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The Problem of Genetic Relations between High-Aluminous and High-Magnesian Basalts of the Klyuchevskoi Volcano, Kamchatka

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Close association between primitive high-magnesian and more ferrous high-aluminous basalts is established at a number of island-arc volcanos. The nature of genetic relations between the varieties presents a complicated petrological problem [3, 11, 14, etc.].

The eruption products of the Klyuchevskoi Volcano, among which high-aluminous basalts predominate, are a typical example of this association. The idea of the unified original magma of the Klyuchevskoi Volcano is widely developed in geological literature [5, 8]; however, opinions vary as to its magmatic source and composition. A high-aluminous original melt is preferred by some researchers [4, 12]. A number of petrologists, including the authors of this study, believe that the high-aluminous basalts are the differentiation products of high-magnesian magmas [1, 2, 6, 7, 15].

Our conclusions are based on the following: (1) the monotonous character of petrochemical trends from high-magnesian (MgO 12%, Al_2O_3 14%)[1] to high-aluminous (MgO 4.5%, Al_2O_3 19%) basalts attests that a common evolutionary series of magmatic melts exists within the feeding system of the Klyuchevskoi Volcano; (2) the regular decrease of the magnesium value [Mgn = 100MgO/(MgO + FeO)] in olivine and clinopyroxene from the phenocryst cores (91–89) through their rims to the microlites (up to 64) reflects the depletion of the melt in MgO; (3) the high *Mgn* values for olivine and clinopyroxene cores noted in both the high-aluminous and high-magnesian basalts suggest that the most Mg-rich and dark-colored minerals crystallized from the high-magnesian magmatic melt.

Important information on the formation conditions of the magmatic series of the Klyuchevskoi Volcano can be derived from study of the chemical composition of solid-phase crystalline inclusions, which are very abundant in the rock-forming minerals of high-magnesian and high-aluminous basalts. This paper presents the results of detailed mineralogical studies of high-aluminous basalts of the Zavaritskii outburst. These data form the empirical basis for the following model of high-aluminous basalt formation from the high-magnesian melt.

The Zavaritskii outburst (1945) is one of the best studied subsidiary eruptions of the Klyuchevskoi Volcano [8]. The rocks formed as a result of this outburst compose the volcano's cone; they are characterized by a regular porphyric texture and belong to typical aluminous basalts. The rock-forming minerals are represented by olivine, clinopyroxene, and predominant plagioclase. These minerals are encountered as phenocrysts, subphenocrysts, and microlites.

Since the phenocrysts and subphenocrysts of dark minerals are rare (< 5%) in the Zavaritskii outburst rocks, the following method was used to separate them from the bulk rock in further investigation of the solid-phase inclusions. Olivine and clinopyroxene grains were extracted from the coarse basalt fraction (2–1 and 1–0.5 mm) in bromoform and then selected under a binocular microscope. Separated crystals were arranged inside a ring and poured over by epoxy glue; the obtained slab was then finely polished. This technique was not applied to plagioclase, which is very abundant in the rock and was studied in polished sections. Crystalline inclusions were analyzed in couples with their host minerals using a Camebax X-ray microspectrometer.

The crystalline inclusions are found in olivine, clinopyroxene, and plagioclase and represented by silicates (olivine, clinopyroxene, and orthopyroxene) and ore minerals (chromospinel and titanomagnetite). Inclusion sizes are in the range of 10–40 μm. Good correlation is noted between the *Mgn* values of clinopyroxene inclusions (89–75) and clinopyroxene-hosting olivine (89–75), on the one hand, and olivine inclusions (78–68) and olivine-hosting clinopyroxene (81–73), on

[1] From here on wt% are used.

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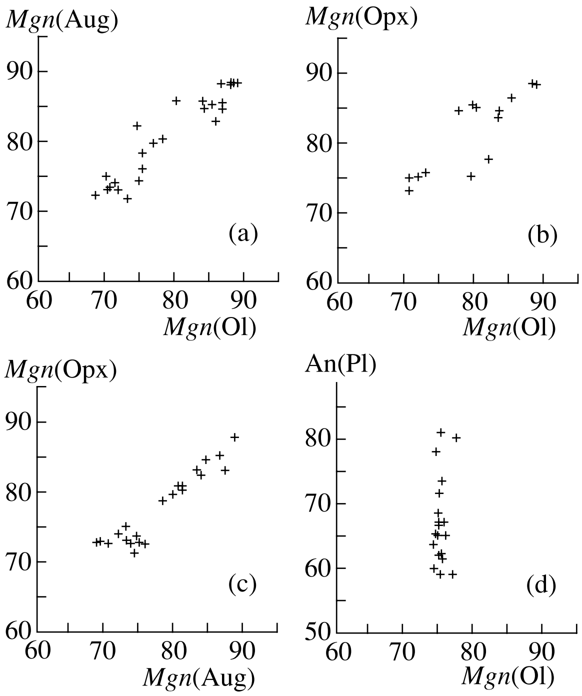


Fig. 1. Relationship between compositions of solid phase inclusion and host mineral in the aluminous basalts of the Zavaritskii outburst: (a) olivine inclusions in clinopyroxene and clinopyroxene inclusions in olivine (Aug is high-calcium pyroxene); (b) orthopyroxene inclusions in olivine; (c) orthopyroxene inclusions in clinopyroxene; (d) olivine inclusions in plagioclase. $Mgn = 100\mathrm{Mg}/(\mathrm{Mg} + \mathrm{Fe}^{2+})$, $\mathrm{An} = \mathrm{Ca}/(\mathrm{Ca} + \mathrm{Na} + \mathrm{K})$.

the other. These data for coexisting olivine and clinopyroxene couples are generalized in Fig. 1a. The correlation of *Mgn* values of orthopyroxene inclusions (89–72) with those of orthopyroxene-hosting olivine (89–68) and clinopyroxene (89–69) is shown in Figs. 1b and 1c. As can be seen in Fig. 1d, only low-magnesian olivine (on average, *Mgn* = 75) and clinopyroxene (on average, *Mgn* = 72) inclusions were captured by plagioclase (host mineral) in the course of its crystallization.

These data, with consideration made for the previously established trends of *Mgn* variation in the dark minerals (from the phenocryst cores to their rims and microlites), suggest that at first, high-magnesian olivine (*Mgn* = 91–90) and clinopyroxene (*Mgn* = 91–90) almost simultaneously crystallized on the liquidus of the original high-magnesian melt. Somewhat later, high-magnesian orthopyroxene (*Mgn* = 89–88) crystallized. The presence of low-magnesian olivine (on the average, *Mgn* = 75) and clinopyroxene (on the average, *Mgn* = 72) inclusions in plagioclase and the insignificant dispersion of their compositions show that plagioclase is the later crystallizing phase, capturing the low-magnesian dark minerals at the final stages of the original melt fractionation.

Combined examination of compositions of spinellide inclusions in olivine and plagioclase yields additional information on the crystallization of plagioclase and ore minerals. As olivine crystallization proceeded (from the high- to the low-magnesian stage), TiO_2 and Cr_2O_3 contents in spinellide microinclusions varied significantly. Thus, when the *Mgn* value in olivine is equal to 76–73, the chromium oxide content drops, while the titanium oxide content steeply rises. Only titanomagnetite inclusions with low Cr_2O_3 content (<1%) were found in plagioclase over the entire course of plagioclase crystallization (An_{84-59}). Such inclusions are similar to those in low-magnesian olivine (*Mgn* = 76–64). This fact is another argument in favor of later plagioclase crystallization relative to high-magnesian olivine and pyroxene.

Presented data point to the successive change of parageneses during the crystallization of the magmatic melt that formed the high-aluminous basalts: the most magnesian olivine (*Mgn* = 91), clinopyroxene (*Mgn* = 91; $En_{49}Wo_{43}Fs_6$), orthopyroxene (*Mgn* = 89; $En_{86}Wo_3Fs_{11}$), and chromospinel (Cr_2O_3 47%, TiO_2 0.5%, MgO 11%, Fe^{2+}/Fe^{3+} 1.6) formed first; later, plagioclase, low-magnesian olivine and clinopyroxene, and titanomagnetite crystallized.

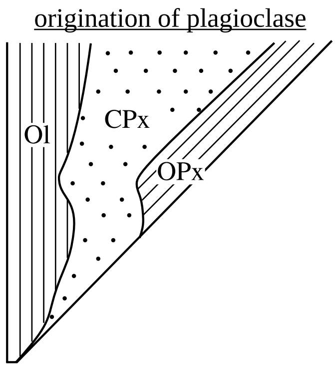
The petrochemical and mineralogical data suggest that the whole basalt series of the Klyuchevskoi Volcano, from high-magnesian to high-aluminous basalt, formed as a result of large-scale fractionation of the primitive basalt magma. This original magma was equilibrated with high-magnesian olivine and clinopyroxene (*Mgn* ~ 91) and high-chromium spinellide, which represent the earliest paragenesis of crystallizing minerals. The fractionation is accompanied by loss of MgO and CaO in the melt evolution and complementary enrichment of magma with the minor constituents of dark minerals (Al_2O_3 above all).

This conclusion is supported by the results of computer modeling obtained with KOMAGMAT software of polybaric fractionation of high-magnesian magma of Klyuchevskoi Volcano [13]. Computation of more than 600 model variants of fractional crystallization of the assumed original magma (average high-magnesian basalt) under isobaric and decompression conditions was performed for water-free and water-containing systems [1]. Computation was carried out for the pressure interval 0–20 kbar with a fractionation step equal to 1 wt %. Oxygen fugacity was buffered by the quartz–fayalite–magnetite equilibrium (QFM).

The main computation results obtained for the optimal model are given in the table. It was established that high-aluminous melts can be formed from high-magnesian melts under decompression fractionation in water-containing systems when phase crystallization and fractionation occur on a pressure decrease of approximately from 19 to 7 kbar. The calculated temperatures for this process range within 1350–1100°C; about a 2% H_2O concentration in the original melt is necessary to provide for formation of the whole composition range of basalts of the Klyuchevskoi Volcano. Another impor-

Results of computer modeling of the formation of high-aluminous basalts of the Klyuchevskoi Volcano by the decompression fractionation mechanism

Composition of minerals				F	Fractionation of minerals, wt %	P, kbar	T,°C	Natural and model melt compositions							
Ol	CPx	OPx	Pl					SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O
79	77	82	70	37		7.0	1104	53.5	1.1	18.3	8.7	5.2	8.2	3.5	1.2
80	78	83		35		7.8	1118	53.1	1.1	18.0	9.1	5.5	8.3	3.6	0.9
82	81	84		30		9.4	1154	52.8	1.1	17.3	9.2	6.3	8.8	3.4	0.9
84	83	86		25		11.1	1189	52.5	1.0	16.6	9.2	7.1	9.3	3.2	0.8
86	85	87		20		12.7	1225	52.1	1.0	15.9	9.2	8.1	9.6	3.0	0.8
87	87	88		15		14.4	1254	52.6	1.0	15.4	9.0	8.7	9.5	2.8	0.7
88	88			10		16.0	1285	52.4	0.9	14.4	8.9	9.5	9.7	2.7	0.7
89	89			5		17.7	1315	52.1	0.9	14.4	8.9	10.4	9.8	2.6	0.7
90	90			0		19.3	1351	51.8	0.9	13.9	8.8	11.6	9.7	2.5	0.6



Computation was performed using KOMAGMAT-3.0 software [13]. The composition of the average high-magnesian basalt of the Klyuchevskoi Volcano taken as the primary magma composition [1] is given within the lower frame; the composition of the average high-aluminous basalt of Klyuchevskoi Volcano [1] is given within the upper frame; F is the degree of melt crystallization (wt %). Olivine, clino-, and orthopyroxene compositions are given in terms of magnesium value (*Mgn*); plagioclase is characterized by anorthite content, mol %. The modeled melt compositions are reduced to those in water-free system and adjusted to 100 wt %.

tant result of the computations performed is the determination of proportions of the fractionating minerals specifying the direction of the modeled petrochemical trends (see table). The data on the modeled mineral compositions given in the table are in general agreement with the foregoing microprobe data.

Thus, the crystallizational fractionation resulting from gravitational separation of crystalline phases and melt within the vertical feeding system of the volcano is the most likely mechanism, providing the observed diversity of the Klyuchevskoi Volcano basalts. From geophysical data, the magmatic-generating system of the volcano is fed by the mantle and characterized by the absence of large crustal and peripheral chambers [10]. Hence, this system is assumed to be a permanently active magmatic column, within which fractionation occurs under the decompression of the crystallizing melt; magnesium and other femic element concentrations increase with depth, and the upper part of the column is occupied by magma of a composition corresponding to the most fractionated aluminous basalts. From the computer-modeled data, the large-scale fractionation accompanied by separation of great quantities of femic minerals takes place at pressures from 19 to 6–7 kbar, that is, at a depth of more than 20 km. The fractionation processes are also likely to continue at shallow depths along the whole magmatic column. Crystallization of the femic minerals, which originated at greater depths, and plagioclase continues as the magma rises. This results in the formation of more and more aluminous magmas of lesser density. This conception is in good agreement with the data on density characteristics of magmatic material in the feeding system of the Klyuchevskoi Volcano [9].

The proposed model makes it possible to explain the abundance of the aluminous basalts, up to high-aluminous varieties, within the Klyuchevskoi Volcano cone and the presence of magnesian basalts in outbursts, at lower hypsometric levels.

CONCLUSIONS

(1) The possibility of restoring the mineral crystallization sequence was demonstrated on the basis of detailed microprobe compositional studies of solid phase inclusions in rock-forming minerals of aluminous basalts with a wide composition range of dark, rock-forming minerals. Thus, the crystallization history of the original magmatic melt can be deduced when highly fractionated aluminous lavas are under study.

(2) As the obtained data show, during the formation of the Klyuchevskoi magmatic series, including all basalt varieties, from high-aluminous to high-magnesian, the rock-forming minerals crystallized in the following succession: the most magnesian olivine, clinopyroxene, orthopyroxene, and ore-mineral chromospinel formed first; later, plagioclase, low-magnesian olivine and clinopyroxene, and magnetite crystallized. It is of principle importance that the high-magnesian olivine, clinopyroxene, and orthopyroxene, which crystallized from more magnesian melts, are nonequilibrium relative to the total rock composition of aluminous basalts.

(3) The early mineral paragenesis including the most magnesian olivine (*Mgn* = 91) and clinopyroxene (*Mgn* = 91; $En_{49}Wo_{43}Fs_6$) and chromospinelide (Cr_2O_3 47%, TiO_2 0.5%, MgO 11%, Fe^{2+}/Fe^{3+} 1.6) corresponds to the high-pressure equilibrium of the high-magnesian basalt with the melt [1]. This composition can be considered as primary for the whole basalt series of the Klyuchevskoi Volcano.

(4) The results of mathematical modeling obtained with the use of KOMAGMAT-3.0 software indicate that the fractionational crystallization of the primary high-magnesian magma occurred under decompression conditions on a monotonous pressure decrease from 19 to 7 kbar within the temperature range of 1350–1110°C at approximately 2% H_2O in the primary melt. Such a fractionation regime provides for the formation of a melt identical to the high-aluminous basalt of the Klyuchevskoi Volcano if 36% of the solid phase represented by dark minerals is eliminated.

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