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# Final Stages of Magma Evolution in Klyuchevskoy Volcano, Kamchatka: Evidence from Melt Inclusions in Minerals of High-Alumina Basalts

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Received October 10, 1999

**Abstract**—Magmatic inclusions were studied in phenocrysts from the high-alumina basalts of Klyuchevskoy Volcano, with special emphasis on melt inclusions in olivine ( $For_{71-79}$ ), clinopyroxene ( $Mg\# = 70-81$ ), and plagioclase ( $An_{47-84}$ ) phenocrysts. Glassy melt inclusions were analyzed for major elements by an electron microprobe, and water content was estimated by various calculation methods. The data obtained allowed us to estimate the physicochemical conditions of melt crystallization. Variation in water content was the major factor controlling liquidus phase relationships of the melts. Water accumulation during olivine and clinopyroxene crystallization resulted in delay of plagioclase crystallization and melt enrichment in  $Al_2O_3$  producing magmas chemically similar to high-alumina basalt. The subsequent evolution of melt composition was controlled by plagioclase crystallization from the magma, which resulted in melt depletion in  $Al_2O_3$ . The phenocrysts of olivine ( $For_{71-79}$ ), clinopyroxene ( $Mg\# = 70-81$ ), and plagioclase ( $An_{47-84}$ ) of high-alumina basalts crystallized from compositionally diverse melts at temperatures 1145–1030°C and pressures no higher than 3.0–3.5 kbar (1.5 kbar, on the average). The earliest of these phenocrysts correspond to melts containing ~5–6 wt % MgO and varying amounts of  $Al_2O_3$  (16–20 wt %) and  $H_2O$  (0–5 wt %). A model is proposed for the final stage of the Klyuchevskoy Volcano magma evolution. According to this model, the crystallization of minerals of the high-alumina basalts occurred under conditions of rapid decompression during magma ascent toward the surface and was accompanied by a decrease in  $H_2O$  content owing to degassing of the magma. It was shown that the formation of dacite melt trapped by the plagioclase and clinopyroxene phenocrysts was probably related to the processes of extensive crystal fractionation of initial basaltic magmas. The formation of more silicic melts can be explained by the specific mechanism of melt inclusion entrapment by plagioclase crystals.

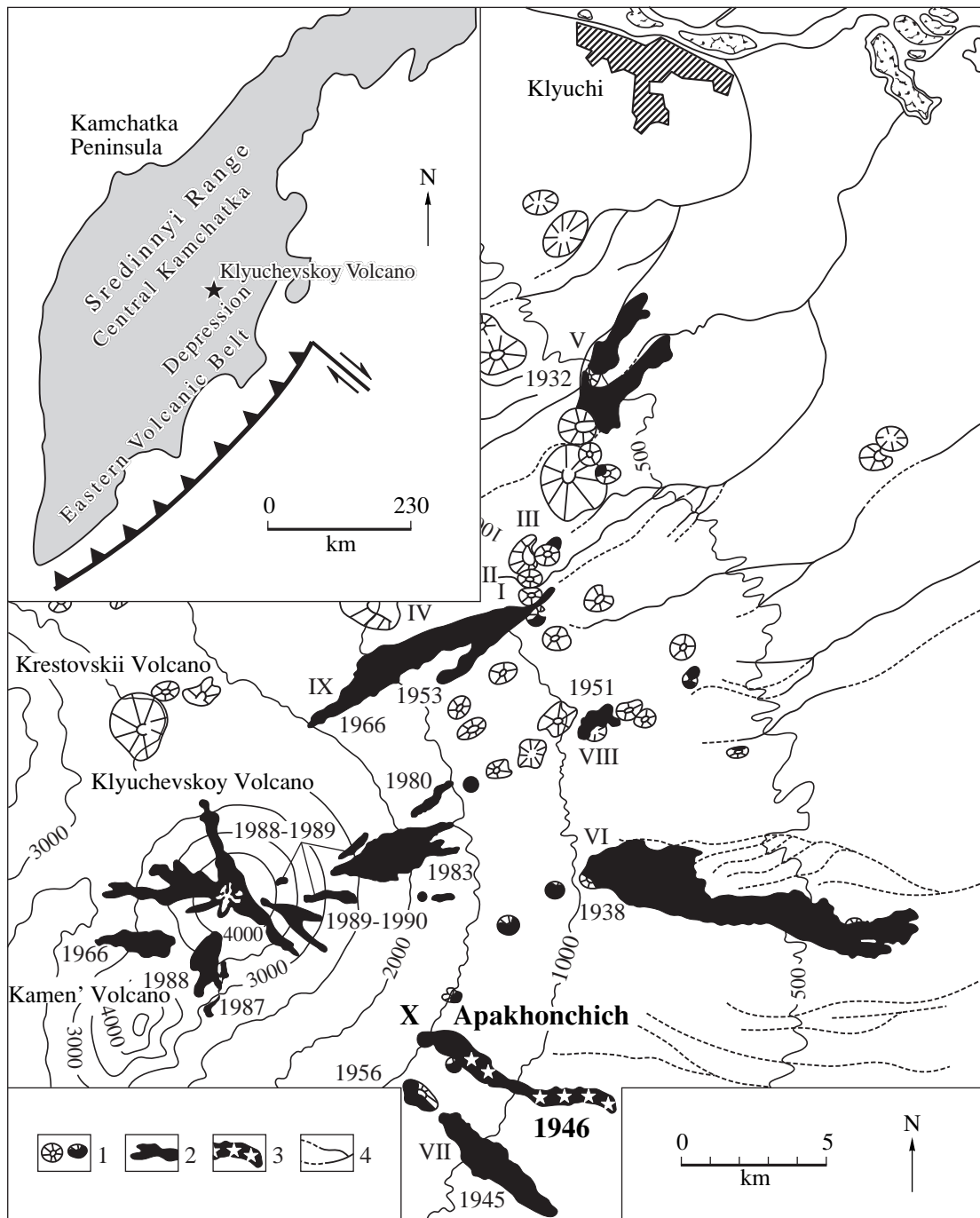
## INTRODUCTION

High-alumina basalts are typical constituents of island-arc volcanic series. They were first distinguished by Tilley (1950) as an independent type of basaltic magmas containing up to 18 wt %  $Al_2O_3$  and, since then, have been studied in detail by various petrologic approaches. Nowadays, most researchers agree that high-alumina basalts are products of the extensive fractionation of primary low-alumina magmas at high partial pressures of  $H_2O$  (Ariskin *et al.*, 1995). However, there are alternative models. For example, Kelemen (1990) supposed that high-alumina basalts were formed through the reequilibration of primary melts and their derivatives with the material of the magma conduit.

Considerable progress in the understanding of the physicochemical conditions of high-alumina basalt generation was related to the results of experimental (e.g., Kadik *et al.*, 1990; Sisson and Grove, 1993) and numerical modeling of magmatic processes (Ariskin *et al.*, 1995). In essence, these methods are indirect and based on the selection of the experimental conditions

(real or numeric) that provide the consistency between the phase composition of the model system and natural observations. There is limited direct evidence on the composition of melts that produced the minerals of high-alumina basalts (Sisson and Layne, 1993), which is of primary importance for the understanding of the genesis of these rocks. Potentially, the deficiency of data on the composition of primary melts of these basalts could be compensated by studying magmatic inclusions in minerals, which provide direct evidence on the crystallization conditions of these minerals (Sobolev, 1996).

The goal of this work was the determination of the physicochemical crystallization conditions of minerals of high-alumina basalt. It involved the estimation of temperature and pressure of magma crystallization, examination of the chemical evolution of melt including volatile component contents, and elucidation of evolution paths of the magmatic system at late crystallization stages. The results are based on a comprehensive investigation of magmatic inclusions in phenocryst minerals (olivine, clinopyroxene, and plagioclase)



**Fig. 1.** A scheme of Klyuchevskoy Volcano location (inset) and its lateral cones after V.N. Dvigalo (Institute of Volcanology, Far East Division, Russian Academy of Sciences) modified by Ariskin *et al.* (1995).

(1) Scoria cones (I, Bulochka; II, Novograbenov; III, Luchitskii; and IV, Slyunin); (2) lava flows of 1932–1990 with the year of eruption (V, Tuila; VI, Bilyukai; VII, Zavaritskii; VIII, Bylinkina; IX, Piip; and X, Apakhonchich); (3) sampling sites in the Apakhonchich flow; and (4) dry river beds.

from the high-alumina basalt of the Apakhonchich flow, Klyuchevskoy Volcano.

### STUDY OBJECT

Klyuchevskoy is one of the most active and productive volcanoes in the world. It is situated in the Central

Kamchatka Depression (Fig. 1) and, together with Bezmyanni, Tolbachik, and other volcanoes, forms the largest volcanic structure in the Kuril–Kamchatka island arc of Holocene age. A comprehensive description of the geologic structure of the volcano was given by Bogoyavlenskaya *et al.* (1985) and *Deistvuyushchie vulkany...* (1991). The age of the volcano is about 7 ka

**Table 1.** Average compositions of (1) the high-alumina basalts of the Apakhonchich flow and (2) interstitial glasses of the groundmass, wt %

	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO*	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Total	
Basalts of Apakhonchich flow											
SD	1	53.26	1.08	17.52	8.55	0.16	5.62	8.45	3.25	1.14	99.04
		0.54	0.02	0.56	0.50	0.01	0.12	0.19	0.16	0.05	
Interstitial glass											
SD	2	70.82	1.48	12.94	3.50	0.00	0.18	1.05	3.75	5.03	98.74
		0.58	0.12	0.24	0.13	0.00	0.15	0.14	0.33	0.10	

Note: The average compositions are based on (1) seven (collection of A.P. Khrenov; *Deistvuyushchie vulkany...*, 1991) and (2) three analyses. SD is standard deviation.

(Braitseva *et al.*, 1994). High-alumina basalts are typical products of its historic eruptions. Older high-magnesia basalts (up to 12 wt % MgO) and transitional rock varieties are also common.

The samples studied in this work were collected during a field investigation of the Apakhonchich high-alumina basalt flow, which was carried out in 1996 by researchers of Moscow State University and the Institute of Volcanology, Far East Division, Russian Academy of Sciences. The formation of this flow is related to the lateral eruption of October 23, 1946 on the eastern slope of Klyuchevskoy Volcano at an altitude of 1620 m (Naboko, 1949). The flow is 10 km long and bears a scoria cone, about 100 m high (Fig. 1). Most of the samples (including alluvial sand from the bed of a dry river) were taken from the lower part of the flow. The initial samples used for inclusion studies were represented by monomineral separates of olivine, clinopyroxene, and plagioclase from the alluvium sand material (Pletchov *et al.*, 2000).

The compositions of host minerals and melt inclusions were determined by the electron microprobe method on an electron microscope CamScan 4DV equipped with an energy dispersive system Link System-10000 (Petrology Chair of Moscow State University, analysts E.V. Guseva and N.N. Korotaeva). The analysis was performed in a back-scattered electron mode at an accelerating voltage of 15 kV and a beam current of 1 nA. The minerals were analyzed by a focused electron beam with a localization of 3 μm, and glasses were scanned over an area of 10 × 12 to 15 × 20 μm.

#### PETROLOGIC AND MINERALOGICAL CHARACTERISTICS OF HIGH-ALUMINA BASALTS FROM THE APAKHONCHICH FLOW

In a hand sample, the lava of the Apakhonchich flow is black or dark gray olivine–clinopyroxene–plagioclase basalt with massive and amygdaloidal structures. The basalts contain phenocrysts of plagioclase (*Pl*), clinopyroxene (*Cpx*), and olivine (*Ol*). Plagioclase is most common among the phenocrysts. The amount of mafic

phenocrysts (*Cpx* and *Ol*) varies considerably increasing toward the base of the flow. Microscopically, this is typical high-alumina basalt with a porphyritic texture and an interstitial texture of the groundmass.

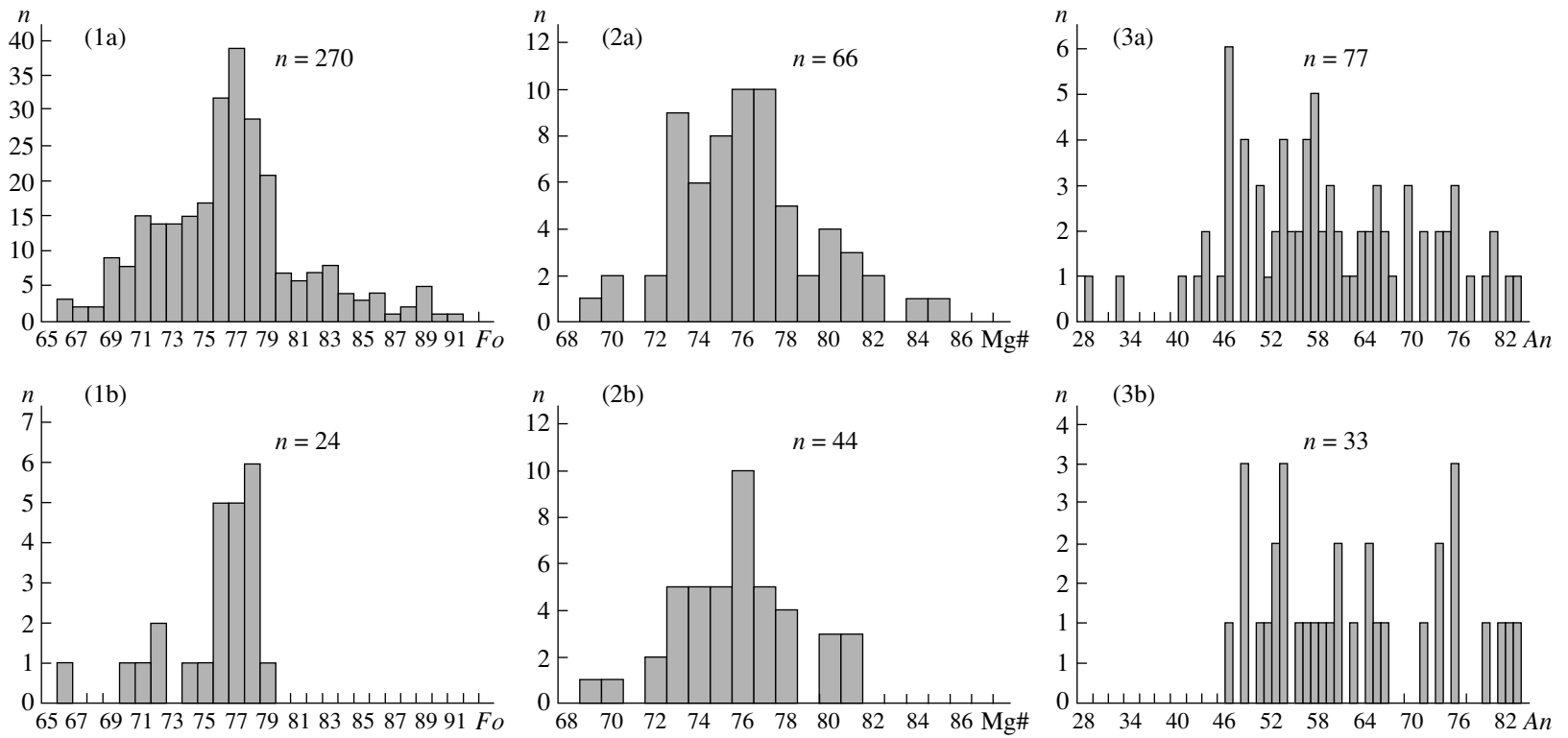
There are two generations of phenocrysts in the basalts. The early generation comprises large (1–5 mm) crystals and glomerophytic intergrowths of olivine ( $Fe_{91-78}$ ) and clinopyroxene [ $Mg\# = Mg/(Mg + Fe) = 86-78$ ]. Clinopyroxene distinctly prevails over olivine. The latter often shows irregular resorbed outlines. The second phenocryst generation includes mesophenocrysts of olivine ( $Fe_{77-70}$ ) and clinopyroxene ( $Mg\# = 77-70$ ; augite or less common pigeonite), 0.1–0.7 mm in size, and large plagioclase (0.5–1.0 mm) phenocrysts  $An_{55-83}$  (Fig. 2). The phenocrysts of the second generation contain abundant melt inclusions.

The rock groundmass is composed of plagioclase microlites ( $An_{50-30}$ ), pigeonite (both as individual grains and rims around olivine microphenocrysts), titanomagnetite, and silicic glass (68–71 wt % SiO<sub>2</sub>).

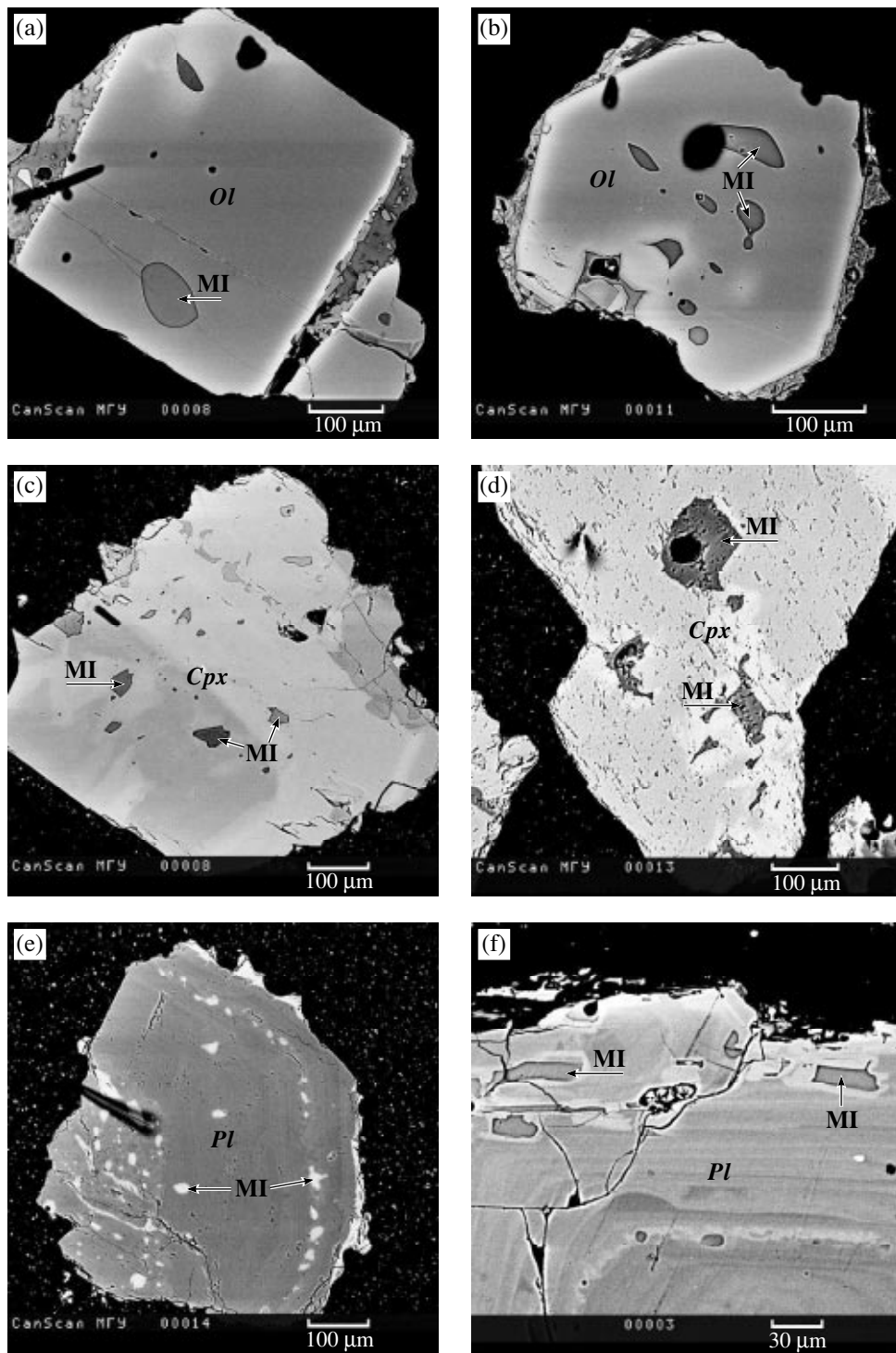
The rocks are characterized by narrow intervals of major element contents and average concentrations of MgO ~ 5.6 wt % and Al<sub>2</sub>O<sub>3</sub> ~ 17.5 wt % (Table 1). Small variations of basalt composition within the flow are probably related to the varying proportions of phenocrysts. Petrochemically, the rocks of the Apakhonchich flow are mostly high-alumina basalts, which are typical of Klyuchevskoy Volcano, at least at the current stage of its evolution.

#### MAGMATIC INCLUSIONS IN MINERALS

Magmatic inclusions are trapped by a mineral during its growth, which defines their unique potential ability to bear information on the continuously changing composition and conditions of a magmatic system (e.g., Roedder, 1984). The following types of magmatic inclusions were recognized in minerals of the Apakhonchich basaltic flow: melt inclusions in olivine, clinopyroxene, and plagioclase; fluid inclusions in olivine and clinopyroxene; and solid-phase inclusions of one mineral in another. Various types of combined inclusions were also found (melt + fluid, melt + spinel, etc.),



**Fig. 2.** Histograms showing the compositions of all (1a) olivines, (2a) clinopyroxenes, and (3a) plagioclases studied from the high-alumina basalts of the Apakhonchich flow, and the compositions of the same minerals (1b, 2b, and 3b) containing melt inclusions.



**Fig. 3.** Photomicrographs of melt inclusions (MI) in (a, b) olivine (Ol), (c, d) clinopyroxene (Cpx), and (e, f) plagioclase (Pl). The lighter zones of mineral grains are richer in iron (olivine and clinopyroxene) or in calcium (plagioclase). Photomicrograph 3e shows melt inclusions with MgO > 3.8 wt % (Table 3, samples PLG86 and PLG87), and photomicrograph 3f shows melt inclusions of rhyolite compositions (Table 3, samples PLG61 and PLG63).

which results from heterogeneous entrapment. Magmatic inclusions in minerals of the high-alumina basalts were studied by earlier workers (Bakumenko *et al.*,

1975; Ariskin *et al.*, 1995; Ozerov *et al.*, 1996; Pletchov *et al.*, 2000). However, this work is the first systematic study of all the inclusion types. The results of this study are

used to derive information on the physicochemical conditions of mineral crystallization in high-alumina basalts.

### Melt Inclusions

Melt inclusions were studied in olivine ( $Fo_{71-79}$ ), clinopyroxene ( $Mg\# = 70-81$ ), and plagioclase phenocrysts ( $An_{47-84}$ ) (Fig. 2).

Inclusions in olivine are usually isometric or ellipsoidal; irregular inclusions with "inlets" occur occasionally (Figs. 3a, 3b). No large inclusion clusters were found. Individual inclusions are most common, whereas groups of two or three inclusions are rarer. Primary inclusions vary from  $20 \times 10$  to  $150 \times 40 \mu\text{m}$  in size, the majority of inclusions are  $40-60 \mu\text{m}$  in diameter. Most inclusions consist of two phases, glass and a fluid bubble; some inclusions are partially crystallized and contain *Cpx*, *Pl*, amphibole, and an opaque mineral (titanomagnetite) as daughter crystals.

There is a general correlation between the composition of host olivine and the abundance of melt inclusions in the mineral. Iron-rich olivine (in our case,  $Fo_{80-70}$ ) shows the largest number of inclusions, whereas more magnesian olivine contains much fewer inclusions.

Melt inclusions in *Cpx* are normally irregular isometric or elongated in shape, sometimes showing negative crystal faces (Figs. 3c, 3d). Their size varies from  $25 \times 20$  to  $120 \times 140 \mu\text{m}$  (most frequently,  $30-50 \mu\text{m}$  across). Inclusions are irregularly distributed within grains and often form clusters of several dozens of inclusions,  $10-20 \mu\text{m}$  in size. Some *Cpx* grains show several zones enriched in inclusions. Most widespread are two-phase melt inclusions (glass and a gas bubble) with a gas bubble accounting for less than 5% of inclusion volume. In partially crystallized inclusions, an opaque mineral, plagioclase, and amphibole occur as daughter phases.

Melt inclusions in plagioclase are divided into two groups depending on their morphological characteristics (Pletchov *et al.*, 2000). The first group comprises anhedral inclusions, about  $15 \mu\text{m}$  in size, occurring in central parts of crystals and forming clusters of several dozens of inclusions (Fig. 3f). The second group involves later inclusions, which form groups confined to certain growth zones in plagioclase (Fig. 3f). The inclusions of this type are elongated and tabular in shape. Such inclusions are surrounded by plagioclase rims, which are more calcic as compared to the host plagioclase (by 7–10 units of *An*). Such inclusion groups are usually situated in zones of anorthite-rich plagioclase.

### Fluid Inclusions

Low-density fluid inclusions were found in the olivine and clinopyroxene phenocrysts. Their typical size is  $5-10 \mu\text{m}$ . The fact of the occurrence of fluid inclusions is considered by us as evidence for melt saturation with

fluid during the crystallization of the high-alumina basalts.

### Crystal Inclusions

The following types of crystal inclusions were found: chrome spinel, orthopyroxene, clinopyroxene, and plagioclase in olivine; orthopyroxene, olivine, and plagioclase in clinopyroxene; and rare inclusions of amphibole and orthopyroxene in plagioclase (Table 2). The analysis of the relationships between minerals and correlation of compositions of inclusions and their host minerals suggests that olivine ( $Fo_{91-78}$ ), clinopyroxene ( $Mg\# = 86-78$ ), and chrome spinel [ $Cr/(Cr + Al) = 63-74 \text{ mol } \%$ ] were early cotectic phases of the basalts. Plagioclase ( $An_{83-55}$ ) crystallized at later stages of melt evolution in association with olivine ( $Fo_{76-70}$ ), clinopyroxene ( $Mg\# = 77-70$ ), and minor amounts of orthopyroxene ( $En_{76-65}$ ). These data are in good agreement with the results by Ozerov *et al.* (1996). Amphibole appears on the liquidus of some melts in association with plagioclase ( $An_{71}$ ) at late stages of high-alumina basalt evolution.

## PHYSICOCHEMICAL CONDITIONS OF PHENOCRYST CRYSTALLIZATION IN THE HIGH-ALUMINA BASALTS

### Melt Composition

The composition of melt, from which the minerals of the high-alumina basalts crystallized, was reconstructed on the basis of the compositions of glassy melt inclusions, i.e., inclusions consisting of quench glass and a fluid bubble only (Figs. 3a, 3b, 3d). A prerequisite for the correct application of inclusion composition data is the demonstration of inclusion–host mineral equilibrium. Table 3 shows that the majority of melt inclusions in olivine and clinopyroxene yield the distribution coefficients of Fe and Mg between the mineral and melt,  $K_d^{\text{Fe-Mg}}$ , which are systematically lower than equilibrium values of  $\sim 0.3$  for olivine (Roeder and Emslie, 1970) and  $\sim 0.28$  for clinopyroxene (Ariskin *et al.*, 1986). Since such inclusions contain no daughter crystals, any changes in their composition after entrapment could be related to the crystallization of the host mineral on the vacuole walls (Anderson, 1974). In the case considered, the amount of silicate material dissolved in the daughter fluid phase can be ignored, because of the low volume of fluid (mainly,  $<10 \text{ vol } \%$ ) and very low silicate solubility in fluid at low pressure (Eggler, 1987).

The recalculation of the compositions of melt inclusions to the equilibrium with the host mineral was based on the modeling of fractional melting of olivine and clinopyroxene from the walls of inclusions using the program package PETROLOG (Danyushevsky *et al.*, 1998). The models of Ford *et al.* (1983) and Ariskin *et al.* (1986) were used for inclusions in olivine and cli-

**Table 2.** Representative analyses of phenocryst assemblages

Component	Host <i>Ol</i>				Host <i>Cpx</i>				Host <i>Pl</i>		
	OL256	OL248	OL291	OL285a	PX62	PX88	PX91	PX87	PL42	PL78	
SiO <sub>2</sub>	37.17	37.27	37.72	39.61	50.46	51.34	50.21	50.33	50.99	51.01	
TiO <sub>2</sub>					0.51	0.59	0.86	0.65			
Al <sub>2</sub> O <sub>3</sub>					3.65	2.94	3.79	3.96	30.67	30.55	
FeO*	26.02	25.78	23.50	13.34	8.06	9.46	9.67	7.94	0.62	0.84	
MnO	0.44	0.31	0.53	0.30							
MgO	35.52	35.89	37.70	45.81	15.47	15.85	15.09	14.98			
CaO	0.25	0.31	0.25	0.24	20.64	18.61	19.32	21.14	13.46	14.13	
Na <sub>2</sub> O									3.95	3.22	
K <sub>2</sub> O									0.12	0	
Total	99.39	99.56	99.71	99.29	98.78	98.79	98.94	99.01	99.81	99.76	
<i>Fo</i> , Mg#, <i>An</i>	70.86	71.27	74.08	85.95	77.4	74.9	73.5	77.1	65.3	70.8	
Crystal inclusions in <i>Ol</i>				Crystal inclusions in <i>Cpx</i>				In <i>Pl</i>			
Component	<i>Pl</i>	<i>Cpx</i>	<i>Opx</i>	<i>Spl</i>	<i>Ol</i>	<i>Ol</i>	<i>Opx</i>	<i>Pl</i>	<i>Opx</i>	<i>Amph</i>	
	OLP256	OLP248	OLP291	OLP285a	PXP62	PXP88	PXP91	PXP87	PLP44	PLG78	
SiO <sub>2</sub>	50.17	49.27	53.54		37.40	37.78	52.74	51.43	52.29	44.80	
TiO <sub>2</sub>		0.87	0.44	0.79			0.26		0.19	3.52	
Al <sub>2</sub> O <sub>3</sub>	30.67	4.71	1.42	15.98			2.84	29.57	1.25	3.77	
FeO*	1.29	10.52	15.03	27.42	22.20	23.93	15.61	0.92	21.57	22.79	
MgO		14.53	27.02	11.50	38.81	37.20	26.08		22.44	10.81	
CaO	14.26	19.31	1.66		0.24	0.24	1.81	13.84	1.52	9.46	
Na <sub>2</sub> O	3.27							3.63		1.39	
K <sub>2</sub> O	0.09							0.17		0.45	
Cr <sub>2</sub> O <sub>3</sub>				43.89							
Total	99.74	99.02	99.10	99.57	98.65	99.14	99.34	99.56	99.25	96.98	
<i>Fo</i> , Mg#, <i>An</i>	70.67	70.85	76.21		75.7	73.5	74.9	67.8	64.95		
<i>T</i> , °C		1082			1049	1156					
<i>P</i> , kbar		2.3			0.6	0.8					

Note:  $Fo = 100 \times Mg / (Mg + Fe^{2+})$  in olivine;  $Mg\# = 100 \times Mg / (Mg + Fe^{2+})$  in clinopyroxene;  $An = 100 \times Ca / (Ca + Na)$  in plagioclase; and FeO\* is the total measured iron content. Oxide concentrations are in wt %;  $T^{\circ}C$  was calculated by the *Ol-Aug* geothermometer (Loucks, 1996); and *P*, kbar was determined by the clinopyroxene geobarometer (Nimis, 1998). See text for further details.

nopyroxene, respectively. The calculations were carried out for water-free conditions, a pressure of 1 kbar, and oxygen fugacity corresponding to the Ni–NiO equilibrium. The correction of the compositions of melt inclusions in plagioclase was based on the model of Pletchov and Gerya (1998).

The recalculated melt compositions are shown in Table 3 and Figs. 4 and 5. In contrast to the compositions of rocks from Klyuchevskoy Volcano, most of the melts that were in equilibrium with the high-alumina basalt minerals fall within the tholeiitic compositional field according to the classification of Miashiro (1974). Of special interest is a considerable range of major oxide concentrations in the melts studied, which

extends the field of Klyuchevskoy basic magmas toward more evolved andesite, dacite, and rhyolite compositions.

About 30% of the melts analyzed (mainly, from olivine  $Fo_{76-79}$  and, more rarely, clinopyroxene) show major-element compositions identical to those of the high-alumina basalts of Klyuchevskoy Volcano, in particular, the compositions of the Apakhonchich lavas (Fig. 5). These melts are characterized by MgO contents from 5.7–4.6 wt % negatively correlated with Al<sub>2</sub>O<sub>3</sub> (17.1–19.8 wt %), moderate SiO<sub>2</sub> contents (no higher than 54 wt %), TiO<sub>2</sub> = 1.0–1.3 wt %, FeO<sub>tot</sub> = 9.2–10.2 wt %, CaO = 7.9–9.4 wt %, Na<sub>2</sub>O = 3.2–4.5 wt %, and K<sub>2</sub>O = 0.8–1.1 wt %. The remaining 70%

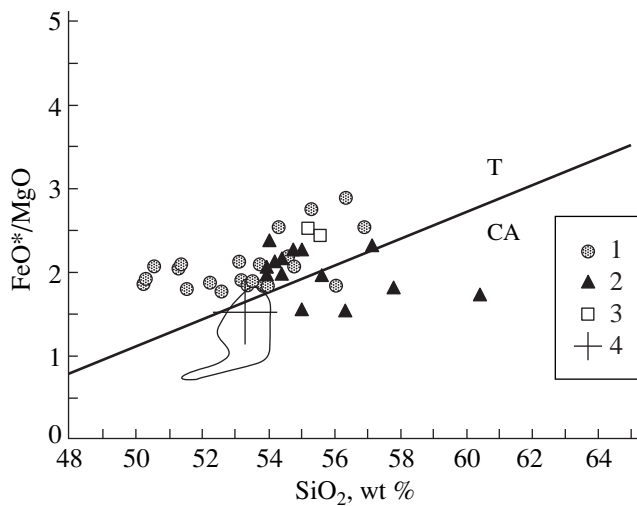


**Table 3.** Compositions of melt inclusions in minerals

Component	Melt inclusions in olivine						Melt inclusions in clinopyroxene						Melt inclusions in plagioclase					
	OLG245	OLG227	OLG235	OLG232	OLG225	OLG213	PXG57	PXG78	PXG63	PXG26	PXG15	PXG70	PLG86	PLG87	PLG58	PLG45	PLG63	PLG61
	70*	40	24	17.5	60	75	32.5	22.5	45.0	27.5	25.0	130.0	20	20	15	20	17.5	25
SiO <sub>2</sub>	50.92	52.41	53.35	54.20	54.58	55.86	55.15	54.18	54.25	58.01	60.83	68.66	55.23	55.65	65.91	76.89	75.55	76.20
TiO <sub>2</sub>	1.21	1.18	1.10	1.36	1.55	1.47	1.13	1.24	1.21	1.42	1.85	1.20	1.77	1.29	1.15	0.72	0.54	0.63
Al <sub>2</sub> O <sub>3</sub>	20.28	20.65	19.13	19.30	16.17	15.31	17.56	16.56	16.61	15.45	16.19	15.59	15.04	16.07	11.92	11.44	12.83	12.26
FeO*	9.26	8.11	8.86	8.53	10.93	10.73	7.99	10.06	10.41	7.62	5.48	2.94	10.81	9.50	7.44	2.83	1.99	2.16
MnO	0.17	0.15	0.29	0.24	0.18	0.15	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.22	0.05	n.d.	n.d.	n.d.	n.d.
MgO	3.77	2.14	3.67	1.92	4.03	3.31	4.84	4.37	3.97	3.93	2.75	0.97	4.29	3.89	2.03	0.48	0.43	0.41
CaO	9.08	10.13	9.27	9.87	6.88	7.38	8.53	8.04	8.20	7.89	5.90	2.51	7.67	7.65	5.00	1.25	1.75	1.28
Na <sub>2</sub> O	4.25	4.26	3.38	3.71	4.27	4.25	3.86	4.50	4.14	4.36	4.43	4.92	3.53	4.45	3.21	2.33	4.10	4.00
K <sub>2</sub> O	1.06	0.96	0.96	0.88	1.41	1.55	0.95	1.06	1.21	1.31	2.57	3.21	1.44	1.44	3.35	4.06	2.80	3.06
Component	OLG*245	OLG*227	OLG*235	OLG*232	OLG*225	OLG*213	PXG*57	PXG*78	PXG*63	PXG*26	PXG*15	PXG*70	PLG*86	PLG*87	PLG*58	PLG*45	PLG*63	PLG*61
SiO <sub>2</sub>	50.62	51.32	52.62	52.30	54.41	55.44	55.04	54.01	54.12	57.85	60.44	67.27	55.23	55.65	65.05	74.60	73.34	72.79
TiO <sub>2</sub>	1.17	1.10	1.05	1.20	1.53	1.43	1.10	1.17	1.17	1.39	1.78	1.11	1.77	1.29	1.05	0.65	0.49	0.56
Al <sub>2</sub> O <sub>3</sub>	19.78	19.12	18.19	17.10	16.01	14.96	17.27	15.90	16.20	15.22	15.83	15.20	15.04	16.07	12.95	13.16	14.46	14.77
FeO*	9.59	9.48	9.54	10.68	11.08	11.12	7.99	10.02	10.42	7.63	5.58	3.46	10.81	9.50	7.09	2.64	1.87	1.94
MnO	0.17	0.14	0.28	0.21	0.18	0.15	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.22	0.05	n.d.	n.d.	n.d.	n.d.
MgO	4.63	4.64	5.38	5.69	4.36	4.03	5.14	5.06	4.38	4.21	3.23	1.90	4.29	3.89	1.93	0.44	0.39	0.35
CaO	8.86	9.38	8.81	8.74	6.81	7.20	8.78	8.62	8.58	8.17	6.39	3.48	7.67	7.65	5.58	2.33	2.84	2.95
Na <sub>2</sub> O	4.14	3.94	3.22	3.29	4.23	4.15	3.76	4.23	3.98	4.26	4.27	4.58	3.53	4.45	3.16	2.49	4.06	3.96
K <sub>2</sub> O	1.04	0.89	0.91	0.78	1.39	1.51	0.92	1.00	1.17	1.28	2.47	3.00	1.44	1.44	3.19	3.70	2.56	2.66
<i>Fo</i> , Mg#, <i>An</i>	76.6	76.4	78.1	77.2	72.7	70.8	80.4	77.0	73.0	78.7	78.7	76.7	59.0	63.5	83.0	63.3	62.2	67.1
<i>X</i> , wt %	2.4	6.9	4.7	10.2	1.0	2.2	2.5	5.5	3.6	2.3	3.6	6.4	0.0	0.0	5.0	10.0	10.0	15.0
H <sub>2</sub> O, wt %	4.7	5.0	3.1	1.8	1.2	1.6	2.2	0.3	1.7	0.7	0.7	0.3	1.3	1.8				
<i>P</i> , kbar							1.4		0.4	1.4	3.2	0.3						
<i>T</i> , °C	1046	1034	1091	1125	1127	1105	1081	1133	1082	1126	1106	1104	1130	1120				

Note: OLG, PXG, and PLG are the compositions of glasses in melt inclusions; OLG\*, PXG\*, and PLG\* are the melt compositions calculated from the compositions of melt inclusions by the inverse fractionation method; *X*, wt % is the amount of the host mineral crystallized on the inclusion walls.  $Fo = 100 \times Mg / (Mg + Fe^{2+})$  in host olivine;  $Mg \# = 100 \times Mg / (Mg + Fe^{2+})$  in host clinopyroxene;  $An = 100 \times Ca / (Ca + Na)$  in host plagioclase; and FeO\* is total iron calculated as FeO. Oxide contents are in wt %; n.d. means not analyzed. All the compositions of melt inclusions are recalculated to a total of 100 wt % without water. H<sub>2</sub>O, wt % is the calculated water content in melt; *T*, °C is the crystallization temperature of the phenocryst at the moment of inclusion entrapment (see text for explanation). *P*, kbar is the pressure calculated by the clinopyroxene geobarometer (Nimis, 1998). The calculation procedures are described in the text.

\* Average diameter of inclusions, μm.



**Fig. 4.** Classification diagram for melts of the high-alumina basalts of the Apakhonchich flow.

The compositions of melts were obtained from the data of melt inclusion investigation in (1) olivine, (2) clinopyroxene, and (3) plagioclase; and (4) the average composition of the high-alumina basalts of the Apakhonchich flow (out of scale) (Table 1). The field shows the compositions of Klyuchevskoy basalts after Ariskin *et al.* (1995). The line dividing tholeiitic (T) and calc-alkaline (CA) compositions is after Miyashiro (1974). FeO\* is the total iron calculated as FeO.

of the melts studied have no analogues among the Klyuchevskoy rocks. The most primitive among them are similar to the high-alumina melts in MgO content, systematically lower in  $\text{Al}_2\text{O}_3$  (less than 17 wt %), and higher in  $\text{SiO}_2$ ,  $\text{TiO}_2$ , and FeO. Lower magnesian melts with  $\text{MgO} < 4$  wt % evolve toward dacite and rhyolite compositions, which is accompanied by an increase in  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  and a decrease in FeO, CaO, and  $\text{TiO}_2$ .  $\text{Na}_2\text{O}$  content in the evolved melts varies irregularly from 2.5 to 4.9 wt %. Rhyolite melts proper were found only in inclusions in the plagioclase phenocrysts (Pletchov *et al.*, 2000). These melts are chemically similar to the interstitial glasses of the Apakhonchich lavas.

#### Estimation of Water Content in Melts

The importance of  $\text{H}_2\text{O}$  for the evolution of the melts studied is directly testified by the occurrence of amphibole as a daughter phase in the partially crystallized inclusions and as a crystal inclusion in plagioclase.

Danyushevsky *et al.* (1996) proposed a method for the estimation of  $\text{H}_2\text{O}$  content in melt equilibrated with olivine and plagioclase. Since their equation was calibrated for mid-ocean ridge basalts containing no more than 1 wt % of  $\text{H}_2\text{O}$ , it is not appropriate for high-alumina basalts. Based on the approach of Danyushevsky *et al.* (1996), we derived another equation from the data by Ariskin *et al.* (1995) on the influence of  $\text{H}_2\text{O}$  on the liquidus temperature of olivine and plagioclase.

According to Ariskin *et al.* (1995), the addition of 1 wt % of  $\text{H}_2\text{O}$  reduces the liquidus temperature of olivine and plagioclase by  $17.5 \pm 4.9$  and  $42.2 \pm 4.8^\circ\text{C}$ , respectively. The resulting equation is  $C_{\text{H}_2\text{O}} = \Delta T/24.7$ , where

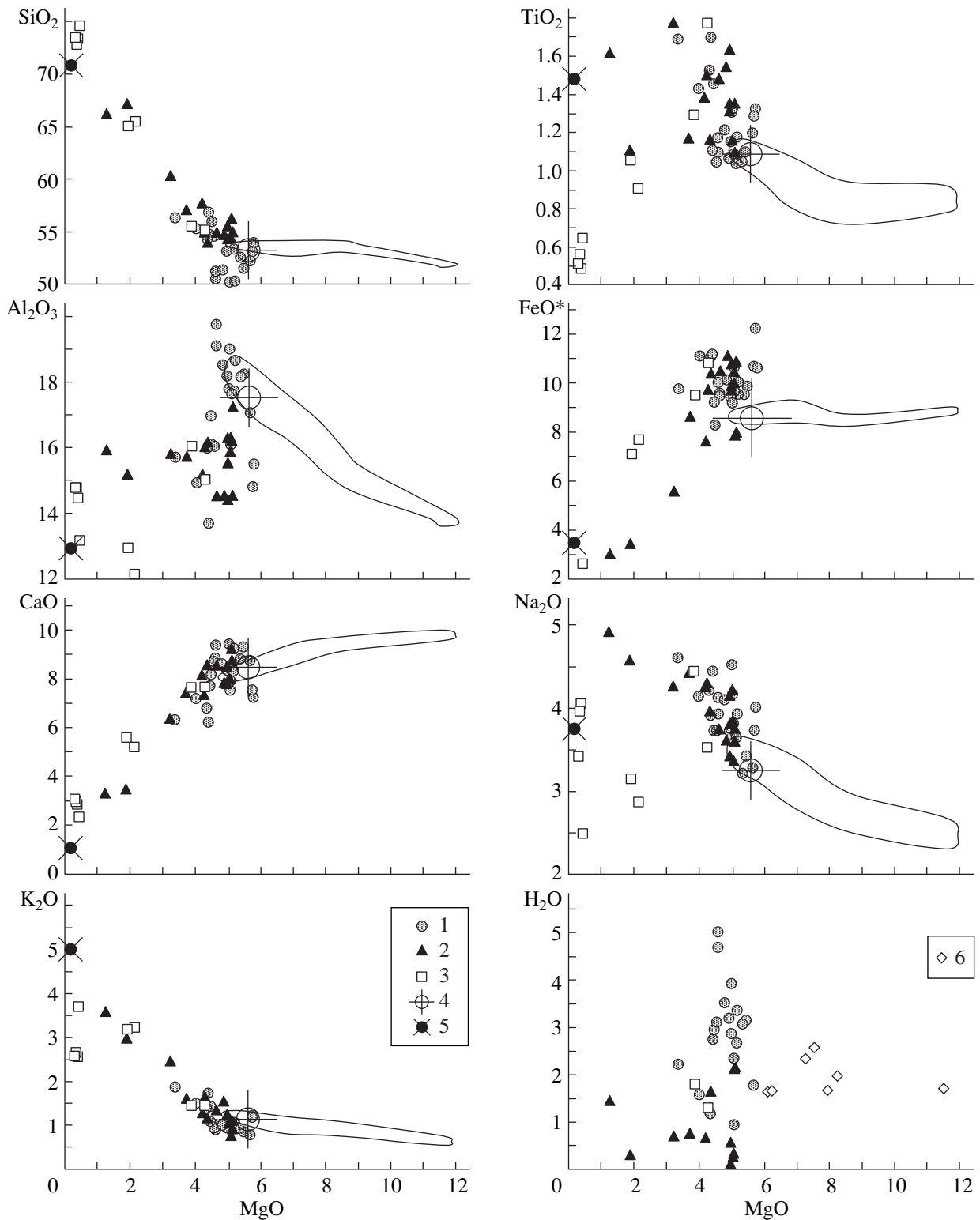
$C_{\text{H}_2\text{O}}$  is the  $\text{H}_2\text{O}$  content of the melt and  $\Delta T$  is the difference between the pseudoliquidus temperatures of dry melt saturation with plagioclase and olivine calculated by the model of Ariskin *et al.* (1986). The equation was checked against the experimental data of Sisson and Grove (1993) and Wagner *et al.* (1995). The accuracy of water content reproduction was 0.3 wt %. Note that, for a melt equilibrated with olivine and not saturated with plagioclase,  $\text{H}_2\text{O}$  content obtained by this method is a minimum estimate.

The water contents calculated from the difference between olivine and plagioclase pseudoliquidus temperatures are shown in Table 3 and Fig. 5. The melts coexisting with olivine, clinopyroxene, and plagioclase ( $\text{MgO} > 3.8$  wt %) contained 0.9–5.0, 0.1–2.2, and 1.3–1.8 wt %  $\text{H}_2\text{O}$ , respectively.

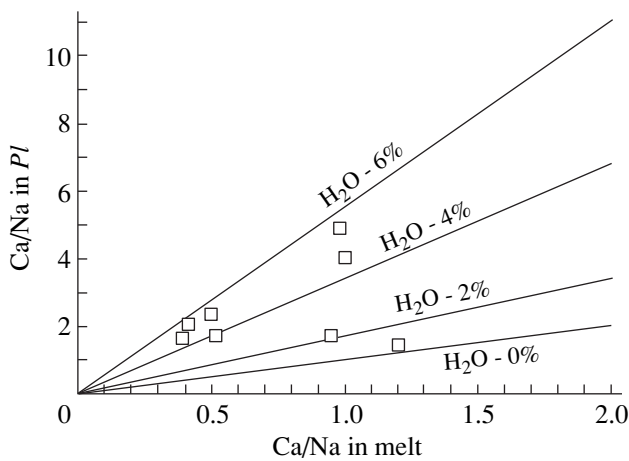
Additional estimates were obtained from the compositions of melt inclusions in plagioclase using the strong dependence of  $K_d^{\text{Ca-Na}}$  between plagioclase and melt on  $\text{H}_2\text{O}$  content in the melt (Housh and Luhr, 1991; Sisson and Grove, 1993). Figure 6 and Table 3 show that the majority of melts from plagioclase have  $K_d^{\text{Ca-Na}} = 5.5\text{--}3.4$ , which corresponds to a water content of about 5 wt % under water-saturated conditions at  $\sim 1\text{--}2$  kbar. The occurrence of amphibole crystal inclusions in the plagioclase provides independent evidence for the correctness of the estimated  $\text{H}_2\text{O}$  contents, because experimental data (Sisson and Grove, 1993) suggest that amphibole appears on the liquidus of high-alumina basalts at  $\text{H}_2\text{O}$  pressure about 2 kbar. Part of melt inclusions in plagioclase are characterized by low  $K_d = 1\text{--}2$  corresponding to water contents below 2 wt %. It is important that these melts are compositionally similar to the group of moderately aluminous melt inclusions in *Ol* and *Cpx*. Similar water contents were obtained for these melts by other independent methods.

The model of Pletchov and Gerya (1998) for plagioclase–hydrous melt equilibrium yielded similar values. According to this model, silicic melts found as inclusions in plagioclase  $An_{62\text{--}83}$  could be in equilibrium with the host minerals under water-saturated conditions at a pressure of 1 kbar and temperatures from 1000 to  $900^\circ\text{C}$ . The concentration of water under such conditions was calculated using the model of Almeev and Ariskin (1996) as 2.8–3.8 wt %.

Summing up the above considerations, we point out the considerable variations of water content in the high-alumina basalt melts. These variations are much higher than the uncertainty of our estimates, 0.3 wt %. The highest concentrations up to 5 wt % were inferred for the high-alumina melts in olivine and high-silica melt



**Fig. 5.** Compositions of melts from the high-alumina basalts of the Apakhonchich flow estimated on the basis of investigations of melt inclusions in minerals, wt %.  
 Melt inclusions in (1) olivine, (2) clinopyroxene, and (3) plagioclase; (4) average composition of the high-alumina basalts of the Apakhonchich flow (out of scale); (5) average composition of interstitial glass from the Apakhonchich basalts; and (6) compositions of melt inclusions in olivines from the magnesian basalts of the Klyuchevskoy Volcano (Sobolev and Chaussidon, 1996; Khubunaya and Sobolev, 1998). The field shows the compositions of Klyuchevskoy basalts after Ariskin *et al.* (1995). Water contents in melt inclusions (1–3) were calculated (see text for explanation).



**Fig. 6.** Estimation of the water contents of melt inclusions in plagioclase.

The squares are the compositions of melt inclusions in plagioclases and lines show various concentrations of water corresponding to certain values of Ca/Na distribution coefficient between plagioclase and melt ( $K_d = 5.5$  at 6.0 wt %  $H_2O$ ;  $K_d = 3.4$  at 4.0 wt %  $H_2O$ ; and  $K_d = 1.7$  at 2.0 wt %  $H_2O$ ). The lines are constructed on the basis of experimental data on the plagioclase–melt equilibrium (Sisson and Grove, 1993).

inclusions in plagioclase. In contrast, some low-alumina melts are rather poor in  $H_2O$ . There are all the transitional varieties between these extremes in  $H_2O$  content of melt. There is no distinct correlation between  $H_2O$  content and MgO concentration in the melt (Fig. 5) or the composition of the host mineral.

#### Crystallization Temperature

The crystallization temperatures of olivine, clinopyroxene, and plagioclase in the high-alumina basalts were estimated from the calculated pseudoliquidus temperatures of equilibrium of these minerals with corresponding melts. The influence of  $H_2O$  on liquidus temperature was accounted for after the data of Ariskin *et al.* (1995) using the above estimates of  $H_2O$  contents in each particular melt. The estimated crystallization temperatures were 1030–1145 for olivine ( $Fo_{71-79}$ ); 1040–1135°C for *Cpx* ( $Mg\# = 70-81$ ); and 1120–1130°C for *Pl* ( $An_{59-64}$ ) (Table 3). The temperature intervals of *Ol* and *Cpx* crystallization are similar, which suggests simultaneous crystallization of these minerals. Similar temperature estimates were obtained by the *Ol–Aug* geothermometer (Loucks, 1996) for the crystal inclusions in olivine and clinopyroxene (Table 2).

#### Crystallization Pressure

The pressure of crystallization was estimated on the basis of barometric expressions for clinopyroxene composition (Nimis and Ulmer, 1998). The values are no higher than 3.0–3.5 kbar at an average of 1.5 kbar. The geobarometer of Nimis and Ulmer (1998) provides an

average accuracy of 2 kbar at a known *Cpx*–melt equilibrium temperature. The uncertainties in temperature estimates reduce the accuracy (by about 1 kbar per 20°C of temperature error). Thus, the obtained pressure estimates should be regarded with care. Nevertheless, even keeping in mind the low accuracy of this geobarometer, it is safe to state that the crystallization and evolution of the clinopyroxenes occurred under shallow conditions at pressures below 5 kbar. Since clinopyroxene is a ubiquitous phase on the liquidus of the melts under investigation, the obtained pressure estimates are adequate for the crystallization conditions within the whole range of mineral compositions.

The depth of crystallization was also estimated from the pressure of saturation with water fluid (Almeev and Ariskin, 1996) for melts close to saturation or water-saturated (which include most of the melts studied). These estimates suggest that the crystallization occurred at low pressure, <2 kbar (on average, ~0.7 kbar).

The obtained crystallization pressures of the high-alumina basalts are comparable with the load exerted by the Klyuchevskoy Volcano edifice at its base (~2 kbar). Some minerals probably crystallized at shallower depths, i.e., within the volcanic edifice and immediately before lava eruption on the surface in the feeding conduit of the Apakhonchich flow.

#### Redox Conditions of Crystallization

Redox conditions were reliably estimated only for the moment of olivine  $Fo_{84-88}$  crystallization. Two independent methods (Ballhaus *et al.*, 1991; Danyushevsky and Sobolev, 1996) were applied for the composition of chrome spinel [ $Cr/(Cr + Al) = 63-74$  mol %] in olivine  $Fo_{84-88}$ . The two methods yielded consistent values of  $\log f_{O_2}$  between –7 and –8. These data suggest that  $f_{O_2}$  of olivine crystallization corresponded to the equilibrium Ni–NiO or even higher at  $T = 1150-1220^\circ C$ . This result agrees with values obtained by Kadik *et al.* (1990) on the basis of experimental data and somewhat higher than the estimates of Khubunaya and Sobolev (1998) for the most primitive olivine–spinel assemblage of the Klyuchevskoy lavas. This discrepancy suggests possible oxidation of the Klyuchevskoy melts relative to buffer equilibria during its evolution from magmatic to high-alumina compositions.

## DISCUSSION

#### Conditions of Formation of the High-Alumina Magmas of Klyuchevskoy Volcano

High-alumina basalts are common in modern and ancient island arcs (Tilley, 1950; Kuno, 1960). The central problem in the discussion on the genesis of these rocks is that of their possible generation either directly by melting of mantle or subducted crustal material (e.g., Brophy and Marsh, 1986) or from a more primitive magma through the processes of crystal fraction-

ation (e.g., Ariskin *et al.*, 1995), plagioclase accumulation (Crawford *et al.*, 1987), or interaction with the country rocks (Kelemen, 1990). The comprehensive evaluation of the genesis of high-alumina basalts is beyond the scope of this paper; however, our data provide valuable information on crystallization conditions, which must be taken into account in any realistic model of the generation of these magmas.

A fundamental result of this work is the finding of high-alumina melts trapped as inclusions in the phenocrysts of the high-alumina basalts. This directly testifies to the existence of high-alumina melts during basalt formation in contrast to the models assuming the processes of plagioclase accumulation (e.g., Crawford *et al.*, 1987). High-alumina melts were found in iron-rich olivine,  $Fo_{76-79}$ . They are characterized by relatively low MgO contents (~5 wt %) and high ratios  $CaO/MgO \sim 1.7$ . These parameters are different from those of the high-alumina products of partial mantle melting (Sobolev *et al.*, 1988; Kinzler and Grove, 1992) and high-pressure fractionation of basaltic magmas under "dry" conditions (Draper and Johnston, 1992; Kadik *et al.*, 1990). Compositionally, the Klyuchevskoy high-alumina melts are most similar to the products of basaltic magma fractionation in the presence of water, which delays plagioclase crystallization and leads to the formation of high-alumina residual liquids (Yoder and Tilley, 1962; Kay and Kay, 1985; Kersting and Arculus, 1994; Ariskin *et al.*, 1995). The estimated water content in the high-alumina melt of Klyuchevskoy Volcano is 3–5 wt %; crystallization temperature, 1030–1145°C; and pressure, ~1.5–2.0 kbar. These parameters are in full agreement with the experimental estimates of Sisson and Grove (1993) and, probably, can be regarded as general characteristics of high-alumina basalts. The estimated water contents are also consistent with the high initial water contents of the primary high-magnesia magmas of Klyuchevskoy Volcano, 2–3 wt % (Sobolev and Chaussidon, 1996; Khubunaya and Sobolev, 1998).

A generalized model of Klyuchevskoy magma evolution through polybaric fractionation of a primary high-magnesia basaltic magma was proposed by Ariskin *et al.* (1995). The model implies water contents and liquidus temperatures of alumina-rich melts, which are generally similar to those obtained in this work. There are some deviations in the pressure estimates of magma crystallization. Ariskin *et al.* (1995) suggested that the crystallization of high-alumina basalts began at ~7 kbar in contrast to our upper estimate of 5 kbar.

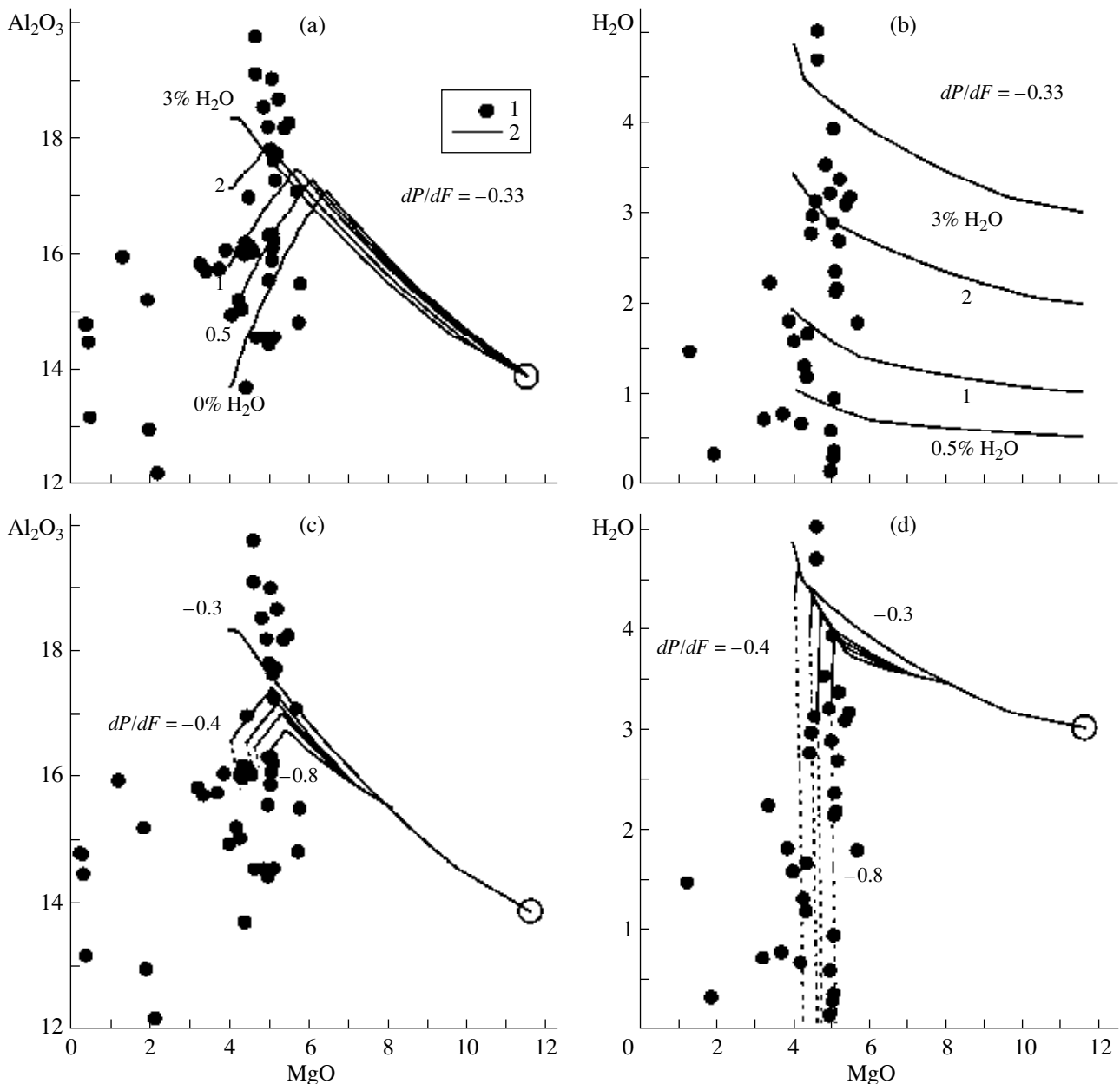
#### *Plagioclase Crystallization and the Role of Degassing at Final Stages of Klyuchevskoy Magma Evolution*

Considerable part of the melts that were responsible for phenocryst crystallization in the Apakhonchich basalts has no analogues among the rocks of Klyuchevskoy Volcano. On variation diagrams (Fig. 5), these melts form a wide field related to no single evolution

trend and located at MgO contents similar or lower than those of the high-alumina basalts; higher contents of  $SiO_2$ ,  $TiO_2$ , FeO, and  $Na_2O$ ; and lower  $Al_2O_3$ . Of particular importance is the fact that such melts were found in plagioclase phenocrysts, whereas high-alumina melts occur only in olivine and clinopyroxene. This observation suggests that the formation of the low-alumina basalts was related to the appearance of plagioclase on the liquidus of magmas. The estimated water contents of the low-alumina melts are highly variable and the appearance of plagioclase could not be related to a certain moment in system crystallization. It is more likely that plagioclase appeared at various stages of system fractionation (at varying MgO contents) depending on the water content of a particular melt portion, which could result in the observed variations of melt composition.

The variations of  $H_2O$  in the low-magnesia melts could be merely due to differences in the  $H_2O$  contents of primary magmas. Figures 7a and 7b suggest that the observed compositional range of the low-alumina melts can be explained by variations in  $H_2O$  contents in various portions of initial magma from 3 to 0 wt %. However, such a model is not consistent with a number of natural observations. The available data suggest a high  $H_2O$  content in the initial magmas of Klyuchevskoy Volcano, no lower than 2.0–2.5 wt % (Sobolev and Chaussidon, 1996; Khubunaya and Sobolev, 1998), whereas no evidence was found for the existence of "dry" primitive melts. In the case of magma fractionation with an initial water content <1 wt %, the model predicts the appearance of plagioclase on the liquidus together with olivine  $Fo_{81-83}$  at an MgO content in the melt of about 6 wt %. In the samples of Klyuchevskoy lavas, the earliest plagioclase was found in a less magnesian olivine,  $Fo_{75-77}$  (Ariskin *et al.*, 1995). Moreover, this model fails to explain the absence of rocks chemically similar to the low-alumina melts at Klyuchevskoy Volcano.

An alternative model assumes that the initial magmas were  $H_2O$ -rich and the variations in  $H_2O$  content were formed at a late stage of crystallization of the magmatic system owing to low-pressure melt degassing. In nature, such a crystallization regime could occur in the following manner. Early stages of system fractionation take place at high pressure ( $P > 2-3$  kbar) in a magma chamber or during slow decompression (Ariskin *et al.*, 1995). At a certain moment of system evolution, the stable (with respect to  $dP/dF$ ) regime of crystallization is changed by rapid magma ascent toward the surface. The magmas experience decompression and rapidly attain the level of  $H_2O$  saturation. The excess  $H_2O$  is released to a fluid phase. At further melt decompression, crystallization pressure is the major factor controlling  $H_2O$  content (e.g., Almeev and Ariskin, 1996). Depending on the rate of decompression crystallization, which may be different in various magma portions, melt crystallization paths is also dif-



**Fig. 7.** Modeling of liquid line of descent at the polybaric fractionation of high-magnesia melt.

(1) Compositions of melts from the high-alumina basalts of the Apakhonchich flow calculated on the basis of melt inclusion compositions; water contents were determined by calculation methods; (2) model liquid lines of descent. The initial composition (large circle) was approximated by the average composition of high-magnesia basalts (Ariskin *et al.*, 1995). The calculations were carried out using the COMAGMAT model (Ariskin, 1999; Portnyagin *et al.*, 1997) with a crystallization increment of 1 mol % under the redox potential of the NNO buffer. The parameter  $dP/dF$  characterizes change in pressure,  $P$  at an increase of the degree of fractionation of the melt,  $F$  by 1 mol %.

Results of modeling: (a), (b) with various initial water content (from 0 to 3 wt %) and constant decompression rate  $dP/dF = -0.33$  kbar/mol (initial pressure  $P_i = 18$  kbar and final pressure  $P_f = 1$  atm); (c), (d) two-stage model including 0–15 mol % fractionation with a decompression rate of  $-0.33$  kbar/mol ( $P_i = 18$  kbar and  $P_f = 13.1$  kbar) and further fractionation with varying decompression rate,  $dP/dF$  from  $-0.3$  to  $-0.8$  kbar/mol ( $P_i = 13.1$  and  $P_f = 1$  atm).

ferent. The results of the numerical modeling of this process are shown in Figs. 7c and 7d. These data demonstrate that slow decompression ( $\sim 0.3$  kbar/mol) could produce high-alumina melts with high  $H_2O$  contents. In contrast, rapid decompression ( $\sim 0.6$ –

$0.8$  kbar/mol) results in the formation of essentially dry melts at the same degree of fractionation. Thus, according to such a model, plagioclase crystallized in the high-alumina basalts in a wide range of  $P_{H_2O}$ – $T$  conditions and, probably, within a fairly short time interval.

It is interesting that rapid crystallization may not prevent the formation of large phenocrysts. A similar conclusion was recently made by Brophy *et al.* (1999), who studied the conditions of clinopyroxene megacryst crystallization in the lavas of the Aleutian Islands.

The occurrence of minerals crystallizing at various rates of decompression in the high-alumina basalts can be explained by magma mixing immediately before the eruption. It is also possible that different magma portions were erupted in different time periods forming various parts of the flow. The available data do not allow us to solve this dilemma.

The plausibility of the model can be supported by a number of arguments. First of all, the agreement between the initial water contents in primary magmas obtained in this work and by other authors (Sobolev and Chaussidon, 1996; Khubunaya and Sobolev, 1998) should be noted. Moreover, there is good agreement between the natural and model characteristics of melt compositions and mineral assemblages of the high-alumina basalts.

Extensive melt degassing should be favorable for the rapid ascent of magma portions toward the volcano surface and explosive eruptions. This finds strong support in volcanological observations (Naboko, 1949).

The lack of rocks compositionally similar to the low-alumina melts can also be readily explained within the proposed model. If mineral crystallization occurs at rapid magma ascent toward the surface, the possibility of crystal separation through flotation or gravitation settling is limited, because of the short-term character of this process. In such a case, the composition of igneous rocks will be similar to those of initial magmas. The lavas may consist of a strongly evolved groundmass and of a wide spectrum of phenocryst compositions, which crystallized within a considerable interval of  $P$ - $T$ - $f_{\text{H}_2\text{O}}$  conditions. This applies in the full extent to the high-alumina basalts of Klyuchevskoy Volcano.

Despite the above arguments, the proposed model cannot be regarded as fully quantitative, because it does not account for the fact that melt decompression is accompanied by exothermic reactions of fluid separation and mineral crystallization, which must release heat energy. At rapid magma ascent and limited heat exchange with the enclosing rocks, this will result in melt heating and melting of earlier crystal phases. Thus, a more sophisticated model must account for the energy aspects of decompression crystallization. The construction of such a quantitative model is among the goals of our future work.

#### *Formation of SiO<sub>2</sub>-Rich Melts*

Silicic magmas with more than 65 wt % SiO<sub>2</sub> account for a small fraction of volcanic products of Kamchatka. There are no rhyolites or dacites among the rocks of Klyuchevskoy Volcano. However, silicic melts were found as melt inclusions in the minerals of

the high-alumina basalts (Pletchov *et al.*, 2000; and this work).

The silicic melts that were found as inclusions in plagioclase  $An_{83-62}$  and clinopyroxene  $Mg\# = 77-70$  are characterized by high SiO<sub>2</sub> (65–75 wt %) and K<sub>2</sub>O (2.5–3.7 wt %); low FeO, CaO, and MgO; and strongly scattered Na<sub>2</sub>O (2.5–5.0 wt %), TiO<sub>2</sub> (0.45–1.6 wt %), and Al<sub>2</sub>O<sub>3</sub> (12–16 wt %) contents. The most silica-rich melts approach the compositions of interstitial melts in the groundmass of the Apakhonchich basalts but are lower in TiO<sub>2</sub> and K<sub>2</sub>O (Fig. 5).

Naumov *et al.* (1997) showed that the occurrence of silicic melts in phenocrysts from andesites of Kamchatka and other regions is a typical phenomenon. However, the origin of such melts is currently disputable. The following hypotheses were proposed for the formation of silicic melt inclusions.

1. Silicic melts are products of the extensive fractionation of initial basaltic magmas (Naumov *et al.*, 1997).

2. Silicic melts result from the assimilation of country rocks by more basic magmas (Douce, 1995; Pletchov *et al.*, 2000).

3. An increase in the silica content of melt occurs during inclusion entrapment by minerals (Nakamura and Shimakita, 1998).

Let us consider these hypotheses with application to the data obtained in this work.

The extensive fractionation of the basaltic magmas of Klyuchevskoy Volcano could probably result in the formation of silicic melts chemically similar to those found in plagioclase and clinopyroxene phenocrysts. Mass balance calculations demonstrated that the formation of the dacitic melts in pyroxene phenocrysts (Fig. 5) requires separation of 5.5 wt % of olivine ( $Fo_{78}$ ), 14 wt % of clinopyroxene ( $Mg\# = 77$ ), 43.5 wt % plagioclase ( $An_{83-59}$ ), and 8.5 wt % of titanomagnetite from the initial high-alumina basaltic melt. The degree of fractionation is 71.5 wt %. The compositions of minerals used for the calculations correspond to the average compositions of phenocrysts from the Apakhonchich basalts and their proportions are close to those observed in the natural rocks. The low residual of these calculations ( $10^{-4}$ ) also indicates that this process could really occur in nature. The calculation carried out for the richest in silica (SiO<sub>2</sub> = 73–75 wt %) melts entrapped by plagioclase phenocrysts and the same initial melt yielded a degree of fractionation of more than 80 wt %, but the calculated melt composition was richer in K<sub>2</sub>O as compared to the real compositions. This suggests either the existence of a K<sub>2</sub>O-poor initial melt or a different mechanism of rhyolite melt generation.

Alternatively, the formation of such melts can be explained by the partial melting of enclosing rocks owing to their interaction with basaltic melt (Douce, 1995; Tolstykh *et al.*, 1999; Pletchov *et al.*, 2000). This hypothesis is particularly inviting because it allows us



to explain the specific features of the composition of rhyolite melts by the compositional characteristics of the assimilated rocks. However, there is no direct evidence supporting this model.

As part of the discussion of possible indicators of magma assimilation, note that the assimilation of the material of an ancient hydrothermally altered crust by fractionating melts could result in a significant change in the isotopic ratios of some elements (for instance, oxygen) in silicic melts and formation of other peculiar geochemical features. Such indications were recognized for the parental melts of the andesites of the Klyuchevskoy Volcano group (e.g., Tolstykh *et al.*, 1999). However, if the Klyuchevskoy magmas assimilated chemically similar rocks (e.g., older high-alumina basalts), the search for assimilation indicators will be more questionable, because the products of low-degree melting of basaltic rocks must be completely identical to the products of extensive fractionation of basaltic magmas under similar *P-T* conditions.

Nakamura and Shimakita (1998) proposed an entirely different mechanism for the formation of silica-rich melt inclusions. The experimental data of these authors demonstrated that the increase of SiO<sub>2</sub> content in a melt inclusion in plagioclase and the formation of a more calcic plagioclase rim around it could result from specific conditions of inclusion entrapment. Such conditions are realized when a plagioclase crystal enters a melt, which is in equilibrium with a more calcic plagioclase. The validity of this hypothesis for the formation of the rhyolite melt inclusions in plagioclases of the Apakhonchich flow is supported by the specific morphology of these inclusions and the presence of calcic plagioclase rims cutting the zoning of the host mineral (Fig. 3f). Assuming that the matrix melt was dacitic in composition, the elevated SiO<sub>2</sub> contents and relatively low K<sub>2</sub>O and TiO<sub>2</sub> in melt inclusions will also be consistent with the trends of compositional evolution of melt inclusions suggested by the model of Nakamura and Shimakita (1998). This is indicative of a high probability that the silica content of melt increased during inclusion entrapment by the plagioclase phenocrysts of the Apakhonchich flow.

Thus, the available data allow us to conclude that the dacite melts could be related to the processes of crystal fractionation of initial basaltic magmas. The formation of more acid melts probably resulted from the specific features of melt inclusion entrapment by plagioclase crystals. However, the influence of assimilation processes cannot be ruled out on the current stage of investigations.

## CONCLUSIONS

1. Magmatic inclusions were studied in phenocrysts of the high-alumina basalts of Klyuchevskoy Volcano. The estimated physicochemical conditions of crystalli-

zation served as a basis for the model of the late-stage magma evolution of Klyuchevskoy Volcano.

2. The phenocrysts of the high-alumina basalts, olivine (*Fo*<sub>71-79</sub>), clinopyroxene (Mg# = 70–81), and plagioclase (*An*<sub>47-84</sub>) crystallized from a wide range of melt compositions at temperatures of 1145–1030°C and pressures of 1–2 kbar. The earliest phenocrysts crystallized from melts containing 5–6 wt % of MgO, variable Al<sub>2</sub>O<sub>3</sub> contents (16–20 wt %), and 0–5 wt % of H<sub>2</sub>O. Variation in the water content of magma was the main factor controlling phase relationships on the liquidus of crystallizing melts. The accumulation of water in melt resulted in delay of plagioclase crystallization and formation of high-alumina melts. The subsequent plagioclase crystallization owing to a decrease in H<sub>2</sub>O content defined the following evolution of melt compositions.

3. A model is proposed for the final stage of Klyuchevskoy magma evolution. According to this model, the crystallization of phenocrysts in the high-alumina basalts occurred at rapid decompression ascent of magmas toward the volcano surface accompanied by active melt degassing.

4. It was shown that the formation of dacite melts trapped in plagioclase and clinopyroxene phenocrysts was probably related to the processes of extensive crystal fractionation of initial basaltic magmas. The formation of more silicic melt can be explained by a specific character of inclusion entrapment by plagioclase crystals.

## ACKNOWLEDGMENTS

The authors are grateful to A.A. Ariskin (Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences) for the useful advice and repeated consultations; E.V. Guseva and N.N. Korotaeva (Faculty of Geology, Moscow State University) for the substantial help at microprobe analyses; and V.A. Kondrat'eva (Faculty of Geology, Moscow State University) for the assistance in sample preparation. The work was financially supported by the Russian Foundation for Basic Research, projects nos. 96-05-64911, 00-05-04000, and 00-05-64384.

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