrations occur in rocks in arc systems). The HREE concentrations are also fairly high. To test whether these concentrations do correspond to the melts of the inclusions, we have analyzed the host plagioclase for the same elements (Table 12). Certain features of the trace-element composition of the melts of these groups validate the recognition of these groups among melts of Gorely volcano. Unfortunately, no statistically reliably material on the trace-element composition of all melts of Gorely volcano is available so far, and this often led us to utilize single analyses of glasses of certain types.

Some LILE exhibit certain specifics in their distribution in the melt inclusions. For instance, these inclusions are relatively high in Li. The average **Li** concentrations in all of the basalt and acid melts are no higher than 40 ppm, while the Na_2O-rich andesite melts contain up to 220 ppm Li (at an average of 92 ppm). Appreciable differences are also detected between the **Rb** concentrations: their maximum values were found in the K_2O-rich andesite melts (>100 ppm), slightly lower contents of this element were detected in acid melts (75 ppm on average), the potassic basalt and sodic andesite melts contain 50 ppm, and the basalt melts carry approximately 20 ppm Rb.

The HFSE concentrations systematically increase from the mafic to acid melts by factors of three to four on average. The **Th and U** concentrations are anomalously low in the sodic basalt melts (0.50 ppm

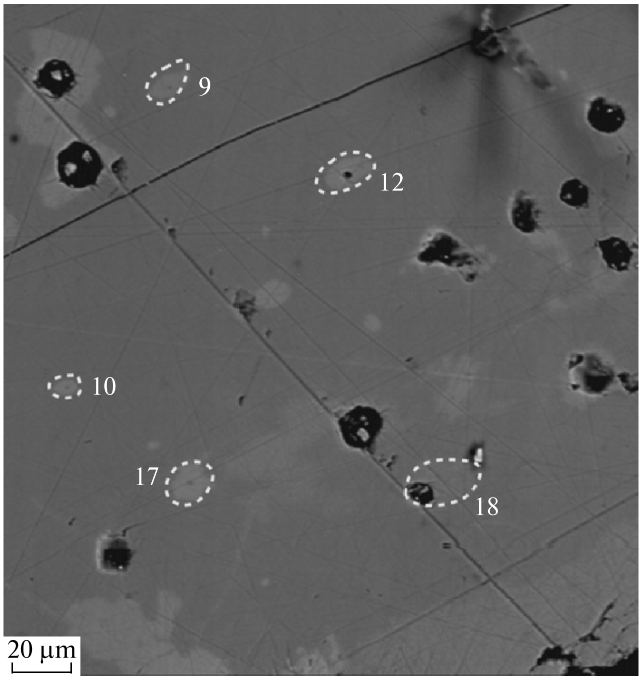

Fig. 5. Fragment of the surface of a plagioclase phenocryst with analytical spots at melt inclusions with various K_2O and P_2O_5 concentrations (melt inclusions 9, 10, 12, 17, and 18 in Table 7).

Th and 0.23 ppm U), which makes them similar to E-MORB of normal composition. The other melt types contain higher concentrations of these elements: 1.33–6.63 ppm Th and 0.59–3.11 ppm U.

An unusual behavior was detected for **B**. The average B concentration of the potassic melts is 690 ppm, and the concentrations in the other melt groups are no higher than 55 ppm. Relatively high **Cr** concentrations were found in the magnesian basalt melts: 610 ppm on average. This value is almost 40 times higher than the Cr concentration in Ti-rich basalt melts, sodic intermediate melts, and acid melts. The potassic andesite melts contains 40 ppm Cr.

The melts are relatively poor in water, as follows from the high totals (close to 98 wt % on average) of microprobe analyses of the glasses. A few ion probe analyses for water (Table 11) confirm this conclusion: the water concentrations are no higher than 0.8 wt %. Another feature worth mentioning in this context is the high F concentrations (>1 wt %) of the K_2O-rich melts of intermediate composition. The Cl concentrations are usually higher in sodic varieties than in potassic ones. No appreciable S concentrations were detected in any of the melts.

DISCUSSION

Our data on melt inclusions in minerals from the Gorely volcanic center provide extensive information.

Relations between the melts and rocks. The rock-forming melts from which phenocrysts of the rocks crystallized show much broader compositional variations than the rocks themselves do. The basalt melts and some ignimbrites contain less silica, whereas the dacite melts are much richer in silica than the rocks in which these inclusions are contained. The ignimbrites and andesites comprise both more mafic and more acid rock varieties than the corresponding melt inclusions (Fig. 2). Melt inclusions of the same type can be found in rocks of different silicity, and conversely, melt inclusions of different types can occur not only in a single samples but even in a single phenocryst (Tables 7, 8, Figs. 5, 6). This led us to conclude that (i) the bulk rock compositions are not analogous to the compositions of the melts from which the phenocrysts crystallized, (ii) any of the rocks represented by our samples is cumulus, and (iii) most of the rocks were generated by the mixing of magmatic melts, as follows from the fact that single rock samples sometimes contain phenocrysts that crystallized under different conditions and from different melts. Also, we cannot rule out that not only the crystallization products of various melts mixed but the melts themselves also did. Similar conclusions concerning a hybrid genesis of basite melts at Gorely volcano were drawn from data on the petrography of the rocks [6]. The occurrence of inclusions of various melts in single phenocrysts testifies that the evolutionary histories of certain phenocrysts could be very complicated and involve their long-lasting crystallization in a compositionally evolving melt or the movement of certain crystals through a compositionally heterogeneous chamber. An analogous conclusion was presented in our earlier publication [16] based on studying andesites from Bezymyannyi volcano in Kamchatka. We have examined melt inclusions in plagioclase from rocks erupted in 1956, 1974, 1979, 1985, and 1987. Inclusions of various melts, low- and high-K among others (56–78 wt % SiO_2 and systematic differences in the concentrations of other components), are often contained in a single phenocryst and are sometimes very closely spaced in it.

A noteworthy feature of these inclusions is their broad ranges of the concentrations of major components, such as SiO_2, FeO, MgO, K_2O, and F, with the most magnesian varieties enriched in K_2O and F. This set of elements suggests that phlogopite-bearing rocks could serve as one of the sources of such melts, and their whole diversity within a single phenocryst could result from the interaction of the melt with the more siliceous, ferrous, and sodic ambient melt. The high-K melts with high F contents were found in mantle rocks (lamprophyres) from West Australia [17, 18] and Spain [19]. Melt inclusions in olivine form these rocks contain 8.8–13.5 wt % K_2O and 0.49–1.43 wt % F. Melts analogously rich in K_2O (5.4–6.4 wt % K_2O) and bearing high F concentrations (0.58–1.27 wt %) were found among glasses in xenoliths from Stromboli volcano in Italy [20]. Compositionally close melts (4.5–8.2 wt %

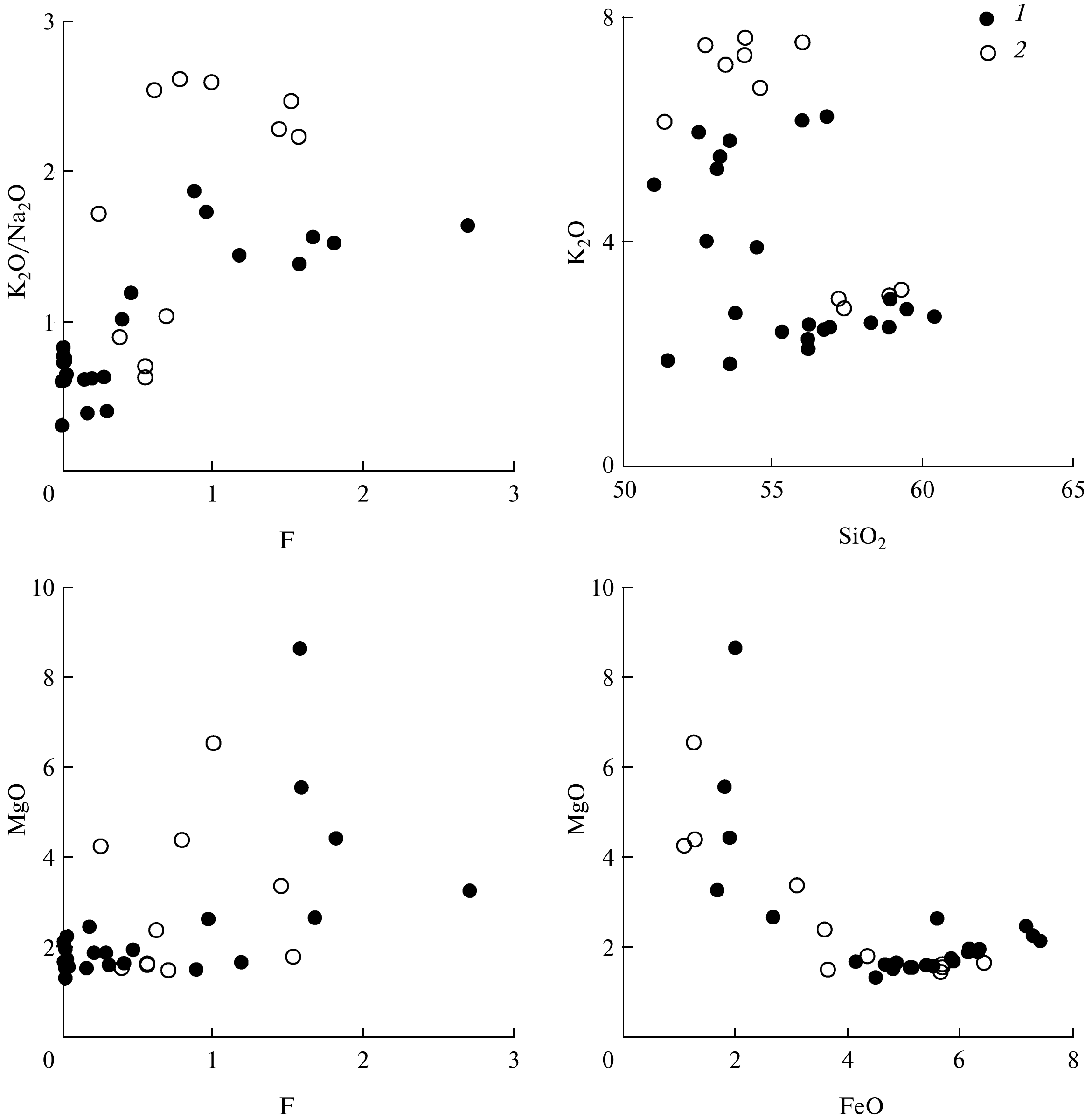

Fig. 6. Variation diagrams for melt inclusions in a single plagioclase phenocryst (*1*—sample Gor-60, *2*—sample Gor-188).

K_2O and 0.32–0.75 wt % F) were detected in eleven melt inclusions in olivine (*Fo* = 86.8–90.7) from two volcanoes in southern Italy [21], and this led the authors of the aforementioned paper to conclude that the K-rich magmas were derived from a mantle source.

Relations between melts of various types. The problem is formulated as follows: can evolutionary relations between melts of various composition be identified in this magmatic system. Variation diagrams (Fig. 3) demonstrate that the MgO, FeO, and CaO concentrations of the melts decrease with increases SiO_2 concentrations. The data points in the FeO–SiO_2 and CaO–SiO_2 plots define continuous trends, practically without compositional gaps, but the MgO concentrations in inclusions from olivine are much higher than in all other melts, even mafic ones. This drastic increase can hardly be accounted for only by the fractionation of mafic minerals. In this context, it is worth more closely considering the variation range of the composition of magnesian basaltic melts from the olivine: at very insignificant differences in the SiO_2 concentrations, the TiO_2, FeO, CaO, Na_2O, and K_2O vary more than twofold.

Very complicated dependences are exhibited in the TiO_2–SiO_2, Na_2O–SiO_2, and K_2O–SiO_2 plots (Fig. 3). The maximum TiO_2 concentrations were found in mafic melts from the andesite and basaltic andesites, and the minimum ones occur in the mafic magnesian

Table 10. Concentrations of F (wt %) and trace elements (ppm) in melt inclusions in olivine and plagioclase from rocks from Gorely volcanic center

Component	Gor-161	Gor-161	Gor-161	Gor-161	Gor-60	Gor-60	Gor-60	Gor-46	Gor-11	Gor-11	Gor-11
	2*	8	10	10	29	35	35	18	59	60	64
F	0.278	0.060	0.012	0.010	0.002	2.26	3.15	0.060	0.009	0.008	0.035
Li	41.7	24.7	29.9	25.5	122	23.5	20.4**	36.7	45.8	24.9	35.7
Be	1.09	0.60	0.87	0.80	1.72	0.70	0.69	1.50	2.28	2.34	2.33
B	649	4.00	483	925	45.6	54.5	32.5	19.7	36.6	26.8	28.7
Cr	208	166	423	1640	28.7	46.6	30.2	14.1	4.80	3.74	10.5
Rb	49.3	17.7	48.3	51.5	61.0	109	104	52.3	96.5	83.5	72.5
Sr	243	538	427	441	371	482	434	375	29.2	114	113
Y	28.1	20.7	20.3	21.6	88.1	13.0	14.1	31.5	45.1	49.1	37.8
Zr	140	74.4	114	99.5	597	109	117	171	471	473	355
Nb	5.58	2.41	3.04	2.66	22.4	3.37	3.81	6.25	13.4	16.8	11.6
Ba	496	276	251	259	828	1310	1110	733	617	797	685
La	14.2	8.35	8.30	12.4	38.5	7.75	8.39	18.6	28.2	36.6	23.0
Ce	35.0	21.1	19.1	25.8	102	17.7	19.7	42.9	64.6	85.5	50.8
Nd	21.9	15.1	11.1	14.4	63.7	9.80	11.0	25.4	33.9	43.6	27.5
Sm	5.26	3.79	3.00	3.00	15.9	2.38	2.76	5.96	7.09	9.33	5.65
Eu	1.53	1.12	1.18	1.12	2.68	0.84	0.55	2.09	0.55	1.03	0.81
Gd	6.24	3.35	2.68	3.09	16.1	2.23	2.58	6.03	6.52	8.47	4.92
Dy	5.29	3.49	3.28	3.60	15.3	2.21	2.48	5.53	7.07	8.97	5.74
Er	3.47	2.17	2.44	2.43	10.5	1.47	1.64	3.70	4.86	6.55	3.89
Yb	3.11	2.19	2.42	2.25	9.95	1.31	1.47	3.87	5.75	7.84	4.35
Hf	3.99	2.41	2.88	3.14	13.6	2.60	2.89	4.66	10.3	13.1	6.76
Th	1.93	0.50	2.55	2.53	5.76	1.33	1.53	2.42	4.84	6.63	3.79
U	0.59	0.23	0.84	0.63	2.74	0.68	0.69	1.11	2.40	3.11	1.71
Th/U	3.3	2.2	3.0	4.0	2.1	2.0	2.2	2.2	2.0	2.1	2.2
La/Yb	4.6	3.8	3.4	5.5	3.9	5.9	5.7	4.8	4.9	4.7	5.3

Notes: * —melt inclusion numbers in Table 6;
** —in addition to the listed trace elements, the inclusion was determined to contain 149 ppm V, 95.9 ppm Cu, 0.62 ppm Ta, and 1.12 ppm Pb. Host minerals: olivine for inclusions 2, 8, and 10 and plagioclase for the other melt inclusions.

Table 11. Concentrations of H_2O, F (wt %) and trace elements (ppm) in melt inclusions in plagioclase and groundmass in rocks from Gorely volcanic center

Component	Gor-60	Gor-60	Gor-60	Gor-60	Gor-60	Gor-60	Gor-60	Gor-15	Gor-15	Gor-15	Gor-19	Gor-60	Gor-60
	30*	34	37	41	42	45	50	26	27	28	57	**	**
H_2O	–	0.40	0.78	0.38	0.72	0.65	0.53	0.73	0.62	0.04	–	0.02	0.10
F	0.003	0.020	0.033	0.012	0.036	0.029	0.031	0.054	0.019	0.001	0.173	1.01	1.14
Li	86.6	115	124	220	171	116	36.6	88.2	127	31.7	42.7	18.5	22.7
Be	1.29	1.69	1.55	1.58	1.46	1.59	1.47	2.03	2.39	1.49	1.82	–	–
B	30.9	27.5	22.7	29.2	24.2	26.3	21.3	29.2	38.8	17.9	16.2	–	–
V	174	249	220	159	264	201	272	150	137	44.2	–	142	72.3
Cr	11.2	20.5	17.6	22.5	21.4	17.7	27.9	11.3	14.5	1.62	5.03	91.3	73.1
Cu	425	550	479	937	676	535	571	374	578	312	–	92.1	200
Rb	27.5	57.4	52.4	48.4	58.4	54.1	57.5	50.0	42.3	35.6	47.7	63.2	98.4
Sr	534	295	347	370	349	340	345	413	665	329	401	498	496
Y	46.4	42.9	40.7	54.9	43.0	42.8	42.7	39.4	38.5	25.1	37.2	9.01	7.97
Zr	328	287	277	376	326	306	284	277	266	190	379	42.9	221
Nb	10.3	9.48	9.24	12.4	10.1	9.92	9.42	9.10	8.97	6.03	9.65	0.57	3.10
Ta	1.43	1.26	1.49	1.78	1.61	1.58	1.99	1.31	2.31	2.35	–	0.94	1.22
Ba	472	706	744	739	777	730	935	789	824	670	852	1660	2080
La	21.1	22.9	22.1	30.2	22.8	23.7	23.5	23.5	22.0	17.1	20.5	3.48	7.25
Ce	55.0	54.6	53.6	72.7	57.7	54.7	59.8	57.9	49.9	41.4	50.8	6.64	14.2
Nd	32.6	32.5	31.2	44.7	33.5	33.7	35.5	32.9	32.2	22.5	27.1	4.94	8.11
Sm	7.90	7.94	7.74	10.1	8.33	7.68	8.59	7.95	7.44	5.18	6.33	1.45	1.93
Eu	1.43	1.75	1.85	1.61	1.66	1.65	2.82	1.98	2.66	1.54	1.48	1.56	1.70
Gd	7.48	7.16	7.13	9.01	8.40	5.95	9.09	6.59	6.91	5.44	7.26	1.97	1.05
Dy	7.48	7.30	7.31	9.40	7.58	7.52	7.72	6.84	7.18	4.61	6.67	1.98	1.98
Er	5.18	4.80	4.70	6.35	5.38	5.07	5.12	4.83	4.82	3.23	4.83	1.05	1.08
Yb	5.26	4.66	4.60	6.26	4.90	5.15	4.89	5.15	4.67	3.08	5.02	0.98	1.01
Hf	7.28	7.15	7.14	8.81	8.13	8.07	7.42	7.19	7.18	4.67	8.65	1.55	5.60
Pb	8.19	10.2	11.3	10.2	13.0	11.3	13.6	8.52	11.2	8.23	–	6.01	13.4
Th	3.21	3.05	3.25	4.23	3.57	3.66	3.31	3.93	2.93	2.93	4.99	–	1.15
U	1.49	1.41	1.59	2.00	1.64	1.60	1.48	1.71	1.38	1.14	1.97	0.88	0.86
Th/U	2.2	2.2	2.0	2.1	2.2	2.3	2.2	2.3	2.1	2.6	2.5	–	1.3
La/Yb	4.0	4.9	4.8	4.8	4.7	4.6	4.8	4.6	4.7	5.6	4.1	3.6	7.2

Notes: * —melt inclusion numbers in Table 6;
** —groundmass in Table 7.

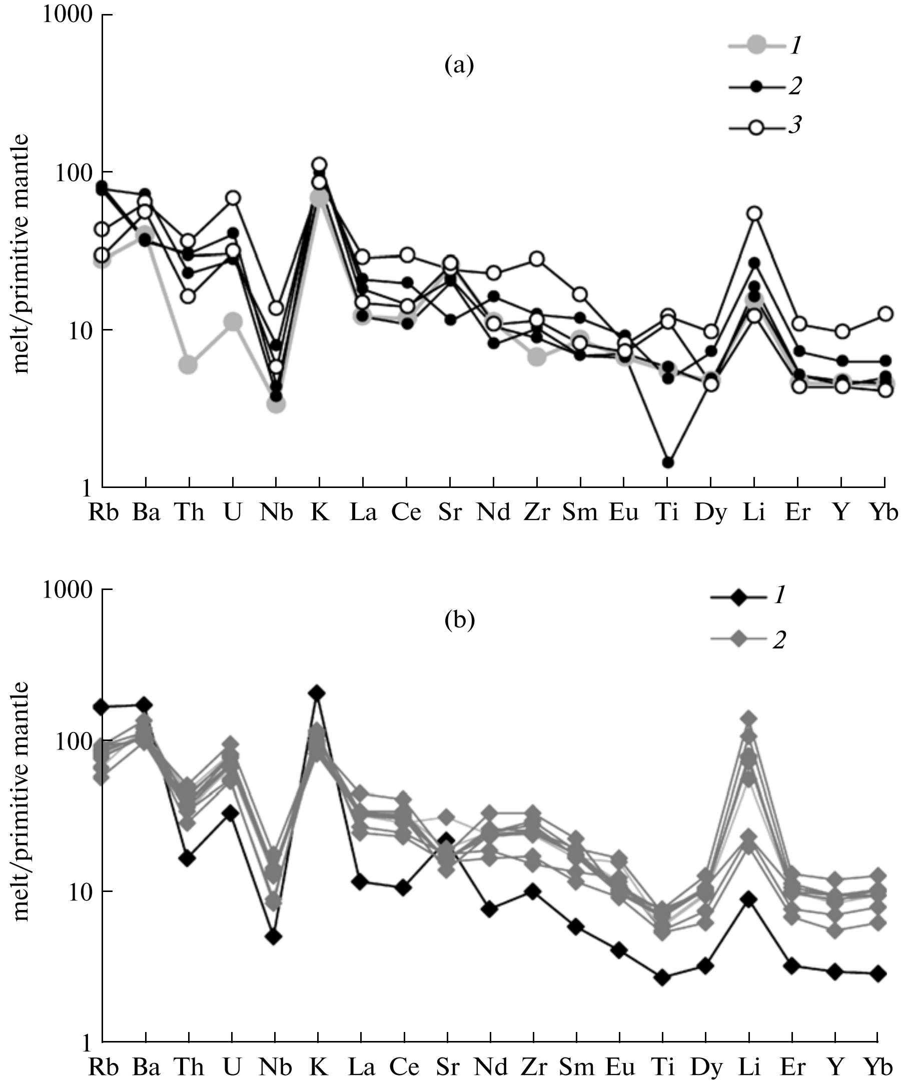

Fig. 7. Primitive mantle-normalized [22] trace-element patterns for melts of various types.
Basic melts (*1–3*—melt types, see Fig. 4), (b) intermediate melts (*1*, *2*—melt types, see Fig. 4), (c) acid melts of type VII: (*1*) in dacite, (*2*) in ignimbrite; (d) average compositions of melts of various types: (*1–5*) types I–V, respectively, (*6*) type VII.

and acid melts. The concentrations of alkalis (first and foremost K_2O) vary within very wide limits at insignificant variations in the SiO_2 concentrations. K_2O does not systematically enrich more evolved varieties, and the maximum K_2O concentrations were found in the ignimbrites but not in the most strongly differentiated dacite.

The variation diagrams demonstrate that (i) the melts/rocks can possibly be genetically related, and (ii) not all rock relations can be explained only by the fractionation of the parental melt, if the latter is assumed to have the composition of the basite melts in sample Gor-161.

Geochemistry of various melt groups from the Gorely volcanic center. Figures 7 and 8 show primitive mantle-normalized [22] trace-element plots for various melts. As can be seen from Fig. 7d (average values for melts of various types), all of the plots are generally similar, have roughly equal slopes, and show a systematic increase in the concentrations of practically all elements and similar local extrema. The only exceptions are Sr (whose concentrations are at a minimum in the acid melts because of plagioclase fractionation), Ti (whose concentrations are notably lower in the acid melts), and Zr (whose concentrations are, conversely, higher in the most strongly differentiated melts). All other geochemical parameters indicative not of the extent melt differentiation but of its source are identical.

It is worth mentioning that this source should have been very unusual. The mafic melts of Gorely volcano are enriched in several incompatible elements relative to the average values of arc melts [23, 24], and the concentrations of some elements, such as Li, B, and Zr, do not

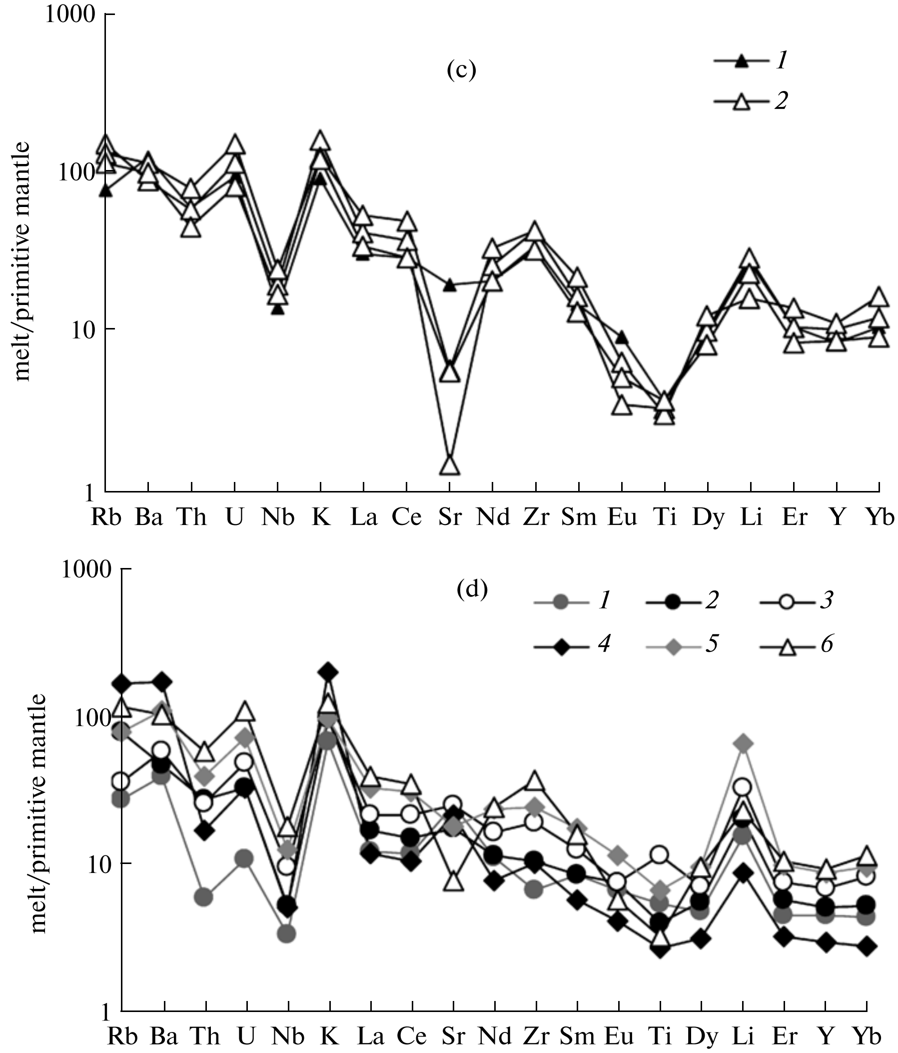

Fig. 7. Contd.

even lie within the confidence level of the concentration values. The only exception is the type-II basite melts, which have lower Th and U concentrations, close to those in typical IAB (Fig. 7). The LILE concentrations in these same melts are at a minimum for Gorely volcano. Since all of these elements are thought to be easily mobilized by fluids, it is reasonable to believe that fluid played an active role in forming the melts.

The average K_2O-rich melt (type IV) contains lower concentrations of all incompatible elements except Ba and Sr. The average melts of the sodic group (type V) have a fairly uniform composition, similar Ba/Rb, Zr/Hf, and Th/U ratios (which are lower than in the basaltic melts), Nb minima, and weak Ti minima.

The acid melts show broad variations in their Sr and Eu concentrations (whose concentrations are at a maximum in acid melts from the ignimbrites). These melts display pronounced Zr maxima and Ti minima.

All fractions of trace elements obviously systematically enriched acid varieties of the melts compared to mafic ones. This enrichment is far from linear, and not all of the elements exhibit correlations. The most clearly pronounced trends are typical of REE (Fig. 9). LREE and HREE behave similarly, and the concentrations of Sm are somewhat lower in the acid melts. Clear-cut trends are also typical of HFSE ratios. The situation with LILE is more complicated. Li is anomalously strongly enriched in the melts of intermediate composition, whereas Rb enriches the potassic melts of various basicity.

Magma sources. To identify the possible sources of the melts, it is expedient to focus on the mafic melts from Gorely volcano as the most primitive members of the magmatic series. It should be mentioned that these melts are fairly unusual. Trace element ratios of melts from Gorely volcano differ from the canonical ratios of basite melts in island arcs [23, 25, 26]: HREE are more

Table 12. Concentrations of H_2O and trace elements (ppm) in (1–4) host plagioclase (sample Gor-60) containing melt inclusions with high K_2O and F concentrations (Table 7) and (5–6) in host plagioclase from andesite from Shiveluch volcano

Component	*1*	*2*	*3*	*4*	*5*	*6*
	An_{54}	An_{54}	An_{54}	An_{54}	An_{49}	An_{50}
H_2O	42	152	109	50	455	163
Li	6.62	5.24	5.64	5.64	3.99	3.17
Be	–	–	0.34	–	–	–
B	–	–	0.34	–	–	–
F	14	98	25	13	8	8
V	9.13	8.40	8.97	8.68	7.13	8.24
Cr	1.82	2.11	1.13	1.04	1.13	16.4
Cu	22.0	15.1	11.0	11.8	12.7	10.1
Rb	1.29	2.60	1.02	1.06	0.86	0.75
Sr	695	689	729	715	1180	1070
Y	0.27	0.28	0.61	0.35	0.33	0.30
Zr	21.9	18.0	4.51	3.98	4.59	3.53
Nb	0.01	0.01	0.03	0.01	0.02	0.01
Ta	0.11	0.08	0.13	0.13	0.07	0.08
Ba	227	242	215	231	132	188
La	1.82	2.08	1.87	1.73	1.48	2.93
Ce	2.99	3.30	3.29	3.39	2.57	4.73
Nd	1.29	1.38	1.54	1.44	1.27	1.92
Sm	0.19	0.20	0.22	0.31	0.21	0.36
Eu	0.68	0.61	0.69	0.60	0.57	0.80
Gd	0.21	0.18	0.19	0.09	0.07	0.19
Dy	0.11	0.10	0.11	0.08	0.07	0.10
Er	0.05	0.05	0.02	0.08	0.01	0.04
Yb	0.04	0.00	0.01	0.05	0.05	0.03
Hf	0.30	0.27	0.16	0.12	0.13	0.14
Pb	1.07	1.34	0.59	0.52	0.65	0.59
Th	0.004	0.004	0.005	0.002	0.00	0.005
U	0.003	0.09	0.04	0.01	0.01	0.02

deficient (La/Yb = 3.4–5.1), and the Th/Yb and Nb/Yb ratios are higher (up to 1.12 and up to 2.6, respectively), while the Th/Ta ratio is, conversely, lower (approximately 2).

Differences between the geochemical features of the melts of types I and II and evidence of their derivation at significant depths (high Mg and Cr concentrations) suggest that the source material should have been lithologically heterogeneous. This conclusion shall, however, be validated by the results of further studies, and data available so far are insufficient to support it (which pertains, first of all, to the sodic basite melts).

Estimates of the possible sources (Fig. 10) demonstrate that the melts of Gorely volcano have ratios of certain elements that are the closest to those of a mixed mantle–crustal source typical of island arcs, and the mantle constituent likely contained an admixture of an enriched OIB component. A similar conclusion published in [6] is that the rocks of Gorely volcano plot on the mixing line of two components (subduction and within-plate ones), which mixed at high degrees of melting and a significant role of the subduction component.

The comparison of the average compositions of basite melts from Gorely volcano and the average compositions of melts from various geodynamic environments [23] reveals that the former are enriched relative to arc melts (Fig. 11). The normalized trace-element patterns of melts from Gorely volcano are closer to the patterns of within-plate melts, although the Gorely

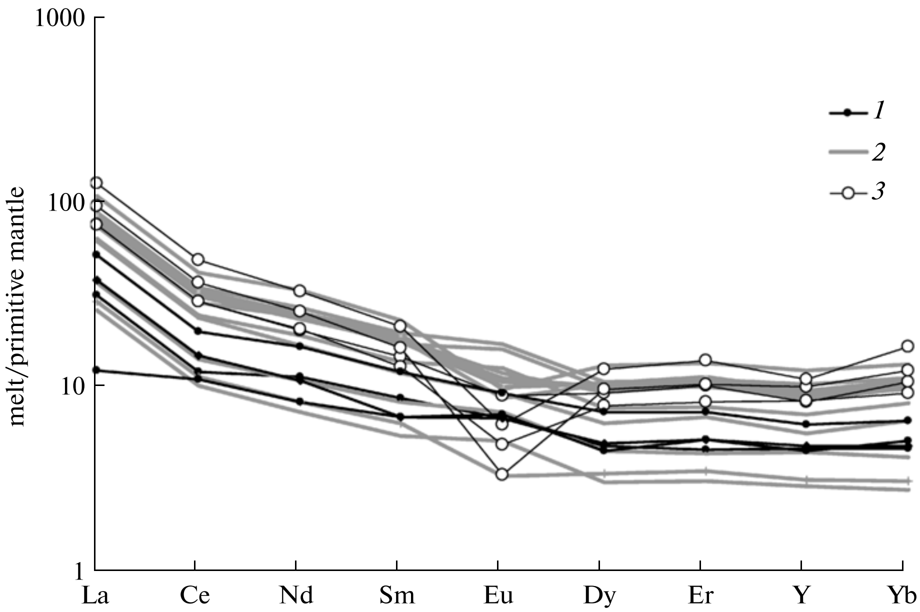

Fig. 8. Primitive mantle-normalized [22] REE patterns for melts of various types. (*1*) Basic melts; (*2*) intermediate melts (*3*) acid melts.

melts still exhibit typical features of arc melts (such as Nb deficit and K maximum).

Indeed, its is reasonable to suggest that the magma was generated at the involvement of enriched sources of within-plate type, although similar features are also displayed by the average composition of the sedimentary sequence of the Kamchatkan subduction zone (KSSC) [28]. It should also be taken into account that the melts could be enriched in LILE, as well as Th and U, in the course of the fluid recycling of the source material.

It should be mentioned that K_2O-rich melts are widespread not only at Gorely volcano but also at several other volcanoes in the Kurile–Kamchatka area. Table 13 summarizes all data published so far on volcanic rocks in this territory in which melt inclusions with high K_2O concentrations ($K_2O/Na_2O > 1$) were found. These data led us to conclude that K_2O-rich melts are widespread in the area: they were found there at the volcanoes Avachinskii, Bezymyannyi, Great Semyachek, Dikii Kamen', Karymskii, Kekuknaiskii, Kudryavyi, and Shiveluch and in the Valaginskii and Tumrok ranges. The hypothetical sources of these melts should have been phlogopite-bearing mantle peridotites [6, 40].

However, mafic melts with elevated K_2O concentrations are still not very common: they were found mostly in older (Cretaceous) rocks in western and eastern Kamchatka (Valaginskii Range, Tumrok, and Kekuknaiskii Massif; Table 13), and the occurrence of these melts there is thought to be explained by changes in the geodynamic environments and the involvement of deeper mantle zones in magma generation in a rifting environment [6].

At modern volcanoes, K_2O-rich basites were found only in the Kuriles [36], and all other potassic volcanic rocks are products of differentiated melts. Hence, Gorely is the only modern volcano in Kamchatka, in the vicinity of its Eastern Volcanic Front, in which mafic melts with high K_2O concentrations were found. It is also worth mentioning that these melts are rich in F, and hence, it is more than probable that the melts were derived from phlogopite-bearing source rocks [17, 18].

Equally potassic melts were recently found as melt inclusions in olivine and plagioclase in island arcs and active continental margins elsewhere: in the western Trans-Mexican Volcanic Belt [41, 42], central Rio Grande Rift [43], Santa Rita magmatic system in New Mexico in the United States [44], and Soufriere Hills Volcano in the Lesser Antilles [45].

Geological evolution of Gorely volcano. The compositions of melt inclusions in various minerals and the compositions of the rocks can be compared in order to reproduce the evolution of the Gorely volcanic center.

The oldest rocks of Gorely (available for us so far) seem to be the ignimbrites (sample Gor-19) corresponding to the caldera-forming stage. These are hybrid rocks produced by melts of types IV, V, VI, and VII. It can be hypothesized that in the late Miocene (i.e., at the end of Pra-Gorely evolution), its chamber was filled with acid ($SiO_2 > 64$ wt %) melt and phenocrysts that crystallized from acid and intermediate melts. Nearly simultaneously (during Pra-Gorely evolution or shortly after the origin of the caldera), deep magnesian basalts were erupted, which were produced by melts of types I and II, including their potassic varieties.

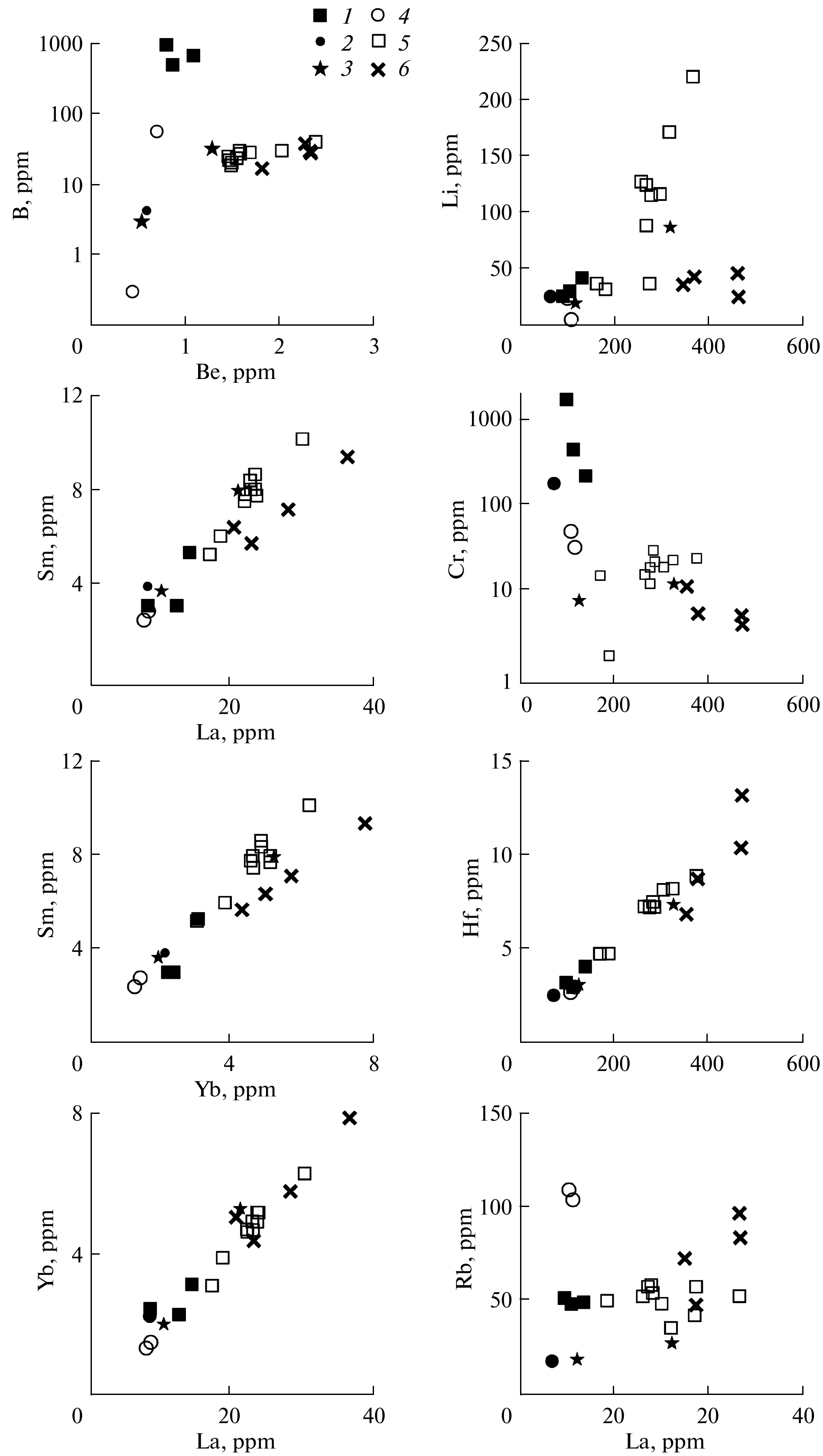

Fig. 9. Variation diagrams for trace elements in melts of various types. (*1–6*) Melt types: (*1–5*) types I–IV, respectively, (*6*) type VII.

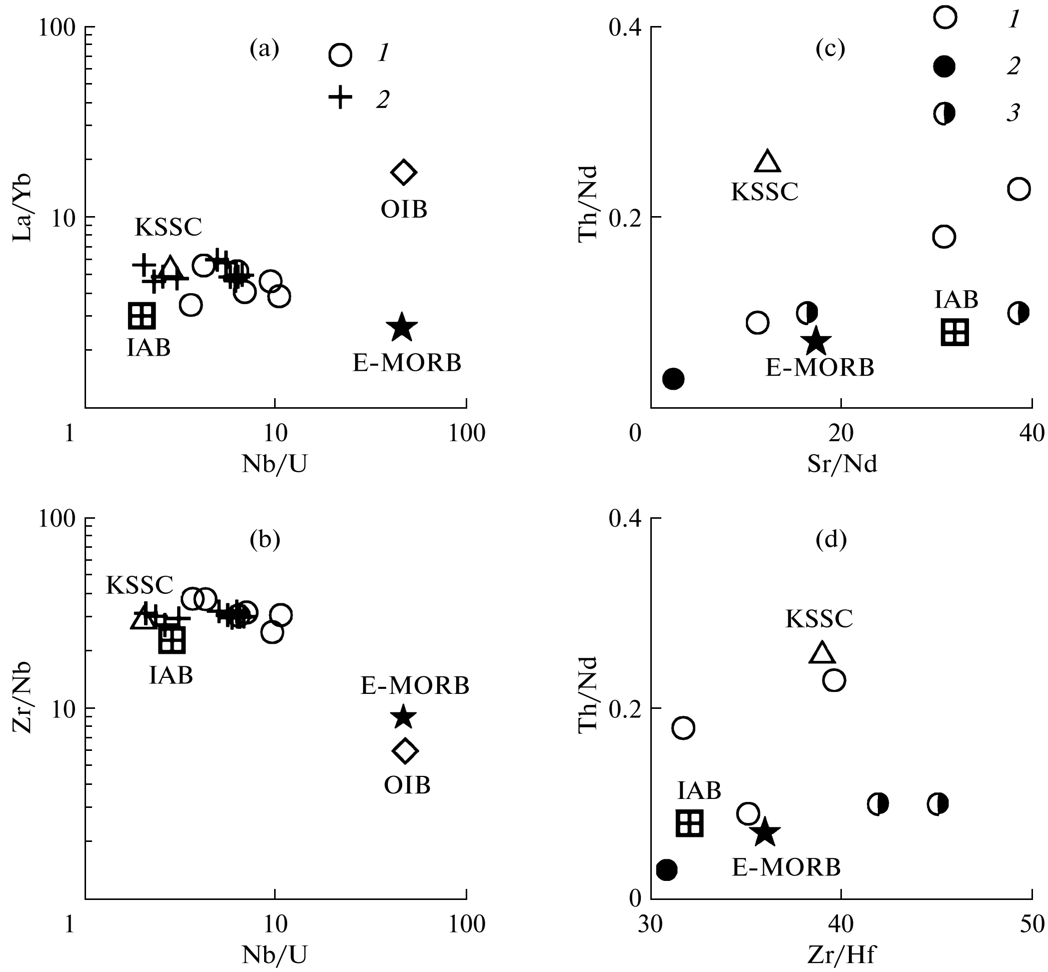

Fig. 10. Relations between basic and intermediate melts of the Gorely volcanic center and the normalized compositions of the magmatic sources.

(a, b) (*1*) Basic melts; (*2*) intermediate melts. (c, d) (*1–3*) Basic melts of types I–III, respectively. Normative compositions: MORB (mid-oceanic ridge basalt), OIB (oceanic island basalt) [25], IAB (island arc basalt) [27], KSSC (average Kamchatkan sedimentary sequence composition) [28].

It could be suggested that the Gorely magmatic system was enriched in K_2O as early as the primary mantle partial melts were derived, and acid melts in the chamber inherited this compositional feature. However, nodules of magnesian basite melts have never been found in any rocks of Gorely volcano, except only for sample Gor-161 from a lava flow erupted from a small side fissure. It cannot be ruled out that these magmas did not interact with the filling of the chamber at all but instead rose along an auxiliary conduit. Indeed, the melts of types I and II look foreign among other Gorely melts, neither do they show any similarities with the melts of the nearby Mutnovskii basite volcanic center [28]. It is thus reasonable to suggest that the magnesian melts belong to the magmatic system of the Gorely volcanic center.

The magmatic chamber emptied by ignimbrite eruptions was refilled with relatively homogeneous acid melts of the sodic group (type VII), and this was associated with dacite eruptions (sample Gor-11). We cannot rule out that these acid melts (SiO_2 > 70%) resulted from the utmost differentiation of the melts that produced the ignimbrites. It is interesting that no potassic specifics was detected in the rocks of this stage (at least no potassic melts were found among the postcaldera dacites).

The structural restyling of the magmatic system resulted in the eruptions of Young Gorely. The eruption products of younger cones are andesites and basaltic andesites (samples Gor-60, Gor-15, Gor-46, and Gor-188) of obviously hybrid genesis. These rocks were produced by the crystallization of intermediate sodic melts (type V) and a minor admixture of phenocrysts with inclusions of intermediate potassic melt (type IV) and mafic melt (type III). The intermediate melt (type V) could perhaps be generated by the mixing of the acid sodic melt typical of the previous evolutionary stage of the volcano and a basite Ti-rich melt that came from greater depths and was much more strongly differentiated than the magnesian basite melts of types I and II.

Table 13. Chemical composition (wt %) of glasses with $K_2O/Na_2O > 1$ in melt inclusions in minerals and in groundmass of volcanic rocks from the Kurile–Kamchatka area

SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cl	Total	ÌÕ*
Avachinskii volcano [29]												
68.72	0.20	16.22	1.64	0.09	0.30	4.02	2.70	5.71	0.07	0.08	99.75	An_{57}**
Bezymyannyi volcano [16]												
55.87	0.16	19.44	3.02	0.14	5.17	7.13	3.23	5.73	-	0.01	99.90	An_{51}
56.30	0.58	17.76	4.97	0.08	1.73	6.45	4.56	4.90	0.28	0.06	97.77	An_{70}
64.80	0.28	16.85	2.51	0.06	1.74	4.01	3.37	5.77	0.08	0.00	99.47	An_{65}
65.67	0.23	15.78	1.48	0.05	0.24	3.98	3.96	5.43	0.12	0.13	97.07	An_{60}
66.07	0.26	17.49	2.59	0.01	0.36	4.72	5.23	5.24	0.10	0.00	102.08	An_{60}
71.78	0.36	13.48	1.09	0.04	0.17	1.42	3.29	6.65	0.03	0.00	98.31	An_{49}
75.11	0.56	11.02	1.52	0.04	0.19	0.85	2.94	4.39	0.10	0.00	96.72	An_{53}
Great Semyachek volcano [30]												
72.01	0.51	12.80	2.30	–	0.75	2.28	3.40	4.75	–	–	98.80	*Gl*
74.80	0.00	12.03	0.52	–	0.05	0.36	3.10	5.35	–	–	96.21	*Gl*
74.87	0.18	12.23	0.94	–	0.14	0.68	4.22	4.54	–	–	97.80	*Gl*
76.34	0.00	11.60	0.30	–	0.00	0.27	3.00	6.03	–	–	97.54	*Gl*
Valaginskii Range, eastern Kamchatka [31]												
45.57	0.61	9.60	8.66	0.15	21.44	8.21	1.83	2.62	0.46	–	99.15	*Ol*
53.60	0.77	12.84	6.91	0.10	9.50	6.33	3.51	3.56	0.74	–	97.86	*Ol*
58.63	0.76	18.01	3.30	0.11	1.99	4.70	4.17	5.17	0.44	–	97.28	*Cpx*
Gorely volcano [5]												
57.06	1.92	13.27	8.51	0.00	2.49	4.20	1.64	3.92	–	–	93.01	An_{50}
57.67	1.84	13.08	8.42	0.00	2.41	4.45	2.31	4.01	–	–	94.19	An_{50}
60.89	1.54	13.87	8/45	0.00	1.45	3.81	2.57	5.05	–	–	97.63	*Gl*
63.75	1.60	14.04	8.62	0.00	1.60	3.92	1.78	5.28	–	–	100.59	*Gl*
67.62	0.01	20.13	0.90	0.00	0.04	3.04	2.89	5.21	–	–	99.84	*Gl*
70.00	0.66	16.82	1.07	0.03	0.00	0.50	3.72	6.53	–	–	99.33	*Opx*
74.15	0.47	13.17	1.49	0.00	0.02	0.72	2.84	5.92	–	–	98.78	*Gl*
74.86	0.35	10.66	1.12	0.00	0.00	0.10	2.02	6.28	–	–	95.39	*Gl*
Dikii Greben' volcano [32]												
70.31	0.20	13.53	1.33	0.07	0.25	2.42	4.11	5.17	0.01	0.10	97.50	An_{63}
74.15	0.15	10.23	0.94	0.07	0.20	0.95	2.91	5.21	0.00	0.12	94.93	An_{46}
74.22	0.32	12.28	1.15	0.03	0.19	1.76	4.57	5.24	0.02	0.14	99.92	An_{63}
74.99	0.23	10.82	1.11	0.08	0.20	0.49	3.87	5.23	0.00	0.30	97.32	An_{37}
75.94	0.26	11.27	1.43	0.02	0.25	1.04	3.87	5.49	0.16	0.10	99.83	An_{67}
76.10	0.13	11.03	0.83	0.08	0.13	0.60	2.87	5.17	0.05	0.31	97.30	An_{32}
76.13	0.24	10.95	1.65	0.01	0.35	1.22	3.80	5.47	0.03	0.12	99.97	An_{59}
76.16	0.26	9.93	1.28	0.00	0.18	0.72	2.83	5.37	0.02	0.09	96.84	An_{39}
76.53	0.22	10.80	0.91	0.04	0.06	0.50	3.24	5.17	0.02	0.26	97.75	An_{37}
76.91	0.21	10.83	0.95	0.06	0.21	0.62	3.26	5.27	0.01	0.30	98.63	An_{37}
77.08	0.30	11.06	1.26	0.03	0.20	0.95	3.41	5.60	0.06	0.10	100.05	An_{61}
77.16	0.19	11.68	0.74	0.01	0.10	0.99	4.06	5.09	0.04	0.17	100.23	An_{41}
Dikii Greben' volcano [33]												
75.55	0.34	12.39	4.96	0.06	0.83	0.16	0.45	4.17	–	–	98.91	An_{45}

Table 13. (Contd.)

SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cl	Total	HM*
77.08	0.31	12.09	2.02	0.08	0.74	0.21	0.59	4.94	–	–	98.06	An_{45}
78.08	0.23	11.88	1.18	0.07	0.59	0.20	1.01	4.80	–	–	98.04	An_{40}
78.63	0.30	11.52	1.25	0.00	0.54	0.11	0.93	5.00	–	–	98.28	An_{45}
Karymskii volcanic center [34]												
55.44	0.86	17.67	5.45	0.09	3.72	8.15	2.64	5.95	0.11	0.01	100.09	An_{82}
72.83	0.11	12.51	0.51	0.06	0.12	0.66	3.32	3.82	0.04	0.11	94.09	*Q*
73.28	0.12	12.98	0.57	0.07	0.16	0.88	3.60	3.74	0.00	0.10	95.50	*Q*
74.02	0.09	12.44	0.54	0.13	0.06	0.62	3.72	3.92	0.06	0.11	95.71	*Q*
75.67	0.11	12.83	0.67	0.11	0.10	0.68	3.64	4.12	0.04	0.10	98.07	*Q*
Karymskii volcanic center [30]												
65.43	1.01	14.99	4.75	–	1.34	3.54	3.37	4.81	–	–	99.24	*Gl*
66.09	0.82	14.83	4.38	–	1.15	2.91	3.39	6.22	–	–	99.79	*Gl*
66.36	0.72	15.01	3.75	–	1.03	2.27	2.89	6.64	–	–	98.67	*Gl*
74.33	0.12	11.72	1.11		0.23	0.38	3.66	4.90	–	–	96.45	*Gl*
Kekuknaiskii volcano, western Kamchatka [35]												
51.17	1.73	15.2	11.4	–	5.31	6.66	3.09	4.13	–	–	98.69	*Ol*
52.76	1.15	17.31	9.62	–	4.87	6.36	3.39	5.56	–	–	101.02	*Ol*
55.26	1.44	19.21	5.10	–	3.27	4.91	3.20	7.16	–	–	99.55	*Ol*
50.18	2.30	15.36	6.29	–	5.76	11.06	3.00	3.68	–	–	97.63	*Cpx*
54.07	0.85	14.29	6.32	–	5.32	8.80	2.27	5.16	–	–	97.08	*Cpx*
55.07	0.83	14.28	6.08	–	5.17	8.77	3.08	5.27	–	–	98.55	*Cpx*
Kudryavyi volcano, Iturup Island, southern Kuriles [36]												
51.45	0.53	17.93	6.48	0.21	4.07	12.85	3.16	3.76	0.16	0.02	100.62	An_{72}
53.00	0.29	19.92	2.64	0.07	7.97	7.28	1.71	4.95	0.10	0.03	97.96	An_{89}
61.66	0.78	17.86	3.84	0.07	0.75	6.38	3.03	5.13	0.36	0.11	99.97	An_{77}
61.88	0.73	15.13	4.70	0.09	0.84	6.19	2.96	6.92	0.37	0.15	99.96	An_{70}
63.02	0.81	16.22	4.53	0.13	1.43	5.99	3.19	3.67	0.15	0.13	99.27	An_{69}
63.32	0.88	15.09	4.49	0.13	0.97	6.52	2.81	5.68	0.34	0.15	100.38	An_{77}
63.56	0.82	15.43	4.35	0.11	0.85	5.01	2.76	6.76	0.15	0.01	99.81	An_{83}
64.00	0.81	13.48	3.36	0.12	1.31	3.68	2.77	6.22	0.30	0.09	96.14	An_{62}
66.60	1.34	13.81	4.21	0.17	1.26	5.51	2.52	3.86	0.36	0.10	99.74	An_{73}
66.71	0.84	14.06	4.77	0.13	0.83	4.01	3.10	5.87	0.15	0.01	100.48	An_{83}
69.33	0.91	11.51	4.54	0.14	1.40	4.14	1.55	5.40	0.18	0.09	99.22	An_{75}
69.36	0.91	11.51	4.54	0.14	1.40	4.14	1.55	5.40	0.18	0.09	99.22	An_{75}
Tumrok Range, eastern Kamchatka [37]												
52.00	0.54	17.34	9.20	0.16	4.38	9.35	3.02	3.24	0.27	–	99.50	*Cpx*
52.79	0.40	16.20	8.31	0.20	4.68	9.62	3.09	3.56	0.47	–	99.32	*Cpx*
53.84	0.33	15.92	8.30	0.17	4.75	8.81	2.84	4.40	0.30	0.38	100.04	*Cpx*
54.09	0.32	15.53	8.62	0.20	4.46	9.10	2.65	4.21	0.31	–	99.49	*Cpx*
Shiveluch volcano [38, 39]												
71.03	0.17	14.59	1.34	0.04	0.23	1.72	2.77	6.47	–	–	98.36	An_{43}
71.58	0.17	12.08	0.97	0.04	0.27	0.84	4.18	4.43	–	0.16	94.72	An_{43}
74.36	0.25	13.23	1.43	0.02	0.91	1.24	3.32	4.31	–	0.09	99.16	*Amph*
75.98	0.18	13.32	0.80	0.01	0.24	0.69	3.67	4.52	–	0.09	99.50	*Amph*

Notes: * —host mineral: *An*—plagioclase, *Ol*—olivine, *Q*—quartz, *Gl*—glass in groundmass, *Opx*—orthopyroxene, *Cpx*—clinopyroxene, *Amph*—amphibole, An_{57}.
** —anorthite concentration in plagioclase.

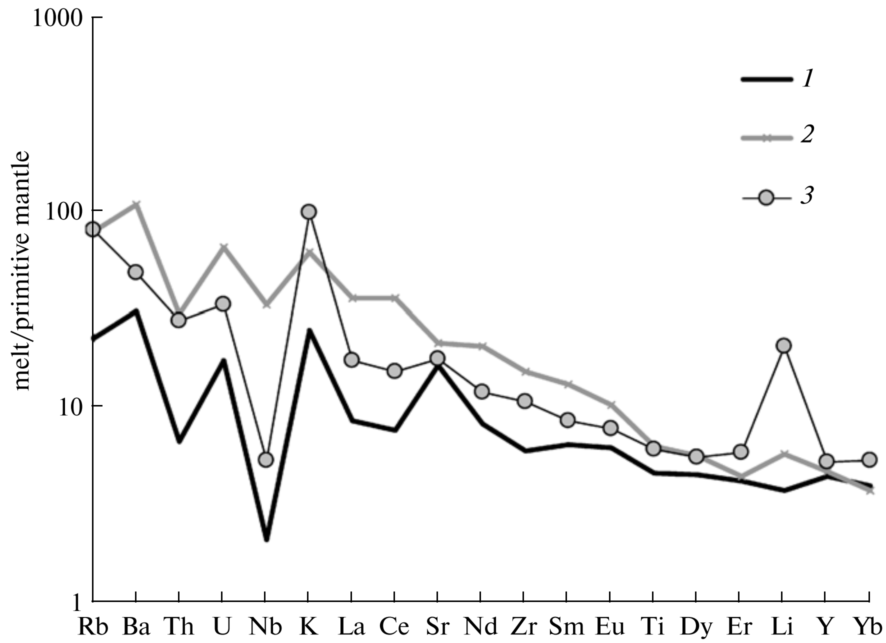

Fig. 11. Primitive mantle-normalized [22] averaged REE patterns for basic melts from various geodynamic environments [23] and Gorely volcano.
(*1*) Island-arc basaltic melts; (*2*) within-plate basaltic melts; (*3*) basaltic melts of Gorely volcano.

However, these melts (of type II) also could conceivably be involved in the mixing process, and fresh basite melt portions could replenish the chamber.

It is interesting that the geochemical features of the melts did not change throughout the whole period of time in question, and the melts were thus pervasively derived from the same sources. The only piece of evidence in favor of the systematic evolution is the drastic decrease of the role of potassic melts with time. Conceivably, this is indicative of a change in the fluid regime and a decrease in the intensity of fluid-induced metasomatism of the source material.

Moreover, the melts of Young Gorely seem to be pervasively rich in Li. Assuming that Li is a typical crustal element [46] and can be brought to a shallow-depth chamber with disintegrated roof fragments, one can suggest that the role of contamination in the generation of the Holocene volcanics of Gorely increased with time.

CONCLUSIONS

(1) Melt inclusions were examined in olivine and plagioclase phenocrysts in rocks of various age at the Gorely volcanic center in southern Kamchatka (magnesian basalt, basaltic andesite, andesite, ignimbrite, and dacite) by homogenizing inclusions and by analyzing the glasses of 100 melt inclusions on an electron microprobe and 24 inclusions on an ion probe. The melts are classified into seven types with different SiO_2, Na_2O, K_2O, TiO_2, and P_2O_5 concentrations. The mafic melts (45–53 wt % SiO_2) comprise potassic (4.2% K_2O, 1.7% Na_2O, 1.0% TiO_2, and 0.20% P_2O_5 on average), sodic melts (3.2% Na_2O, 1.1% K_2O, 1.1% TiO_2, and 0.40% P_2O_5), and those rich in P_2O_5 (2.2% TiO_2, 1.1% P_2O_5, 3.8% Na_2O, 3.0% K_2O). The intermediate melts (53–64 wt % SiO_2) also comprise potassic (5.6% K_2O, 3.4% Na_2O, 1.0% TiO_2, and 0.4% P_2O_5) and sodic (4.3% Na_2O, 2.8% K_2O, 1.3% TiO_2, and 0.4% P_2O_5) varieties. The acid melts (64–74 wt % SiO_2) include potassic (4.5% K_2O, 3.6% Na_2O, 0.7% TiO_2, and 0.15% P_2O_5) and sodic (4.5% Na_2O, 3.1% K_2O, 0.7% TiO_2, and 0.13% P_2O_5) varieties.

(2) The Gorely volcanic center is characterized by the occurrence of K_2O-rich rocks spanning the whole range of SiO_2 contents in the melts. Melt inclusions of various types are often found not only in a single sample but even in a single phenocryst. Sodic and potassic melt types contain different Cl and F concentrations: the sodic melts are richer in Cl, and the potassic ones are notably enriched in F. We were the first to find potassic melts with very high F concentrations (up to 2.7 wt % at an average of 1.19 wt %, data of 17 analyses) in the Kurile–Kamchatka area. The average F concentration in the sodic melts is 0.16 wt % (37 analyses).

(3) The melts are enriched in trace elements of various groups: LILE, REE (particularly HREE), and HFSE (except Nb). The melts generally show features of geochemical similarities. The concentrations of trace elements systematically increase from the mafic to acid melts (except only for the concentrations of Sr and Ba

because of plagioclase fractionation and that of Ti, an element contained in ore minerals).

(4) The processes that could be invoked to account for the diversity of the melts and rocks of Gorely volcano are complicated and diverse and include magma and melt mixing, fractionation, and crustal contamination.

(5) We have summarized all available literature data on volcanic rocks in the Kurile–Kamchatka area in which melt inclusions with high K_2O concentrations ($K_2O/Na_2O > 1$) were found. This information led us to conclude that K_2O-rich melts are widespread in the area are were erupted by Avachinskii, Bezymyannyi, Great Semyachik, Dikii Greben', Karymskii, Kekunaiskii, Kudryavyi, and Shiveluch volcanoes and at the Valaginskii and Tumrok ranges.

ACKNOWLEDGMENTS

The authors thank N.L. Mironov and P.Yu. Plechov for valuable comments on the manuscript and its discussion.

This study was financially supported by the Russian Foundation for Basic Research, project no. 10-05-00209.

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