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Magnesian Basalts of Shiveluch Andesite Volcano, Kamchatka

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Abstract—The eruptive history of the Shiveluch andesite volcano included two Holocene events, during which the volcano erupted unusual rocks: medium-potassium, amphibole-bearing magnesian basalts (7600 years ago) and high-potassium magnesian basalts with phlogopite and amphibole (3600 years ago). The volumes of tephra were approximately 0.1 and 0.3 km^3, respectively. Some of the mineralogical and geochemical features of the Holocene basalts were inherited by the subsequent basaltic andesites and andesites. These are similar in Mg variation ranges of olivine, clinopyroxene, and amphibole phenocrysts, high Mg contents, and high Cr and Ni concentrations. This and the results of mass-balance calculations do not contradict the view that the Shiveluch volcanic rocks originated during the crystal fractionation of Holocene basalt melts. However, the other geochemical features of the Shiveluch rocks, e.g., their similar REE contents, cast doubt on the formation of the magnesian basaltic andesites through fractional crystallization of magnesian basalt magma and suggest that they originated as a result of interaction between magnesian basalt magma and a depleted mantle material at a shallow depth. At the same time, the different mineral compositions of the Holocene medium- and high-potassium basalts and the results of mass-balance calculations indicate that their parental magmas might be produced by the melting of different rocks.

INTRODUCTION

The chemical compositions of the erupted products of the active Kamchatkan volcanoes indicate that in terms of their K$_2$O contents, the rocks of each volcano generally belong to one series, even though they may vary from basalt to dacite (*Deistvuyushchie vulkany*..., 1991). Their geochemical characteristics are usually inherited from the basic to the acid rocks (Volynets, 1994). Most investigators interpret these facts as evidence supporting the formation of the intermediate and acid rocks by the fractionation of basalt magma and consider the basalts to be the least evolved products of the primary magma. Each deviation from this rule calls for a special study because it may indicate that some unusual deep-seated tectonomagmatic processes took place beneath the volcano in question, or that the rocks of one volcano were derived from different primary magmas, or that several series of rocks differing in K$_2$O content were produced during the evolution of one primary magma.

As regards the eruptive history of Shiveluch volcano, its Holocene activity alone included at least 40 large Plinian eruptions (each producing more than 0.5 km^3 of erupted material) and some 30 medium-size eruptions (with volumes ranging between 0.1 and 0.5 km^3), each event being accompanied by the extrusion of viscous lava domes. The most striking feature of the volcano is the invariable composition of its Holocene lavas—medium-potassium magnesian andesites and basaltic andesites (Melekestsev *et al.*, 1991; Ponomareva and Pevzner, 1994), with the exception of two events in which basalt lavas were erupted. The basalts of both eruptions are magnesian but belong to different geochemical series in terms of their K$_2$O contents: the lavas of the older eruption are (as all other Shiveluch lavas) moderately potassic rocks, whereas those of the younger event are highly potassic lavas. In this paper we pursue two objectives: first to describe the geology, petrography, mineralogy, and geochemistry of the two groups of rocks unusual for Shiveluch; the second, main objective is to analyze the genetic relations between these magnesian basalts with different K$_2$O contents, and also between them and the dominant products of Shiveluch eruptions.

GEOLOGY OF THE HOLOCENE SHIVELUCH BASALTS

Shiveluch is the northernmost active volcano of Kamchatka: the coordinates of its active crater are 56°38′ N and 161°19′ E. The volcano is located in the junction zone between the Kuril–Kamchatka and Aleutian island arcs. The first descriptions of its geologic structure were given in the early works of Vlodavets (1940), Menyailov (1955), and Vlodavets and Piip (1957). The catastrophic explosion of 1964 demolished the old andesite dome and produced a crater approximately 1.5 by 3 km in size (Gorshkov and Dubik, 1969). A volcanic dome grew in the crater to a height of 160 m above its floor with a volume of 37 million m^3 during the next (1980–1984) period of extrusive activity. The andesite dome grew considerably larger in 1993 at the beginning of the next renewal of volcanic activity, and its volume was more than 170 million m^3 by the end of 1993 (Fedotov *et al.*, 1995). According to these authors, the andesites of the 1993 eruption are more silicic than the products of all previous eruptions. The present-day edifice of the volcano consists of the Pleistocene Staryi (Old) Shiveluch Massif, deformed by a large crater, and the Molodoi (Young) Shiveluch Volcano, rising as an extrusive dome in the latter. The southwestern portion of the Staryi Shiveluch Massif, the Baidarnyi Otrog (offshoot), is made up of lavas produced by numerous isolated vents.

Molodoi Shiveluch Volcano is one of the major explosive centers of Kamchatka. The results of tephrochronological studies indicate that during at least the last 10 000 years its catastrophic explosive eruptions ejected huge volumes (0.5–5.0 km^3) of magmatic material in the form of tephra and pyroclastic flows. The growth of volcanic domes and the associated mild or medium-size explosive eruptions occurred in periods between the catastrophic explosions.

The tephra of the large and medium-size eruptions, deposited in the soil–pyroclastic cover at the base of the volcano, consist mainly of fairly uniform, light (white, gray, or yellow) pumice lapilli and volcanic gravel of moderately potassic andesite composition. The sequence includes several conspicuous units of black and dark-gray volcanic sands. According to our study, some of them were erupted by Ploskii and Klyuchevskoi volcanoes situated not far from Shiveluch: the units grow thicker and the sand coarser toward these volcanoes. Moreover, the compositions of the sands correspond with the compositions of the subalkalic aluminous basaltic andesites of Ploskii and with the moderately potassic, high-Al basalts and basaltic andesites of Klyuchevskoi (Table 1). At the same time, two units of basaltic volcanic sand and gravel have been found in sections of all sectors of the Shiveluch Volcano base. These units definitely grow thicker, and their particles become larger toward the volcano (Figs. 1 and 2). It should be emphasized that no *in situ* exposured Holocene basalts have been found on Shiveluch. This encouraged us to carry out a special study of the unusual tephra, which seem to provide the only evidence of some important events in the geologic history of the volcano.

Table 1. Representative analyses (wt %) of transit basalt and basaltic andesite ash deposits at the base of Shiveluch Volcano

Oxide	Ploskii		Kluchevskoi	
	$1264^b/1$	$1264^b/4$	90199/3	1291/3
SiO_2	54.24	52.63	51.56	50.76
TiO_2	1.07	1.53	1.03	1.37
Al_2O_3	16.97	18.76	18.46	18.84
Fe_2O_3	4.63	4.14	3.12	2.58
FeO	3.30	3.37	5.75	3.51
MnO	0.12	0.13	0.15	0.12
MgO	2.68	1.91	5.02	3.74
CaO	6.08	7.17	8.52	9.24
Na_2O	2.70	2.96	2.84	3.09
K_2O	2.00	1.68	0.74	0.83
H_2O^-	1.83	2.04	–	1.13
H_2O^+	2.09	1.86	–	1.29
P_2O_5	0.67	0.31	0.15	0.20
LOI	0.66	0.31	0.15	0.20
Total	99.67	99.74	100.32	99.92
K_{mg}	36.5	32.5	51.2	53.3

Note: Here and in Tables 2, 4, 5, and 6 K_{mg} = 100Mg/(Mg + Mn + Fe_{tot}), at. %; the dash means "not analyzed." Sample 90119/3 was analyzed at the Institute of Volcanology, Far East Division (FED), Russian Academy of Sciences (RAS), analyst T.G. Osetrova; the other samples at the Geological Institute, Russian Academy of Sciences, analyst E.V. Cherkasova.

The older of the two tephra units occurs in the lower portion of the sequence (Fig. 1) and consists of thin layers of black volcanic sand and fine ash, whose composition corresponds with the composition of amphibole-bearing, moderately potassic magnesian basalts (analyses 1–3 in Table 2). The age of the deposits was found to be 7600 years (hereafter all dates are carbon-14 ages) on the basis of their position between a marker of the Kizimen ash dated 7500–7600 years (Braitseva *et al.*, 1992) and the soil dated 7580 ± 120 and 7610 ± 60 years (Table 3). This unit has been correlated in different sections of the soil–pyroclastic cover for a distance of 25 km from the volcano over the entire perimeter of its base (Fig. 2). The patterns of the tephra distribution and stratification suggest that the material was deposited during an eruption that built a cinder cone on the near-crater slope of the Molodoi Shiveluch cone. The volume of the erupted tephra was not more than 0.1 km^3.

The younger basaltic tephra unit occurs at a higher interval of the sequence. It consists of stratified scoria lapilli and gravel at a distance of 20 km from the volcano and of volcanic sand further outward (Fig. 2). The scoria composition is similar to the composition of high-potassium phlogopite- and amphibole-bearing magnesian basalts, which are exotic for this area (analyses 5 and 6 in Table 2). Several carbon-14 age determinations of the soils and coals occurring immediately above and below the unit dated it to be 3600 years old (Fig. 1, Table 3). Large fragments of rocks having a similar composition (analyses 4 in Table 2) were found by one of the authors on the surface of the Baidarnyi Otrog of Staryi Shiveluch at distances of 4–6 km from the modern crater. It is likely that these are ballistic projectiles—erupted fragments that were hurled out of the crater along a ballistic trajectory in contrast to the tephra which were transported by an eruptive cloud. The discovery of these large blocks and the character of the tephra (angular and poorly vesicular particles) sug-

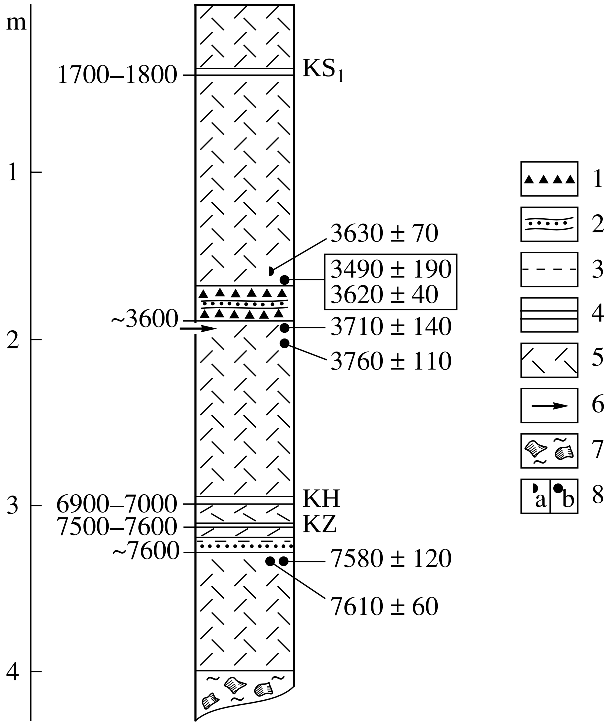

Fig. 1. Composite sequence of soil and pyroclastic beds at the foot of Shiveluch Volcano, showing basalt tephra units and their carbon-14 ages.

1, Scoria lapilli and gravel, 2, volcanic sand, 3, fine stratified ash, 4, ash markers: KS_1, Ksudach Volcano, KH, Khangar Volcano, KZ, Kizimen Volcano, all ^{14}C ages are given after Braitseva *et al.* (1992); 5, other soil and pyroclastic deposits; 6, stratigraphic position of a Shiveluch debris avalanche; 7, moraine; 8, material used for ^{14}C dating: a, coal; b, buried soil. Boxed figures are ages of successive alkali leachates from the same sample.

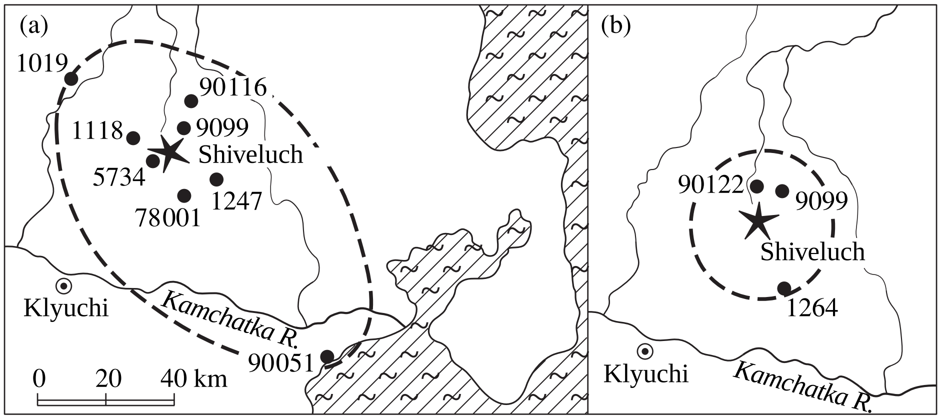

Fig. 2. Distribution of Shiveluch basalt tephra and sample sites.
(a) Eruption 3600 years ago, (b) eruption 7600 years ago.

gest that the ejected tephra were derived from some not completely solidified magmatic material. The tephra dispersal pattern indicates that the vent was not far from the present-day active volcanic apparatus. This conclusion agrees with our observation that approximately 100 years before this event the upper part of Molodoi Shiveluch Volcano collapsed, and a rockslide avalanche traveled for a distance of not less than 15 km (Ponomareva and Pevzner, 1994). This was similar to the avalanche of lithic debris that took place at Shiveluch during the 1964 eruption (*Deistvuyushchie vulkany...*, 1991; Belousov, 1992) and to the large landslide that occurred during the 1980 eruption of Mount St. Helens (*The 1980 Eruption...*, 1981). The landslide removed

Table 2. Representative analyses (wt %) of the Shiveluch basalt tephra

Oxide	$9099^b/7$	90122/2	1264/2	5734	1188/1	1188/19
	1	2	3	4	5	6
SiO_2	51.46	49.76	52.01	51.18	50.06	49.80
TiO_2	0.77	0.76	1.28	0.72	0.67	1.28
Al_2O_3	13.77	13.27	15.10	13.67	12.27	12.67
Fe_2O_3	2.69	2.60	3.62	3.20	3.12	3.87
FeO	5.69	6.29	4.25	5.55	5.52	4.92
MnO	0.15	0.16	0.14	0.18	0.13	0.17
MgO	11.33	13.26	9.57	12.08	15.02	12.19
CaO	6.32	7.60	7.66	8.36	8.46	9.19
Na_2O	2.38	2.38	2.77	2.55	2.31	2.28
K_2O	1.16	0.77	0.95	1.67	1.68	1.69
H_2O^-	–	–	1.04	0.10	–	0.34
H_2O^+	–	–	1.04	0.70	–	0.54
P_2O_5	0.12	0.10	0.11	0.37	0.56	0.24
LOI	4.08	0.94	0.68	–	0.64	0.42
Total	99.92	99.89	100.01	100.33	100.44	99.60
K_{mg}	74.4	73.3	69.2	71.9	76.3	72.1

Note: 1–3, tephra erupted 7600 years ago; 4–6, tephra erupted 3600 years ago. Analyses 1, 2, 4, and 5 were performed at the Institute of Volcanology, FED, RAS, analysts T.G. Osetrova and N.A. Solov'eva; analyses 3 and 6 at the Geological Institute, RAS, analysts E.V. Cherkasova and M.I. Stepanets.

Table 3. Radiocarbon ages of the Shiveluch Holocene basalt tephra

Age	Lab. sample no.	Sampling site	Material
3620 ± 40	GIN-7807g_I	W foot, Mutnyi Cr.	Soil
3490 ± 190	GIN-7807g_{II}	Same	Soil
3630 ± 70	GIN-7839	SE foot, Kabeku R.	Coal
3710 ± 140	GIN-7845	Same	Soil
3760 ± 110	GIN-7400	W foot, Mutnyi Cr.	Soil
7580 ± 120	GIN-7395	Kabeku R.	Soil
7610 ± 60	GIN-7814	Mutnyi Cr.	Soil

the upper part of the cone and created a huge horseshoe-shaped crater where a surface basalt body began to form. The eruption produced some 0.3 km^3 of tephra.

METHODS OF STUDY

The carbon-14 ages of the Shiveluch basalt tephra were determined at the Laboratory of Isotope Geochemistry and Geochronology of the Geological Institute, Russian Academy of Sciences, using a technique described by Sulerzhitskii (1976) and Braitseva *et al.* (1993). Trace elements were determined in tephra and lava samples by instrumental neutron activation analysis (New Mexico Institute for Mining and Technology, United States; Cornell University, United States; and Research Institute of Mineral Resources, Russia) and by XRF analysis (Copenhagen University, Denmark), using conventional techniques. The bulk chemical analyses of ash, tephra, and lava samples, carried out at the Institute of Volcanology, Far East Division, Russian Academy of Sciences, Petropavlovsk-Kamchatskii, and at the Geological Institute, Russian Academy of Sciences, Moscow, were done by wet methods with the exception of Na_2O and K_2O, which were determined by flame photometry. Minerals were analyzed using a Camebax X-ray microprobe at the Institute of Volcanology, Petropavlovsk-Kamchatskii.

HOLOCENE BASALT TEPHRA

Petrography. The volcanic sand and ash ejected by the eruption that occurred 7600 years ago consist of fragments of basalt, containing phenocrysts of olivine (up to 10 vol %) and clinopyroxene (2–4 vol %), subphenocrysts of plagioclase, and fragments of these minerals. The olivine phenocrysts are usually larger than those of clinopyroxene (up to 1.0–1.5 and 0.5–0.6 mm, respectively). The olivines contain spinel inclusions. The groundmass has an intersertal, pilotaxitic, or hyalopilitic texture and consists of plagioclase, olivine, clinopyroxene, orthopyroxene, and magnetite microlites and a varying amount of glass. Several tephra samples have been found to contain scoria fragments of basalt with amphibole phenocrysts; some of the tephra samples contain fragments of olivine–two-pyroxene–plagioclase basaltic andesite.

The tephra erupted 3600 years ago (e.g., Sample 1188/1) are dominated by particles of poorly vesicular basalt with phenocrysts of olivine (5–10 vol %), amphibole (15–20 vol %), clinopyroxene (2–4 vol %), and phlogopite (0–2 vol %) and scarce subphenocrysts of spinel, set in a hyalopilitic groundmass consisting of brownish glass and numerous microlites of plagioclase, clinopyroxene, orthopyroxene, and magnetite. The olivines usually contain spinel inclusions, which are much less numerous in the amphiboles. Fragments of olivine, amphibole, and intermediate plagioclase are scarce. The olivine and amphibole phenocrysts are usually large (1–2 mm, sometimes as large as 4–5 mm); the clinopyroxenes and phlogopites are smaller (max. 0.6 mm). The olivine grains are often surrounded with amphibole rims. The high-potassium basalt found in large blocks on the Baidarnyi Otrog (e.g., Sample 5734) is petrographically similar to this tephra but contains, in addition, numerous inclusions of ultrabasic rocks (dunite, harzburgite, and lherzolite) and melanocratic metamorphic rocks (schists).

Chemistry. As has been mentioned above, the tephra of both eruptions are similar in composition to magnesian basalts: the K_{mg} value (100Mg/(Mg + Mn + Fe$_{tot}$), at %) ranges between 69 and 78 in the samples of the older tephra (7600 years ago) and between 68 and 76 in the samples of the material deposited 3600 years ago (Fig. 3a). High K_{mg} values are also typical of the basaltic andesites and andesites of the Shiveluch cone, whereas the lavas of numerous independent centers on the southwestern slope of the volcano (e.g., Baidarnyi Otrog) are notably less magnesian with the same silica content (Fig 3a). It is important to mention that the lavas of small Pleistocene volcanoes located in the vicinity of the Shiveluch southwestern base (Kharchinskii basalt–basaltic andesite stratovolcano, Zarechnyi basalt–andesite volcano, and the Kharchinskii zone of basalt cinder cones) are also highly magnesian (the K_{mg} values of the basalts and andesites are 65–80 and 58–65, respectively). The K_{mg}–SiO_2 diagram of Fig. 3a shows that the regions of the basalt tephra of different ages overlap and that the region of the Shiveluch lavas continues their trend. Moreover, the basalts of both eruptions have low Al_2O_3 contents: eleven of the fourteen samples analyzed showed Al_2O_3 concentrations ranging between 11 and 14 wt %. This geochemical feature of the Holocene basalts was inherited by the Shiveluch basaltic andesites and andesites, whose Al_2O_3 contents range between 15 and 17 wt %.

Having similar Al_2O_3 concentrations and comparable K_{mg} values, the Holocene Shiveluch basalts are markedly different in K_2O content: the basalts erupted 7600 years ago are moderately potassic, whereas those erupted 3600 years ago are high-potassium rocks. The K_2O–SiO_2 diagram of Fig. 3b shows that the region of the older basalts is continued by the Shiveluch lavas, whereas the data points of the younger basalts form a distinct region of their own. A similar situation is observed when we compare the concentrations of lithophile trace elements, e.g., Rb and Ba, in the basalt tephra of the two eruptions and in the Shiveluch lavas (Figs. 4a, 4b, and Table 4). The Rb/Sr and Ba/Sr ratios are generally somewhat higher in the basalts erupted 3600 years ago (0.06–0.09 and 1–1.1, respectively) than in the basalts erupted 7600 years ago and in the Shiveluch lavas (0.03–0.05 and 0.6–1, respectively). The REE concentrations, however, are very slightly higher in the high-potassium basalts than in the medium-potassium variety, both rock types showing almost identical La/Yb ratios. This is also characteristic of the Shiveluch basaltic andesite and andesite lavas (Table 4, Fig. 5).

Generally, the lavas of Shiveluch Volcano and the adjacent volcanic centers are more magnesian and less aluminous than the lavas of the Klyuchevskoi volcanic group situated more southward (Melekestsev *et al.*, 1991). The latter are dominated by high-Al, medium- and low-magnesian varieties except for very scarce magnesian basalts found among the products of some flank eruptions of Klyuchevskoi Volcano and the Tolbachik regional zone of cinder cones (*Deistvuyushchie vulkany...*, 1991; Khubunaya *et al.*, 1993; Kerstig and Arculus, 1994; Ariskin *et al.*, 1995). Moreover, most of the magnesian basalts of the Tolbachik cinder cones and of the Klyuchevskoi flank eruptions (e.g., Bulochka, Novograblenov, Maleev, and Tuila), are notably higher in CaO and lower in K_2O than the basalts of Shiveluch and the adjacent volcanic centers (Fig. 6).

Rock-forming minerals have been studied only in the basalt erupted 3600 years ago (Table 5, Fig. 7). The phenocrysts of mafic minerals are not uniformly magnesian and often show distinct evidence of nonequilibrium. For instance, the olivine phenocrysts usually have cores of forsterite (Fo_{90-93}) and margins of chrysolite (Fo_{72-80}). Moreover, as was mentioned above, the olivine phenocrysts are often surrounded with amphibole rims. Chromian diopside with K_{mg} = 84–90 and 0.5–1.2 wt % Cr_2O_3 and augite with K_{mg} = 81–84 and 0.02–0.20 wt % Cr_2O_3 were found among the clinopyroxene phenocrysts. Some of the amphibole phenocrysts have magnesian (K_{mg} = 72–78) and some ferroan (K_{mg} = 61–67) cores. The former may have both

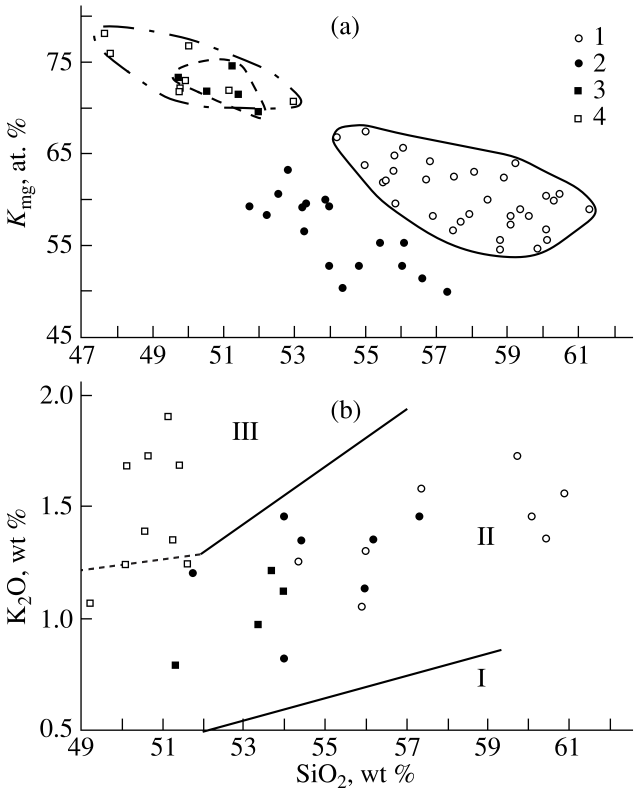

Fig. 3. Variations of K_{mg} values (a) and K_2O concentrations (b) as a function of SiO_2 contents in the Shiveluch rocks.

1, Shiveluch lavas; 2, lavas of Pleistocene lateral volcanic vents (Baidarnyi Otrog) and similar Shiveluch lavas; 3, basalt tephra ejected 7600 years ago; 4, basalt tephra ejected 3600 years ago. The region of the Shiveluch lavas is shown with a solid line, the field of the basalt tephra erupted 7600 years ago with a dashed line, the region of the basalt tephra erupted 3600 years ago with a dot-and-dash line. Figure 3b displays the regions of low-potassium (I), normal-potassium (II), and high-potassium (III) rocks after Peccerillo and Taylor (1976).

more ferroan and more magnesian margins with a small difference in the K_{mg} value (2–5) between the cores and margins, whereas the latter have more magnesian margins with a K_{mg} difference between the cores and margins ranging between 7 and 13. In terms of a ratio between the numbers of Al atoms in the tetrahedral coordination and Fe atoms in the formula unit of the mineral, the magnesian and ferroan amphiboles have been identified as hastingsite (most of the grains analyzed) or as ordinary magnesian–ferroan hornblende (a smaller amount of grains). The phlogopite is distinguished by the medium contents of Al_2O_3 (15–16 wt %) and TiO_2 (1.2–2.0 wt %) and a more narrow K_{mg} variation range as compared with the other minerals. The spinel contains 0.2–0.6 wt % TiO_2 and 42–55 wt % Cr_2O_3. Although the spinel which occurs as inclusions in the cores of the olivine phenocrysts is generally more magnesian than the spinel in the cores of the magnesian amphibole and chromian diopside phenocrysts (41–60 and 35–42, respectively), they have approximately similar $K_{Cr} = 100Cr/(Cr + Al + Fe^{3+})$ values (64–72 and 58–70, respectively). The spinel subphenocrysts are often surrounded with chromian magnetite rims. Chromian magnetite also occurs as inclusions in the ferroan amphibole phenocrysts and in the margins of the ferroan olivines with forsterite cores.

The clinopyroxene of the groundmass is augite (K_{mg} = 73–77), the orthopyroxene is ferrous bronzite (K_{mg} = 74–77), the plagioclase is labradorite (An_{54-66}), and the ore phase is titanomagnetite with a varying TiO_2 content (3–20 wt %) and a low K_{mg} value (9–12). The groundmass glass varies from latite to potassium rhyodacite (Table 5).

DISCUSSION

Interpretation of the nonequilibrium mineral associations in the Shiveluch lavas. The origin of the nonequilibrium mineral associations in the magnesian basalts can be interpreted in different ways. For instance, assuming the extent of iron oxidation in the basalt magmas to be 0.15 and taking the Mg distribution coefficient between the olivine and the magma to be 0.3, we calculated that the basalt of Sample 1188 (analysis 5 in Table 2) was in equilibrium with olivine $Fo_{91.8}$ and the basalt of Sample 90122 (analysis 2 in Table 2) with olivine $Fo_{90.7}$. Although this calculation is justifiable only for subaphyric rocks, it demonstrates that magnesian olivines, compositionally similar to the olivines from the basalts under study, might crystallize from magmas comparable with these basalts. However, the more magnesian olivines found in the rocks ($Fo_{92.4-93.0}$) must have crystallized from more magnesian magmas. Nevertheless, the primary high-magnesian nature of the Holocene basalts seems to be obvious enough. A particular supporting point is the fact that after the removal of olivine crystals from the magnesian basalt of Sample 5734 the residual material remained (according to the results of chemical analysis) highly magnesian (K_{mg} = 68), although, naturally, less magnesian than the original whole rock. The composition of the remainder (SiO_2 = 52.18, TiO_2 = 0.80, Al_2O_3 = 14.20, FeO* = 7.62, MgO = 9.00, CaO = 9.30, Na_2O = 3.20, K_2O = 2.11, P_2O_5 = 0.43, wt %) was close to the composition of a real magmatic rock found in the area—phlogopite–amphibole–clinopyroxene basalt from the neck of Kharchinskii Volcano (Tsvetkov *et al.*, 1993).

Olivines similar to the olivines examined ($Fo_{90.0-91.5}$) have been found in association with magnesian clinopyroxene (K_{mg} = 89–91) and chrome spinel (K_{cr} = 70–72) in the magnesian basalts (K_{mg} = 68–71) of flank eruptions at Klyuchevskoi Volcano (Khubunaya *et al.*, 1993; Ariskin *et al.*, 1995). The origin of these magnesian basalts, as well as the origin of the whole mineral association, was attributed to the high-pressure (*P* = 19 kbar) and high-temperature (*T* = 1350°C) crystallization of magnesian (K_{mg} ca. 70) basalt magma (Ariskin *et al.*, 1995) on the basis of petrologic factors (Khubunaya *et al.*, 1993) and computer simulation

Table 4. Contents of SiO_2 (wt %), potassium and trace elements (ppm) in the Shiveluch basalt tephra and lavas

Component	Tephra, 7600 years ago		Tephra, 3600 years ago					Lava	Extrusion
	90122/2	$9099^b/7$	1188/1	5734	1188/19	1247/1	1247/2	5764	5740
SiO_2	49.76	51.46	50.06	51.18	49.80	49.55	49.85	54.28	57.96
K	6392	9630	13947	13864	14030	11290	10875	10626	12120
La	7.88	8.24	8.96	11.0	(<10)	(<10)	(<10)	7.47	9.08
Ce	18.8	19.5	22.3	23.0	–	–	–	18.9	22.3
Nd	10.5	–	15.0	–	–	–	–	–	12.4
Sm	2.86	2.65	4.20	3.6	–	–	–	2.99	2.98
Eu	0.91	0.76	1.23	1.1	–	–	–	0.80	0.84
Tb	0.45	0.40	0.60	0.87	–	–	–	0.41	0.42
Yb	1.58	1.31	1.70	2.1	–	–	–	1.62	1.38
Lu	0.205	0.193	0.245	0.28	–	–	–	0.23	0.21
Y	–	–	(20)	(19)	(23)	(23)	(18)	(16.1)	(13)
Sr	330	310	(462)	(406)	(400)	(370)	(350)	(498)	497
Ba	242	238	(509)	(452)	(400)	(330)	(370)	330	482
Rb	16	–	36	(32)	(32)	(22)	(21)	(21.1)	(21.7)
Cs	0.91	1.32	1.00	–	–	–	–	0.60	0.71
U	0.5	0.5	0.6	–	–	–	–	0.54	0.66
Th	1.35	1.59	0.89	–	–	–	–	0.92	1.22
Hf	2.33	2.27	2.57	–	–	–	–	2.01	2.82
Ta	0.14	0.15	0.08	–	–	–	–	0.11	0.16
Nb	–	–	(2.3)	(2.3)	–	–	–	(2.5)	(3.0)
Co	45.5	43.8	46.8	46	–	–	–	34	25.5
Sc	28.9	24.1	33.0	36	–	–	–	28.9	19.1
Cr	725	722	884	790	–	–	–	483	307
Ni	–	–	(230)	(234)	–	–	–	(112)	72
V	–	–	(248)	(257)	–	–	–	(197)	(137)
La/Yb	5.0	6.0	5.3	5.2	–	–	–	4.6	6.6
Ba/La	31	41	41	41	–	–	–	44	33
K_{mg}	73.3	71.4	76.3	71.9	72.1	71.9	74.4	66.7	62.5

Note: The figures without parentheses are the results of instrumental neutron activation analysis obtained at the New Mexico Institute of Mining and Technology, USA, (samples S90122/2, $9099^b/7$, and 1188/1), at Cornell University, United States, (samples 5764 and 5740), and at the Research Institute of Mineral Resources, Russia (Sample 5734). The values in the parentheses were obtained by XRF at the Copenhagen University, Denmark, (samples 1188/1, 5764, and 5740).

(Ariskin *et al.*, 1995). The phenocrysts of this mineral association are accordingly nonequilibrium phases with respect to the minerals that crystallized from the same basalt magma at lower *P* and *T*. Nonequilibrium mineral associations are known to be widely developed in the highly magnesian and high-Al (highly fractionated) basalts of Klyuchevskoi Volcano. Some investigators (Khubunaya *et al.*, 1993; Kerstig and Arculus, 1994; Ariskin *et al.*, 1995) explain this phenomenon by the mechanical mixing of mineral phases and melts that originated during various periods of the primary magma evolution.

Many aspects of this situation can be found in the lavas of Shiveluch Volcano. The nonequilibrium mineral phases of the magnesian basalts have been discussed above. As regards the basaltic andesite and andesite lavas and pumice of this volcano, they usually contain, as can be seen in Fig. 7, larger or smaller amounts of highly magnesian olivine, clinopyroxene, and amphibole varieties, whose compositions are similar to the phenocryst minerals of the high-potassium magnesian basalt from the Holocene tephra. The relatively ferrous mineral phases of this basalt are compositionally similar to the minerals which occur as phenocrysts in the basaltic andesite and andesite lavas. These relations may be indicative of the admixture of andesitic material in the basalt, on the one hand, and of the presence of basaltic material in the andesite, on the

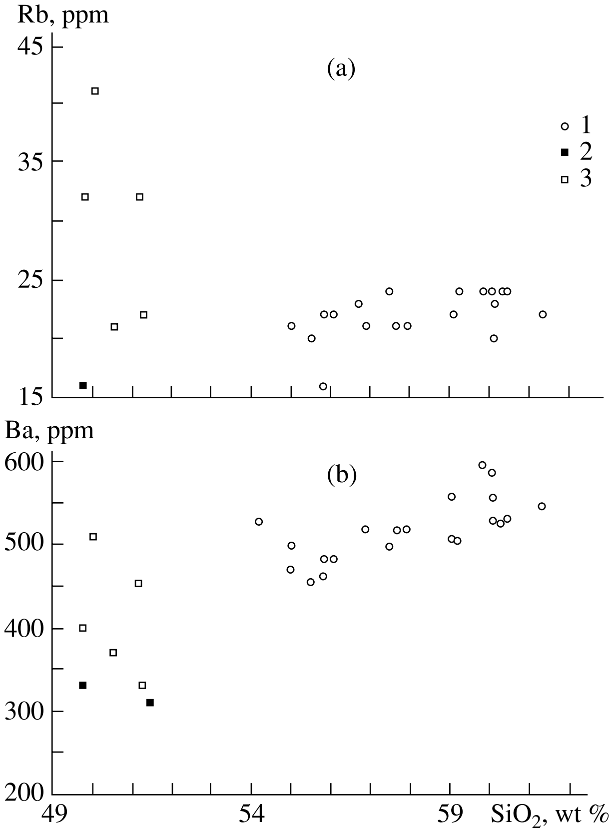

Fig. 4. Rb–SiO_2 (a) and Ba–SiO_2 (b) diagrams for the Shiveluch rocks.

1, Shiveluch lavas, 2, basalt tephra erupted 7600 years ago, 3, basalt tephra erupted 3600 years ago.

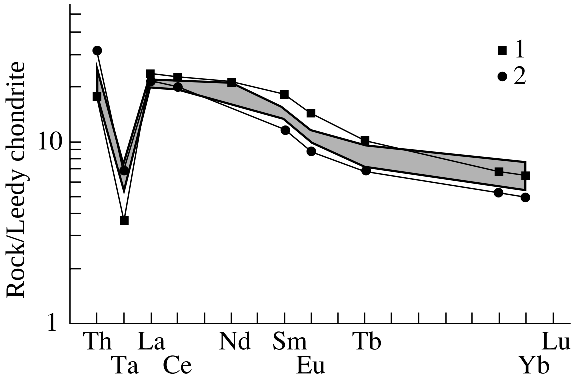

Fig. 5. Distribution of trace and rare earth elements.

1, High-potassium magnesian basalt erupted 3600 years ago (sample 1188/1), 2, medium-potassium magnesian basalt erupted 7600 years ago (Sample 9099b/7). The cross-hatched area is the region of the Shiveluch basaltic andesite and andesite lavas.

other. It is important that even the relatively ferrous minerals of the Shiveluch basaltic andesites and andesites are generally more magnesian than the respective mineral phases from the moderately magnesian calc-alkaline andesites of Kamchatka and the Kuril Islands (Fig. 7), this fact being additional evidence supporting the primary magnesian nature of the Shiveluch lavas.

Another interpretation of the occurrence of highly magnesian minerals in the rocks of Shiveluch Volcano assumes that the high-magnesian phenocrysts are foreign to them and that their unusual compositions and peculiar relations in the Shiveluch lavas can be accounted for by the contamination of the magma with ultramafic mantle material or by the disintegration of ultramafic xenoliths. The supporting evidence of this theory is the abundance of ultramafic xenoliths not only in the lavas and pumice of this volcano (Koloskov and Khotin, 1978), but also in the blocks of magnesian basalt on Baidarnyi Otrog. Moreover, the compositions of minerals from dunite–harzburgite xenoliths are generally compatible with the compositions of the magnesian minerals in the lavas (Table 6), which is consistent with the experimentally proved stability of these minerals in basalt melt (Kutolin *et al.*, 1976). However, there are some differences between the minerals of ultramafic xenoliths and those of the Shiveluch lavas.

Although the magnesian olivines from the Shiveluch lavas generally have rather low CaO contents (Fig. 8a), only a small group of their data points occurs in the region of the olivines from the dunite–harzburgite xenoliths of the Kamchatka and Kuril lavas, even though this region is larger than the field of olivines from mantle rocks proper (Hervig *et al.*, 1986). The other, larger group of data points representing the magnesian olivine cores shows CaO concentrations that are somewhat higher than the mantle CaO content (0.11–0.14 wt %). According to experimental studies (e.g., Kohler and Brey, 1990), the CaO content of olivines depends on pressure and temperature: it is believed that low concentrations of this element (<0.1 wt %) indicate that olivine crystallized at high pressure and low temperature. It is important to note in this context that the olivine from the Shiveluch rocks, varying from Fo_{79} to Fo_{93}, has a very narrow variation range of CaO concentrations and shows no correlation between these parameters (Fig. 8a). It can be concluded, therefore, that the relatively ferrous olivines of the $Fo_{79–85}$ composition can hardly be of mantle origin.

Weak positive and negative correlations have been established between the CaO contents and the mole fractions of the *Fo* component in the olivines of magnesian basalts from the Hawaiian Islands and Reunion: equally magnesian olivines from the same sample showed substantial CaO variations over the $Fo_{74–90}$ range (Sobolev and Nikogosyan, 1994). These authors reported that the CaO content in the olivine did not show any dependence on the CaO content in the host rocks. However, our data on the composition of olivine from the magnesian basalts of Kamchatka suggest that this dependence is quite possible. In the previous section, where we described the chemical compositions of the Shiveluch rocks, we mentioned variations in the

Table 5. Representative analyses (wt %) of phenocryst minerals and glass from the basalt tephra erupted 3600 years ago

Oxide	1188/1													
	Ol			*Spl*		*Cpx*			*Hbl*			*Phl*		*Gl*
	c	c	m	i_1	i_1	c	m	c	c	c	m	i_1	c	b
SiO_2	41.42	41.23	39.18	0.04	0.10	54.28	52.91	54.43	45.43	41.82	45.88	39.92	39.34	58.38
TiO_2	0.00	0.00	0.00	0.41	0.59	0.10	0.17	0.21	0.97	1.16	1.21	1.28	2.02	0.41
Al_2O_3	0.00	0.00	0.00	11.93	11.33	1.44	2.18	1.71	11.08	14.72	10.84	15.96	15.02	18.24
Cr_2O_3	0.08	0.10	0.08	54.25	45.50	0.49	0.07	0.06	0.30	0.03	0.10	1.35	0.00	0.00
Fe_2O_3	–	–	–	8.62	12.67	–	–	–	–	–	–	–	–	–
FeO	7.28	8.87	17.69	17.44	21.16	4.83	6.39	6.81	9.87	13.95	10.16	7.54	8.07	4.84
MnO	0.10	0.20	0.35	0.45	0.54	0.16	0.15	0.19	0.15	0.21	0.17	0.00	0.00	–
MgO	49.67	48.70	41.04	10.91	8.28	18.26	15.71	16.35	16.12	12.46	16.67	21.77	19.98	1.69
CaO	0.04	0.05	0.09	0.00	0.01	20.85	21.58	21.11	11.05	11.53	11.09	0.03	0.04	5.90
Na_2O	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.06	1.86	2.17	2.17	0.60	0.51	3.64
K_2O	0.00	0.00	0.03	0.03	0.04	0.00	0.03	0.02	0.85	0.77	0.90	8.92	9.18	3.86
Total	98.59	99.15	98.43	101.08	100.23	100.45	99.24	100.96	97.69	98.81	99.20	97.37	94.16	96.79
K_{mg}	92.3	90.5	80.2	52.1	40.5	86.7	81.4	80.5	74.2	61.1	74.2	83.8	81.5	38.4

Oxide	5734													
	Ol			*Spl*			*Cpx*			*Hbl*			Cr-*Mag*	*Gl*
	c	m	c	i_1	i_2	i_3	c	c	m	c	m	c	i_3	b
SiO_2	41.10	38.26	40.18	0.30	0.29	–	54.28	53.33	52.45	46.01	43.58	41.82	0.12	70.06
TiO_2	0.00	0.00	0.00	0.31	0.22	0.36	0.21	0.34	0.35	1.25	1.32	1.97	1.68	0.49
Al_2O_3	0.01	0.00	0.00	9.00	9.63	11.27	2.07	2.24	2.70	9.94	10.99	12.13	11.25	16.91
Cr_2O_3	0.04	0.02	0.06	54.84	52.69	51.66	1.23	0.13	0.17	0.09	0.03	0.04	9.49	0.03
Fe_2O_3	–	–	–	8.07	6.97	6.89	–	–	–	–	–	–	45.57	–
FeO	7.24	24.95	8.64	14.85	22.89	22.98	4.48	6.05	6.54	10.01	11.72	11.53	25.14	1.10
MnO	0.10	0.54	0.11	0.29	0.50	0.52	0.13	0.14	0.15	0.16	0.25	0.18	0.58	0.01
MgO	49.96	37.02	49.32	11.96	6.64	7.09	16.04	15.53	15.36	14.95	14.19	13.16	5.73	0.32
CaO	0.06	0.08	0.13	0.01	0.00	–	21.74	21.60	21.17	11.22	11.21	11.33	0.28	2.71
Na_2O	0.10	0.03	0.02	0.02	0.00	–	0.25	0.27	0.22	1.97	2.26	2.25	0.09	4.31
K_2O	0.00	0.00	0.00	0.00	0.00	–	0.01	0.00	0.01	0.53	0.73	0.79	0.00	5.80
Total	98.59	100.91	98.46	99.65	99.60	100.74	100.43	99.62	99.12	96.13	96.29	95.20	99.92	101.73
K_{mg}	92.4	72.1	90.9	58.5	33.6	35.0	86.1	81.7	80.4	72.7	67.9	66.7	28.4	33.7

Note: Here and in Tables 6 and 7 *Ol*—olivine, *Spl*—spinel, *Cpx*—clinopyroxene, *Hbl*—amphibole, *Phl*—phlogopite, Cr-*Mag*—chromian magnetite, *Gl*—glass; c—core, m—margin, i—inclusion in phenocryst (i_1 in *Ol*, i_2 in *Cpx*, i_3 in *Hbl*), b—basis. Here and in Table 6 the analyses were carried out on a Camebax X-ray microprobe at the Institute of Volcanology, FED RAS; analysts G.P. Ponomarev and T.M. Filosofova.

CaO content of magnesian basalts from the Tolbachik cinder cones and Klyuchevskoi flank eruptions (Fig. 6). This figure clearly shows three groups of rocks with progressively increasing CaO contents: (1) Shiveluch, Zarechnyi, and Kharchinskii volcanoes; (2) Klyuchevskoi Volcano; and (3) Tolbachik cinder cones. Accordingly, the CaO concentration in the Fo_{86-90} olivine from the Shiveluch basalts (0.05–0.13 wt %) is comparable with that of the Kharchinskii and Zarechnyi lavas (0.07–0.13 wt %), somewhat lower than that of the Klyuchevskoi lavas (0.11–0.18 wt %), and notably lower than that of the basalts from the Tolbachik cinder cones (0.19–0.28 wt %). It can thus be concluded that the low CaO concentration in the olivine of the Shiveluch lavas is not an indication of its mantle origin but can be attributed to the specific regional geochemistry of magmas.

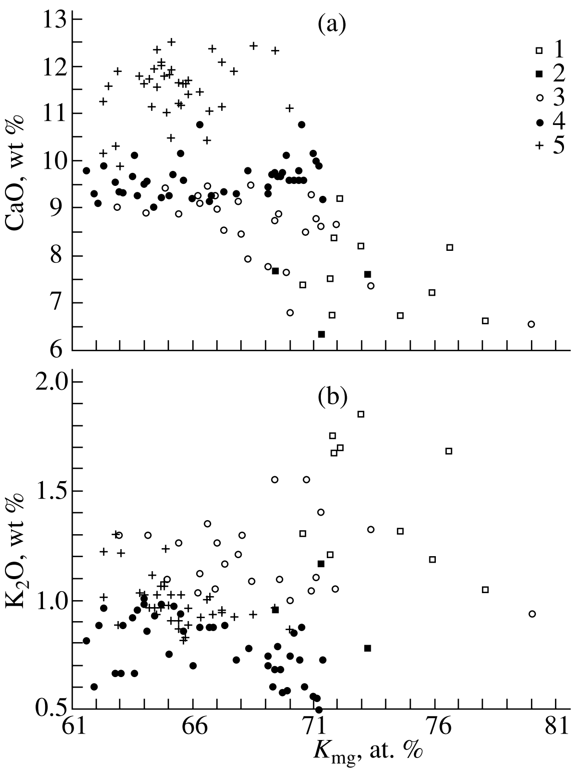

Fig. 6. Variations of CaO (a) and K_2O (b) contents as a function of K_{mg}.
1, Shiveluch Volcano, eruption 3600 years ago, 2, eruption 7600 years ago, 3, Kharchinskii and Zarechnyi volcanoes and Kharchinskii zone of areal eruptions, 4, some of Klyuchevskoi flank eruptions, 5, Tolbachik regional zone of cinder cones.

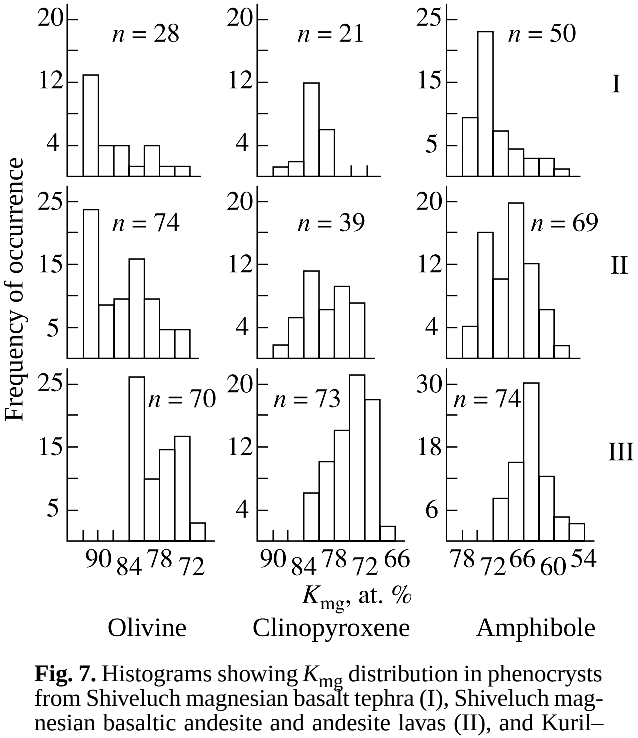

Fig. 7. Histograms showing K_{mg} distribution in phenocrysts from Shiveluch magnesian basalt tephra (I), Shiveluch magnesian basaltic andesite and andesite lavas (II), and Kuril–Kamchatka island-arc calc-alkaline medium-magnesian andesites (III).

The spinel occurring as inclusions in the highest magnesian olivines from the Shiveluch basalts and basaltic andesites is plotted in the region of the olivine–spinel association of mantle rocks after Arai (1992); its chromium content decreases but slightly with the successively decreasing magnesium content of the host olivines (Fig. 8b). At the same time, the basalts do not contain low-Ti spinel (0.00–0.15 wt %) or relatively aluminous spinel (K_{Cr} = 33–55), both characteristic of some ultramafic xenoliths.

The above data show that neither of the interpretations offered for the origin of high-magnesian minerals in the Holocene Shiveluch basalts can now be accepted unambiguously: neither the high-pressure and high-temperature crystallization of magnesian basalt magma, nor the contamination of magma by ultramafic mantle material or disintegrated ultramafic xenoliths. Moreover the compositional similarity of minerals from dunite–harzburgite xenoliths and phenocrysts forming as a result of high-pressure magnesian basalt crystallization is realistic: magnesian basalt magmas are generated and crystallize under *P–T* conditions close to the conditions at which mineral associations of ultramafic rocks are stable.

Genetic relations between compositionally different Shiveluch lavas. A comparative study of the Shiveluch magnesian lavas differing in silica content was undertaken as an attempt to find genetic relations between them.

The most distinct rocks of the volcano are the high-potassium magnesian basalts erupted 3600 years ago. They contain too much K_2O to be interpreted as the products of the evolution of the primary magma from which the medium-potassium magnesian basalts of 7600 years ago, as well as the later medium-potassium magnesian basaltic andesites and andesites, were derived. Indeed, though the high- and medium-potassium basalts are markedly different in their K_2O content, they have quite similar K_{mg} values, a fact prohibiting the formation of high-potassium basalt as the result of the fractionation of its medium-potassium analog. An attempt to compute the high-potassium basalt composition from the melt of the slightly more magnesian medium-potassium basalt by the removal of its magnesian olivine and chromian spinel (model 7 in Table 7) was unsuccessful mainly because of a considerable difference (ca. 50 rel. %) between the K_2O contents of the natural and calculated compositions. On the other hand, it is unlikely that the medium-potassium basaltic andesites and andesites of Shiveluch could be the fractionation products of the high-potassium magnesian basalt magma: being higher in SiO_2, they are lower in K_2O than the basalt. The only factor capable of modifying the composition of the derivative magma in this direction might be a mass phlogopite crystallization, but this is prohibited by the petrologic data.

Table 6. Representative analyses (wt %) of minerals from dunite–harzburgite xenoliths in the Shiveluch lavas

Oxide	5702						5734/2					5702/49		5743A
	Ol	*Ol*	*Spl*	*Spl*	*Spl*	*Opx*	*Ol*	*Spl*	*Opx*	*Cpx*	*Cpx*	*Ol*	*Spl*	*Spl*
SiO_2	40.80	40.72	0.00	0.00	0.00	58.00	40.31	0.12	57.47	54.44	54.14	40.52	–	–
TiO_2	0.00	0.00	0.00	0.00	0.14	0.00	0.04	0.45	0.05	0.05	0.05	0.00	0.37	0.28
Al_2O_3	0.00	0.00	16.55	24.15	33.59	1.06	0.08	12.07	0.62	1.00	1.21	0.00	10.9	9.05
Cr_2O_3	0.14	0.00	49.10	41.61	31.39	0.19	0.00	37.84	0.08	0.12	0.16	–	45.03	55.08
Fe_2O_3	–	–	7.30	7.31	7.26	–	–	17.61	–	–	–	–	14.90	6.93
FeO	6.46	9.04	13.96	12.99	12.04	4.65	8.84	20.49	6.56	2.96	2.89	8.60	20.12	20.75
MnO	0.15	0.10	0.27	0.27	0.22	0.17	0.21	0.35	0.26	0.10	0.13	–	–	0.40
MgO	51.02	49.77	13.42	14.99	16.70	35.29	48.51	10.35	33.00	17.52	16.86	49.44	8.33	8.35
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.65	22.41	22.96	0.05	–	–
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.02	0.08	0.10	0.00	–	–
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.00	–	–
Total	98.56	99.62	100.61	101.32	101.33	99.38	98.11	99.29	98.73	98.70	98.53	98.61	99.14	101.00
K_{mg}	93.4	90.8	63.1	67.3	71.2	93.1	90.5	47.4	89.6	91.0	89.5	91.1	42.5	41.8

Note: Samples 5702 and 5702/49—xenoliths in the andesite pumice of the 1964 eruption; samples 5734/2 and 5734A—xenoliths in the magnesian basalt erupted 3600 years ago.

At the same time the mineral and chemical compositions of the high-potassium magnesian basalts erupted 3600 years ago and the other Shiveluch lavas provide evidence of a certain succession. Examples are the occurrence of magnesian olivine phenocrysts containing inclusions of Cr-rich spinel in all rock varieties and the fact that all of the Shiveluch magnesian lavas have a common trend in the SiO_2–K_{mg} diagram (Fig. 3a). It is likely that these features point to some affinity between the sources of magmas parental to the rocks discussed.

The mutual arrangement of the data points of the Shiveluch basaltic andesites and andesites on the SiO_2–K_2O, SiO_2–Rb, and SiO_2–Ba diagrams (Figs. 3b, 4a, and 4b, respectively) shows that the genesis of these rocks as a result of medium-potassium magnesian basalt magma fractionation is more realistic. As follows from the data listed in Table 7, this process can be simulated by computing the mass balances of the components involved using the least squares approximation. For instance, the basaltic andesite (Sample 5764) could be derived from the melt of the medium-potassium magnesian basalt (sample 90122/2) as a result of the simultaneous removal of magnesian olivine and Cr-rich spinel (magnesian basalt protocrysts), as well as of magnesian amphibole and Cr-bearing magnetite (sub-

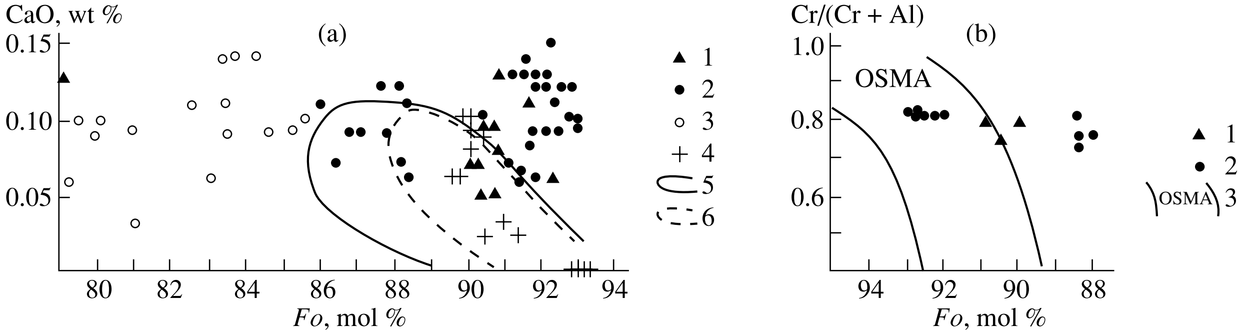

Fig. 8. Compositions of olivine phenocrysts (a) and spinel inclusions in them (b) from Shiveluch lavas.

(a): 1, Phenocrysts of magnesian basalts (samples 5734 and 1188/1); 2, 3, phenocrysts of Shiveluch magnesian basaltic andesites (samples 5764 and 5749/6): 2, cores, 3, margins; 4, olivines from dunite–harzburgite xenoliths in Shiveluch lavas; 5, region of olivines from ultramafic xenoliths in Kuril–Kamchatka island-arc lavas; 6, region of olivines from mantle rocks (Hervig*et al.*, 1986; Sobolev and Nikogosyan, 1994).

(b): 1, olivine–spinel paragenesis of Shiveluch magnesian basalts (samples 5734 and 1188/1); 2, olivine–spinel paragenesis of Shiveluch basaltic andesites (samples 5764 and 5749/6); 3, region of olivine–spinel paragenesis of mantle rocks after Arai (1992).

sequent phenocrysts). However, in spite of the low sum of squared residuals (model 1 in Table 7), the relative error of the K_2O content was as large as 18% with the K_2O percentage of the model composition being lower than that of the real rock. The computed K_2O content was almost equal to the real value (with a difference of less than 1 rel. %) when the melt of the Kharchenskii magnesian basalt (Sample 1023) was used as the primary magma: the K_2O content of this basalt is almost equal to that of the basalt erupted 7600 years ago with the K_{mg} value being considerably higher (K_{mg} = 80) (model 2 in Table 7). The results of further computations showed that the acid basaltic andesites and andesites could be derived as a result of the fractionation of the basic basaltic andesite magma with the removal of magnesian olivine along with clinopyroxene, plagioclase, and magnetite (models 3 and 4 in Table 7). The formation of the acid andesite magma could take place by either of the following two mechanisms: (1) the fractionation of the acid basaltic andesite magma with the removal of the mineral association comprising the protocrysts and the later phenocrysts—magnesian olivine + clinopyroxene + spinel + amphibole + magnetite (model 5 in Table 7) or (2) the removal from the andesite magma of the late minerals—relatively ferrous olivine, plagioclase, and amphibole (model 6 in Table 7). In both cases the K_2O content of the computed composition was higher than in the real one: 5 rel. % higher in model (1) and 12 rel. % higher in model (2).

Despite a good agreement between the model and real compositions, the results of the computation cannot be taken as direct proof that the Shiveluch magnesian basaltic andesites and andesites were formed as a result of the fractional crystallization of moderately potassic magnesian basalt magma. Moreover, the almost equal concentrations of many incompatible trace elements, including REE, Th, U, Hf, and Ta, in the basic basalt andesites (analysis 8 in Table 4) and in the moderately potassic magnesian basalts (analyses 1 and 2 in Table 4) contradict the fractionation theory. The genesis of the Shiveluch andesites from the fractionating basaltic andesite magma seems to be more realistic: this mechanism has been confirmed not only by the satisfactory results of the model computations but also by the fact that the real rocks show the same shift in the concentrations of the above-mentioned incompatible elements.

We considered another possible interpretation of the genesis of the magnesian basaltic andesites and andesites and of the fact that they show some mineralogic and geochemical affinity to the basalts. In accordance with Kelemen's (1990) model, magnesian basaltic andesites and andesites can be derived as a result of interaction (assimilation–fractionation–contamination) between mantle magnesian basalts and depleted harzburgite mantle immediately below the crust. This mechanism can account for the fact that the magnesian basaltic andesites and andesites contain nonequilibrium magnesian olivine crystals with chromian spinel inclusions and orthopyroxene and amphibole rims (these may be mantle material xenocrysts or magnesian basalt phenocrysts). This assumption is supported by the occurrence of numerous ultramafic xenoliths both in the basaltic andesites and andesites and in the magnesian basalts of the volcano.

The results of experimental studies (Elthon *et al.*, 1984) indicate that melts with K_{mg} values similar to those of the Shiveluch magnesian basalts might be in equilibrium with olivine Fo_{91-93} at pressure around 15 kbar and temperature of 1400°C. The presence of amphibole in the basalts suggests a substantial water content in their parent magma. This suggestion is corroborated by analogy with the primary magmas of the Klyuchevskoi magnesian basalts, which have been proved to contain much water (Sobolev and Chaussidon, 1996). The amphibole itself obviously crystallized at a shallower depth, in the region of interaction

Table 7. Computed fractional crystallization models

Model	Rock		Component							R
	primary	final	melt	*Ol*	*Spl*	*Cpx*	*Mag*	*Pl*	*Hbl*	
1	90122/2	5764	0.831	0.120	0.004		0.020		0.025	0.262
2	1023	5764	0.739	0.258	0.004					0.567
3	5764	5749	0.806	0.340		0.056	0.006	0.100		0.167
4	5749	5740	0.829	0.031		0.071	0.020	0.049		0.136
5	5749	7401	0.792	0.038	0.001	0.003	0.006		0.160	0.017
6	5740	7401	0.849	0.010				0.018	0.123	0.077
7	90122/2	5734	0.960	0.035	0.005					1.305

Note: Sample 90122/2—analysis 2 in Table 2; Sample 5764—basaltic andesite (54.28 wt % SiO_2, 8.41 wt % MgO); Sample 5749—basaltic andesite (55.59 wt % SiO_2, 7.44 wt % MgO); Sample 5740—andesite (57.96 wt % SiO_2, 5.58 wt % MgO); Sample 7401—andesite (61.84 wt % SiO_2, 3.97 wt % MgO); Sample 1023—magnesian basalt of Kharchinskii Volcano (51.28 wt % SiO_2, 18.88 wt % MgO, 0.93 wt % K_2O); Sample 5734—an. 4 in Table 2; R, sum of squared residuals. The blanks in the columns denote that these minerals were not used in the computation.

between basalt magma and mantle harzburgite at T = 1000–1050°C.

The CaO content of the Shiveluch basalts, lower than that of the Klyuchevskoi magnesian basalts (Fig. 6), suggests a more depleted (probably harzburgite) source from which they were melted; their higher K_2O contents suggest the secondary enrichment of this primary depleted source by fluids or partial melts from the subducted plate. Variations of the K_2O concentrations in the basalts erupted 7600 and 3600 years ago were most likely caused by injections of magma from chambers located in differently enriched mantle regions without (for the basalts erupted 7600 years ago) and with phlogopite (for the basalts erupted 3600 years ago).

The basalt eruptions during the Holocene eruptive history of the Shiveluch andesite volcano do not seem to be accidental: although the volumes of the basalt tephra they produced were smaller than the tephra volumes of very large explosive eruptions, these events reflected some important tectonomagmatic rearrangements in the region of the volcano's magma source. This view is supported by the coincidence of these eruptions with some regional volcanic events of Kamchatka. The eruption that occurred 7600 years ago coincided with the most powerful paroxysm of Holocene explosive activity, which occurred in Kamchatka 7800–7500 years ago when the huge Karymskaya and Il'inskaya (Kuril Lake) calderas were formed, and very large eruptions took place at some other volcanoes (Braitseva *et al.*, 1994). The eruption that occurred 3600 years ago was contemporary with major events such as the outbreak of Klyuchevskoi flank eruptions and the beginning of the growth of the Molodoi (young) cone on Avacha Volcano (Braitseva *et al.*, 1994).

CONCLUSION

(1) This study has revealed that two basalt eruptions occurred at Shiveluch 7600 and 3600 years ago during the Holocene activity of this andesite volcano. The eruptions were synchronous with the periods of regional intensification of volcanic activity in Kamchatka, obviously associated with some tectonic events that promoted the rise of magma to the surface.

(2) The basalts of both eruptions are high-magnesian rocks, are equally low in Al_2O_3 and CaO, but differ in K_2O content: the basalts erupted 7600 years ago, as all other Shiveluch lavas, are moderately potassic rocks, whereas those erupted 3600 years ago are high-potassium lavas. On the diagrams of the pair correlations of K_2O, Rb, and Ba with SiO_2, the basalts of the earlier event are plotted on the trend of the basaltic andesite and andesite lavas of the volcano, whereas the younger basalts form an isolated field.

(3) The basalts of both eruptions are similar in their K_{mg} value and CaO content to the basalts of the nearby volcanoes Zarechnyi and Kharchinskii and the Kharchinskii zone of areal eruptions (the moderately potassic basalts being similar in their K_2O content). They differ from the magnesian basalts of the Klyuchevskoi volcanic group by their lower CaO concentrations and higher K_2O contents and are obviously the products of the partial melting of CaO-depleted (harzburgite) mantle material, which had been subject to potassium metasomatism.

(4) The basalts erupted 3600 years ago contain nonequilibrium mineral associations: phenocrysts of olivine with forsterite cores containing Cr-rich spinel inclusions, as well as phenocrysts of chromian diopside and phlogopite coexist with chrysolite (rims on the phenocrysts) and the phenocrysts of augite and relatively magnesian and relatively ferrous amphibole. Mineral associations of this kind may result from the mixing of the products of basalt magma fractionation at different pressures and temperatures or from basalt magma contamination by ultramafic mantle material.

(5) The results of numerical modeling agree with the theory that the Shiveluch basaltic andesites and andesites were formed as a result of fractional crystallization of magma compatible with the basalt erupted 7600 years ago, but the patterns of incompatible trace element distribution contradict this theory. P. Kelemen's model offers a more realistic interpretation: magnesian andesite melt was generated by the interaction of magnesian basalt magma with harzburgite mantle immediately beneath the crust. The phenocrysts of magnesian olivine with Cr-rich spinel inclusions and reaction rims of rhombohedral pyroxene and amphibole found in the basaltic andesites and andesites are likely to be mantle material relicts or high-pressure phenocrysts of magnesian basalt magma.

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