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The role of polybaric crystallization in genesis of andesitic magmas: Phase equilibria simulations of the Bezymianny volcanic subseries

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ABSTRACT

Using the updated COMAGMAT model, the crystallization sequences of a Bezymianny Volcano basaltic andesite (Kamchatka, Russia) are simulated in a wide range of thermodynamic conditions (P–T–fO_2) as a function of H_2O concentration. Comparison of the modeled liquid lines of descent with petrochemical trends of the volcanic suite indicates the parental melts contain 1.5–2 wt.% H_2O stored under 490–520 MPa pressure in the magma plumbing system beneath Bezymianny Volcano. The initial magma originates as a result of the polybaric evolution of mantle-derived high-Mg basaltic magmas of the adjacent Kliuchevskoi Volcano. The subsequent evolution of derivative hydrous and alumina-rich basaltic andesite magmas may proceed under polybaric conditions with an average decompression of ~12 MPa per 1% of crystallization. In the course of polybaric crystallization, compositions of pyroxene-bearing andesites can be numerically reproduced and the modeled liquid compositions follow the natural liquid line of descent. However, hornblende-bearing magmas cannot be produced as a result of continued crystallization from parental basaltic andesite through the stage of pyroxene-bearing andesite formation. They require high water contents and high pressures of crystallization. In this case, liquid composition should deviate from the chemical trend defined by the whole rock compositions.

1. Introduction

High-magnesia (HMB) to high-alumina (HAB) basalts of Kliuchevskoi Volcano and andesites to dacites of Bezymianny Volcano (Kamchatka, Russia) represent a suite of genetically related rocks that demonstrate systematic co-variations in both compatible and incompatible elements. This allowed us to consider the combination of two volcanic subseries that follows a general calc-alkaline trend typical of island arc magma differentiation (Almeev et al., 2013). The more evolved Bezymianny lavas inherit the geochemical and isotopic signatures of the Kliuchevskoi basalts, thus arguing for a common, slightly heterogeneous mantle source (Almeev et al., 2013). Previously, magma differentiation within the plumbing systems of both volcanoes was attributed to (1) prolonged ascent-driven decompressional crystallization (~2 to 0.7 GPa) of parental HMB magmas in the magmatic channel of Kliuchevskoi Volcano followed by multiple eruptions of voluminous HABs (Ariskin et al., 1995; Ariskin, 1999), and to (2) essentially isobaric crystallization (0.4–0.7 GPa) of HAB-like derivative magmas under water-saturated conditions in a magma chamber underneath Bezymianny Volcano, where andesites and dacites were generated (Ozerov et al., 1997).

The decompressional regime of magma crystallization in the conduit of Kliuchevskoi Volcano has been supported by simulations of phase equilibria for HMB parental magma using the COMAGMAT-3.5 model (Ariskin, 1999; Ariskin and Barmina, 2004). The authors assumed fractional crystallization during continuous magma ascent from a depth of 60 km. The results of these calculations demonstrated that petrochemical trends observed in the Kliuchevskoi basalts can be reproduced by ~40% fractionation of $Ol + Cpx + Sp \pm Opx$[1] assemblages during ascent of the parental HMB magma over a 1.9–0.7 GPa pressure range, with a magma "ascent rate" (expressed as dP/dF, where P is pressure and F is the degree of crystallization) of 33 MPa/% crystallized at 1350–1110 °C; ~2 wt.% H_2O was present in the initial melt and ~3 wt.% H_2O in the resultant high-Al basaltic liquid. Recently Mironov (2009) and Mironov and Portnyagin (2011) applied the same polybaric crystallization mechanism to Kliuchevskoi magma evolution, but advocated lower crystallization pressures of 1–0.5 GPa.

In a complementary paper (Almeev et al., 2013), based on results of geothermobarometry of mineral phenocrysts, we concluded that in the Bezymianny plumbing system the HAB-like magma fractionation could also proceed during magma ascent (Figs. 16–17 in Almeev et al.,

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[1] Mineral abbreviations: *Ol* — olivine; *Plag* — plagioclase; *Cpx* — clinopyroxene; *Opx* — orthopyroxene; *Hbl* — hornblende; *Sp* — spinel; *Mt* — magnetite; *Ilm* — ilmenite.

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2013), so that isobaric crystallization was a rather subordinate mechanism. In addition, we provided geochemical evidence for both (1) fractional crystallization in prehistoric lavas, and (2) magma mixing in andesites from historical eruptions (Almeev et al., 2013). We interpreted trends displayed by the Bezymianny whole rock compositions as approximating Liquid Lines of Descent (LLDs) that are mostly preserved in lavas of the pre-Bezymianny stage of volcano evolution contemporaneously with the formation of dacitic lava domes. We also recognized the prominent effects of magma replenishment and degassing-driven crystallization which complicated the original LLDs. In general, the major and trace element data presented in the (Almeev et al., 2013) are consistent with the model of a single LLD from the mafic end member, but it does not exclude the possibility of multiple injections and the existence of the magma source variability. The possibility, involving similar magmas from a major and trace element viewpoint, should be evaluated by more systematic isotopic studies, since Almeev et al. (2013) provided isotope data only for a limited number of samples.

Thus, reconciling the effects of magma mixing vs. fractional crystallization is still crucial for understanding magma evolution in the Bezymianny plumbing system. In our experimental study at 100 and 700 MPa, which was conducted for a synthesized "parental" basaltic andesite (Almeev et al., submitted for publication), the experimental LLDs did not fit the petrochemical trends perfectly. The major problem was in the behavior of TiO_2 in experimental liquids which exhibited enrichment or insignificant changes in TiO_2 contents, in contrast to natural trends indicating a sharp depletion in this component.

The major goals of this study are: (1) to investigate the relative role of intensive crystallization parameters on chemical evolution of a sequence of Bezymianny Volcano derivative magmas; (2) to identify conditions responsible for multiple saturation of the parental basaltic andesite with the *Plag* + *Cpx* + *Opx* ± *Mt* assemblage by comparing modeling results with natural observations (Almeev et al., 2013); and, finally, (3) to reproduce numerically the petrochemical trends observed in the Bezymianny volcanic subseries.

2. Calc-alkaline suite from Bezymianny Volcano

Bezymianny Volcano lavas include basaltic andesites, two-pyroxene (*2Px*), orthopyroxene- (*Opx*), and hornblende- (*Hbl*) bearing andesites, and dacites (groups BZ-I to BZ-V in Table 1, see also Almeev et al., 2013). The first four rock types are volcanic products observed as lavas, pyroclastic flows, and deposits from the directed blast of the stratovolcano itself, all representing activity during the last ~4.7 ky of volcano history (Braitseva et al., 1995). Dacites and *Hbl* andesites compose numerous lava domes that were formed prior to the formation of the main stratocone 15–20 ky ago (*Pre*-Bezymianny stage, Braitseva et al., 1991; Almeev et al., 2013), although a few also grew simultaneously with the formation of the Bezymianny edifice. Basaltic andesites and pyroxene-bearing andesites are sparsely phyric (~5–7% crystals) to porphyritic (up to 25% crystals) rocks composed of *Plag*, *Cpx*, *Opx*, and *Ol* phenocrysts. *Plag* is always a predominant mineral, whereas proportions of *Ol* and *Cpx* decrease and the proportion of *Opx* increases in transition from basaltic andesites to *Opx*-bearing andesites. *Hbl*-bearing andesites are the most phyric (25–30%) rocks containing *Hbl*, *Plag*, and rare *Opx*. Dacites are sparsely *Plag* and *Hbl* phyric lavas (5–15%). Fe–Ti oxides, mostly observed as *Mt* (and rare *Ilm*), occur in all lava types; their proportion gradually increases from trace amounts (<1% among phenocrysts) in basaltic andesite to 5–7% in dacites. Apatite is present as microphenocrysts in some *Hbl* andesites or as abundant inclusions in *Plag*. Mineral compositions of phenocrysts vary over a wide range with a unimodal distribution for Mg# (Mg# = Mg/(Mg + Fe^{2+})) in mafic minerals and a polymodal distribution for An in *Plag*. Throughout the entire lava sequence, from basaltic andesite to dacite, *Cpx*, *Opx*, *and Hbl* cores tend to evolve to Fe-rich compositions and Mg# tend to decrease with increasing silica content in the host lava. *Plag* is characterized by a bimodal pattern in many samples, with two distinctive peaks at ~An_{85-80} and ~An_{65-60}. In general, Bezymianny lavas are classified as medium-K calc-alkaline rocks exhibiting a systematic decrease in CaO, MgO, FeO, and TiO_2 and an increase in Na_2O and K_2O with enrichment in SiO_2 (Figs. 1–5). The compositional trends might be interpreted as a combined result of crystal fractionation and magma mixing. Results of the geothermobarometry from phenocryst cores and rims revealed a range of *P*–*T* magma storage conditions which differ depending on the different magma types: basaltic andesites: 1100–1150 °C, 500–600 MPa; *2Px* andesites: 1050–1130 °C, 600–700 MPa; *Opx* andesites: 990–1040 °C, 470–560 MPa; *Hbl* andesites: 950–1000 °C, 150–450 MPa; and dacites: 900–950 °C, 250–410 MPa. More details can be found in our complementary paper (Almeev et al., 2013).

3. Methods: the COMAGMAT model

In this study we used the COMAGMAT model (Ariskin, 1999; Ariskin and Barmina, 2004) designed for computer simulations of equilibrium and fractional crystallization of basaltic magmas across a range of thermodynamic parameters (*P*–*T*–fO_2).

3.1. Model refinements and limitations

Recent modifications of COMAGMAT include its capability to simulate hydrous magma crystallization more precisely, based on experimental calibrations of the effect of H_2O on near-liquidus crystallization temperatures of *Ol*, *Plag* (Almeev et al., 2007; Almeev et al., 2012),

Table 1
Basaltic andesite and average compositions of the main groups of Bezymianny and Kliuchevskoi volcanic lavas (Almeev et al., 2013). Sample OB-19 was used as a starting composition. HMB — high magnesia basalt, HAB — high alumina basalt.

Group	BZ-I	BZ-I	BZ-I	KL-I	KL-IV	BZ-I	BZ-II	BZ-III	BZ-IV	BZ-V
Rock type	Basaltic andesite	Basaltic andesite	Basaltic andesite	HMB	HAB	Basaltic andesite	*2Px* andesite	*Opx* andesite	*Hbl* andesite	Dacite
Sample	OB-19	OB-21	OB-35			Average of the group				
Number of samples				15	131	3	9	14	18	16
[wt.%]										
SiO_2	53.17	53.87	53.15	51.76	53.50	53.26	56.27	57.52	61.21	66.21
TiO_2	1.12	1.13	1.04	0.86	1.09	1.10	0.88	0.80	0.62	0.40
Al_2O_3	17.54	17.44	18.26	13.86	18.26	17.75	16.59	18.00	17.32	17.48
FeO_{tot}	9.26	9.35	9.04	8.83	8.67	9.22	7.97	7.56	6.07	3.96
MnO	0.17	0.17	0.16	0.17	0.16	0.17	0.16	0.15	0.14	0.13
MgO	5.81	5.23	5.13	11.55	5.24	5.39	5.32	3.72	2.98	1.12
CaO	8.78	8.69	9.00	9.73	8.22	8.82	8.42	7.45	6.49	4.67
Na_2O	3.03	3.03	3.16	2.47	3.45	3.07	3.01	3.40	3.52	4.12
K_2O	0.94	0.91	0.89	0.63	1.20	0.91	1.20	1.20	1.45	1.70
P_2O_5	0.17	0.17	0.18	0.15	0.20	0.17	0.18	0.20	0.19	0.21
Mg/(Mg + Fe^T)	0.53	0.50	0.50	0.69	0.52	0.51	0.54	0.47	0.47	0.34