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Polybaric degassing of island arc low-K tholeiitic basalt magma recorded by OH concentrations in Ca-rich plagioclase

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ABSTRACT

Hydrogen in nominally anhydrous minerals (NAMs) in volcanic rocks can be used as a proxy for dissolved H_2O in melt prior to eruption. Plagioclase is a NAM that accommodates hydrogen in concentrations of up to hundreds of wt. ppm H_2O. The species of hydrogen in volcanic plagioclase is structural OH. We report the analytical results of OH concentrations in Ca-rich plagioclase from the 1986–1987 summit eruption of Izu-Oshima volcano, a frontal-arc volcano in Izu arc. We demonstrate that the island arc low-K tholeiitic basalt magmas erupting from the frontal-arc volcanoes are H_2O-saturated and undergo polybaric degassing during the magma ascent. The analyzed OH concentrations in plagioclase range from 20 to 300 wt. ppm H_2O, and three levels of OH (20–80 wt. ppm H_2O, 100–180 wt. ppm H_2O, and 220–300 wt. ppm H_2O) are found. These variations in OH indicate that crystallized plagioclase is equilibrated with H_2O-saturated melt at three depths beneath the Izu-Oshima volcano prior to eruption: near the surface level ($\approx$1 wt.% H_2O in melt), at a 4-km-deep magma chamber ($\approx$3 wt.% H_2O in melt), and at a 8–10-km-deep magma chamber ($\approx$5 wt.% H_2O in melt). It is proposed that deep-seated island arc low-K tholeiitic basalt magmas erupting from frontal-arc volcanoes are richer in H_2O than previously thought, containing approximately 1 wt.% H_2O based on analyses of "leaked" melt inclusions and phase equilibrium studies at "low-pressure conditions".

1. Introduction

Quantifying the H_2O concentration in arc magmas is critical for understanding their generation, differentiation, and eruption because H_2O has profound effects on melting temperatures, crystallization pathways, and explosivity. Among arc magmas, island arc low-K tholeiitic basalts from frontal-arc volcanoes are generally thought to be H_2O-undersaturated and to contain approximately 1 wt.% H_2O based on melt inclusion analyses (Kazahaya et al., 1994; Saito et al., 2005) and phase equilibrium studies (Grove and Baker, 1984; Kawamoto, 1996; Sakuyama, 1979). In contrast to these previous petrological studies, recent melt inclusion analyses report higher H_2O concentrations in low-K tholeiitic basalts obtained from subaqueous Izu arc volcanoes (up to 5 wt.% by Straub and Layne, 2003) and Miyakejima volcano (up to 3.5 wt.% by Saito et al., 2010). At Izu-Oshima volcano, a frontal-arc volcano in Izu arc, the H_2O concentration in plagioclase-hosted melt inclusions is <2 wt.% regardless of anorthite content of the host plagioclase ($An_{87–96}$; Hamada and Fujii, 2007), while olivine-hosted melt inclusions contain higher H_2O concentrations (up to 3.4 wt.%; Ikehata et al., 2010). There remains some uncertainty in our understanding of the H_2O abundances of island arc basalts. Both Hamada and Fujii (2007) and Ikehata et al. (2010) reported that the CO_2 concentration in all the melt inclusions from Izu-Oshima volcano is below the detection limit (<50 ppm), and therefore, variations in H_2O concentration are not due to CO_2 fluxing from the depths, a process identified at many arc basaltic volcanoes (Johnson et al., 2008; Spilliaert et al., 2006). Melting experiments of hydrous basalts have demonstrated that Ca-rich plagioclase (approximately An_{90}) crystallizes from H_2O-rich ($\geq$3 wt.%) melt (Sisson and Grove, 1993a; Takagi et al., 2005). From these results, Hamada and Fujii (2007) assumed that the melt is originally H_2O-rich and that H_2O vapor in trapped melt inclusions leaks through microcracks in the plagioclase phenocryst at shallow levels. This assumption can explain the low (<2 wt.%) concentrations of H_2O and the undetectably low concentrations of CO_2 in the plagioclase-hosted melt inclusions. However, this assumption also suggests that the H_2O concentration in melt inclusions does not always represent the H_2O concentration at the time the melt was trapped.

An alternative method to constrain the H_2O concentration in pre-eruptive melt is to analyze hydrogen in nominally anhydrous minerals (NAMs). The hydrogen in NAMs can be an indicator of H_2O activity in melts and can act as a speedometer of the magma ascent (Demouchy

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et al., 2006; Peslier and Luhr, 2006; Peslier et al., 2008). Plagioclase is one of those NAMs, and it accommodates hydrogen up to hundreds of wt. ppm H_2O. The speciation of hydrogen in plagioclase from volcanic rocks has been demonstrated to be structural OH (Johnson and Rossman, 2003, 2004). In this study, we analyzed the OH concentration in plagioclase from the Izu-Oshima summit eruptions during 1986–1987 using a Fourier transform infrared spectrometer (FTIR) to estimate the H_2O concentration in the island arc low-K tholeiitic basalts. Plagioclase is easy to collect because it is the most abundant phenocryst in erupted magmas (up to 15 vol.%). The question remains of whether analyzed OH in plagioclase is intrinsic or already diffused out during eruption. Limited experiments on the diffusivity of hydrogen in feldspars have clarified that the diffusivity values range between 10^{-11} m^2/s at 900 °C and 10^{-15} m^2/s at 500 °C (K-feldspar; Kronenberg et al., 1996) or between 10^{-13} m^2/s at 1000 °C and 10^{-14} m^2/s at 800 °C (An_{30} plagioclase; Johnson, 2003), which allows the hydrogen in feldspars to diffuse out over periods of hours to days. To quantify this effect, we also analyzed OH in plagioclase from three distinctive types of summit eruptions of Izu-Oshima volcano during 1986–1987: the Strombolian eruption in 1986, an effusive eruption emitting lava flow in 1986, and a less energetic eruption in 1987. The variation in OH in plagioclase might be related to these eruptive styles.

2. Outline of the Izu-Oshima 1986–1987 summit eruptions

The volcanic rocks of Izu-Oshima volcano are dominated by low-K tholeiitic basalts with minor andesites. During the 1986–1987 eruptions, basaltic magmas erupted from the summit vent and andesitic magmas erupted from two fissure vents in the caldera and on the outer flank. The total volume of erupted magmas was 0.053 km^3 (0.032 km^3 DRE; Endo et al., 1988). In this study, we focus on the basaltic eruptions from the summit vent. The summit eruption in 1986 was marked by two distinctive sequences: (1) Strombolian activity (November 15th, 1986, and thereafter) and (2) the emission of lava flow (November 18th, 1986 and thereafter). A continuous magma supply formed a lava lake on the summit vent, which eventually spilled as lava flows on November 18th and thereafter. The lava flows descended down the edifice of the volcano and stopped moving within 3 days. After the 1986 eruptions, the magma head retreated into the conduit, while the level of the summit's lava lake remained steady for a year until a summit eruption on November 16th, 1987. This eruption was less energetic and was triggered by a gas explosion in the conduit, and it generated flaky bombs (Watanabe et al., 1998). The volume of erupted magma on November 1987 was 0.05% of the total erupted volume of magmas during 1986–1987 (Endo et al., 1988).

Geophysical studies detected two major magma chambers beneath the Izu-Oshima volcano: a 4-km-deep magma chamber (Ida, 1995) and an 8–10-km-deep magma chamber (Mikada et al., 1997). In addition, approximately 0.011 km^3 of magma was stored in the summit's lava lake (300 m in diameter and 200 m in depth) during the 1986–1987 eruptions. The summit's lava lake and the 4-km-deep magma chamber were thought to be connected through a conduit based on observations of crustal deformation in November, 1987 (Ida, 1995).

3. Studied samples

We analyzed the OH concentration in plagioclase from three distinctive eruptions to relate the eruptive styles to the variations in OH in plagioclase: air-fall scoria from the Strombolian eruption in 1986, lava flow from an effusive eruption in 1986, and flaky bombs from the eruption in 1987. The compositions of the air-fall scoria from the 1986 eruption and the flaky bombs from the 1987 eruption were analyzed with an X-ray fluorescence spectrometer (RIGAKU system 3070) at the Institute for Geothermal Sciences (IGS), Kyoto University, using a calibration line optimized for a wide compositional range (Sugimoto et al., 2007). The operating conditions were 15 kV and 5.0×10^{-8} A. The data were corrected using a ZAF correction. Although the whole-rock major element compositions and the modal compositions of the three rocks are similar (Table 1), their groundmass textures are different. The 1986 scoria exhibits a glassy groundmass and small (<100 μm) bubbles (Fig. 1a), while the 1986 lava flow has plagioclase characterized by a <10-μm anorthite-poor rim (An_{70} to An_{75}) on plagioclase phenocrysts and microcrystalline

Table 1
Whole-rock major element compositions and modal compositions of volcanic rocks from the summit eruptions of Izu-Oshima volcano during 1986–1987. The composition of lava flow (LA-III) is from Nakano and Yamamoto (1987).

	1986 eruption		1987 eruption
	Air-fall scoria	LA III lava*	Flaky bomb
Major element compositions (wt.%)			
SiO_2	53.6	53.2	52.6
TiO_2	1.20	1.24	1.12
Al_2O_3	14.7	15.2	15.5
FeO*	13.1	12.8	13.0
MnO	0.22	0.20	0.21
MgO	4.70	4.67	4.60
CaO	10.2	10.4	10.6
Na_2O	1.84	1.88	1.86
K_2O	0.38	0.41	0.38
P_2O_5	0.10	0.08	0.10
Cr_2O_3	0.01	–	0.04
NiO	0.01	–	0.02
Raw total	99.1 (wt.%)	99.6 (wt.%)	100.5 (wt.%)
Modal compositions (vol.%) of phenocrysts (>0.1 mm)			
Plagioclase	5–10		10–15
Clinopyroxene	<1		<1
Orthopyroxene	<1		<1
Groundmass phases			
	Glass Plagioclase	Plagioclase Clinopyroxene Magnetite	Glass Plagioclase Clinopyroxene Magnetite