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Phase petrology reveals shallow magma storage prior to large explosive silicic eruptions at Hekla volcano, Iceland

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ABSTRACT

Understanding the conditions that culminate in explosive eruptions of silicic magma is of great importance for volcanic hazard assessment and crisis mitigation. However, geological records of active volcanoes typically show a wide range of eruptive behavior and magnitude, which can vary dramatically for individual eruptive centers. In order to evaluate possible future scenarios of eruption precursors, magmatic system variables for different eruption types need to be constrained. Here we use petrological experiments and microanalysis of crystals to clarify the P–T–x state under which rhyodacitic melts accumulated prior to the H3 eruption; the largest Holocene Plinian eruption of Hekla volcano in Iceland. Cobalt-buffered, H_2O-saturated phase equilibrium experiments reproduce the natural H3 pumice phenocryst assemblage (pl > fa + cpx > ilm + mt > ap + zrc) and glass chemistry, at 850 ± 15 °C and P_{H_2O} of 130 to 175 MPa, implying shallow crustal magma storage between 5 and 6.6 km. The systematics of FeO and anorthite ($CaAl_2Si_2O_8$) content in plagioclase reveal that thermal gradients were more important than compositional mixing or mingling within this magma reservoir. As these petrological findings indicate magma storage much shallower than is currently thought of Hekla's mafic system, we use the constrained storage depth in combination with deformation modeling to forecast permissible surface uplift patterns that could stem from pre-eruptive magma intrusion. Using forward modeling of surface deformation above various magma storage architectures, we show that vertical surface displacements caused by silicic magma accumulation at ∼6 km depth would be narrower than those observed in recent mafic events, which are fed from a lower crustal storage zone. Our results show how petrological reconstruction of magmatic system variables can help link signs of pre-eruptive geophysical unrest to magmatic processes occurring in reservoirs at shallow depths. This will enhance our abilities to couple deformation measurements (e.g. InSAR and GPS) to petrological studies to better constrain potential precursors to volcanic eruptions.

1. Introduction

Large explosive eruptions of silicic magma constitute perhaps the most dramatic natural phenomena on Earth. Yet to date, only a small number of events with erupted magma volumes >1 km^3 have been scientifically monitored (Lipman and Mullineaux, 1981; Harlow et al., 1996; Jay et al., 2014). Our ability to identify precursors to such eruptions is critical in the context of improved hazards assessments and mitigation of these events, which may develop quickly and be exceedingly explosive (Castro and Dingwell, 2009). Clearly, geophysical signals such as surface deformation and seismicity that serve as harbingers to big eruptions can be monitored (e.g., Parks et al., 2012), and because such signals are controlled by magmatic processes beneath volcanoes (e.g., Castro et al., 2016), investigations of magmatic system variables such as pressure (depth), temperature, and volatile budget, provide critical information to augment modeling and interpretation of monitoring signals, as shown by a number of studies (Muir et al., 2014; Caricchi et al., 2014; Jay et al., 2014).

Muir et al. (2014) used experimental petrology and modeling of surface displacement to show that the recent broad (∼70 km) deformation of Uturuncu volcano in the Central Andes is probably caused by intrusion of intermediate magma at mid-crustal rather than shallow (<6 km) depths, while Caricchi et al. (2014) employed thermal and petrological calculations to identify the most likely processes controlling the 1997 to 2008 subsidence of the Okmok caldera (Aleutians). Jay et al. (2014) combined geodetic measurements and petrological microanalysis to "inversely" determine magmatic storage depths (5–9 km) and volume changes

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that fed the 2011 eruption at Cordón Caulle (Chile). These examples illustrate the rich potential of petrological studies to identify magma storage positions, geometries, and processes that underpin geophysical monitoring signals at restless volcanoes. However, the rarity of big silicic eruptions and monitoring datasets thereof limits such inversion to being synoptic rather than forecasting in nature. Forward modeling of petrological results—that is the use of experimentally constrained magma depths as *initial* inputs to surface deformation models—is an hitherto unexplored yet fertile approach that could yield forecasts of pre-eruptive deformation. Such an approach is the goal of this paper.

Linking signs of pre-eruptive unrest to the sub-volcanic architecture of magma bodies requires a first-order understanding of the depths over which magmas reside and crystallize in the crust, which may vary substantially across tectonic setting. As this information is completely lacking for highly evolved volcanoes in Iceland, we consider magma dynamics at Hekla volcano, one of the largest centers of explosive volcanism in Iceland. Hekla has produced at least five paroxysmal Holocene eruptions with Volcanic Explosivity Indices of 5 (Jónasson, 2007), and the associated hazards and risks of such large events, were they to repeat, could extend beyond Iceland into Europe. In particular, we performed phase equilibria experiments to constrain the $P_{H_2O}–T–fO_2$ conditions under which the rhyodacitic magma that fueled the largest Hekla eruption (H3) last equilibrated prior to eruption, and thus to provide an estimate of magma storage depth. We further interrogate chemical zoning profiles in plagioclase phenocrysts to investigate thermal and compositional perturbations in Hekla's H3 pre-eruptive reservoir. We show, using a novel combination of pre-eruptive storage conditions and deformation models, that in contrast to more recent mafic to intermediate eruptions, silicic volcanism at Hekla is shallowly sourced. Shallow magma reservoirs, if perturbed by replenishment events, should generate detectable surface deformation prior to silicic eruptions (e.g., Jay et al., 2014). As rejuvenation of near-solidus evolved magma bodies in the crust can operate on timescales relevant for eruption forecasting (Barker et al., 2016), our study has implications for forecasting eruptions of chemically diverse magma reservoirs at Hekla and other volcanoes with bi-modal eruption tendencies.

2. Hekla volcano: magma storage and studied samples

Hekla volcano in southern Iceland is one of the most active volcanoes in Europe. Indeed, Hekla's Holocene eruption history, as manifested by detailed historical records (Thordarson and Larsen, 2007) and in prehistoric tephra layers (Sverrisdottir, 2007), is marked by two contrasting types of behavior. Well-documented historical eruptions, typically of basaltic andesite composition and volumes <0.22 km^3 DRE, start with an explosive Plinian phase, and are followed by lava effusion. Hekla's activity is also characterized by large, purely explosive dacitic to rhyolitic eruptions. Several such silicic tephra layers have been identified in the geological record: The H5 (6200 BP; 0.7 km^3 DRE), H4 (3830 BP; 1.8 km^3 DRE), HSelsund (3515 BP; 0.4–0.5 km^3 DRE), H3 (2879 BP; 2.2 km^3 DRE) and H1104 (846 BP; 0.61 km^3 DRE).

Recent geodetic monitoring data for Hekla's historical eruptions (Sturkell et al., 2013) implies that such events are fed from a deep crustal magma source, yielding distinctly broad surface deformation patterns around the volcano. A number of geophysical studies have been conducted to estimate the depth of the magma storage region beneath the volcano. Early studies, including repeated electronic distance measurements (Kjartansson and Gronvold, 1983), borehole strain monitoring (Linde et al., 1993), and GPS ground deformation studies (Sigmundsson et al., 1992; Tryggvason, 1994), pointed to a reservoir between 5 and 11 km depth for basaltic andesite eruptions. However, Sturkell et al. (2013) pointed out that these estimates are no longer considered to be reliable, due to a previously unrecognized artefact in the strain data. Deep magma storage is implied by seismic studies, which have not detected molten material in the depth range between 4 and 14 km (Soosalu and Einarsson, 2004). Modeling of GPS (Geirsson et al., 2012) and InSAR time series (Ofeigsson et al., 2011; Sturkell et al., 2013) revealed that magma is accumulating in the lower crust, ranging somewhere between 10 and 24 km depth, feeding the present-day more mafic to intermediate eruptions.

Table 1
Chemical composition of Hekla (H3 eruption) bulk rock and matrix glass determined by XRF and EMPA.

Major elements (wt.%)	H3 whole rock[a]	H3 matrix glass $n = 30$	1 SD
SiO_2	69.93	72.59	0.53
Al_2O_3	14.72	14.67	0.26
FeO (t)	4.83	3.21	0.07
MnO	0.14	0.12	0.04
MgO	0.13	0.13	0.01
CaO	2.66	2.14	0.07
Na_2O	4.85	4.74	0.18
K_2O	2.33	2.55	0.05
TiO_2	0.34	0.22	0.01
P_2O_5	0.05	0.05	0.02
SO_3	0.02	0.04	0.01
F	–	0.18	0.12
Cl	–	0.05	0.01
LOI	1.19		
Total[b]	99.1	100.6	0.85

[a] Normalized to 100% anhydrous.
[b] Hydrous total.

Samples from the largest Holocene eruption of Hekla volcano (H3) were collected from a proximal (about 8 km from the vent) Plinian fallout deposit, which was dated by Dugmore et al. (1995) with an age of 2879 ± 34 yr. BP (calibrated ^{14}C age). Tephra with a volume of 10 to 12 km^3 (2.2 km^3 Dense Rock Equivalent) was ejected into the atmosphere during this eruption (Larsen and Thorarinsson, 1977). The whole rock geochemistry of the deposit is zoned from rhyodacitic (~68 wt.% SiO_2) in the lower and middle layers to andesitic (~56 wt.% SiO_2) in the uppermost deposit, probably reflecting the injection of a basaltic andesite dyke that also triggered the eruption (Sverrisdottir, 2007). Since we are primarily interested in constraining the equilibrium magma storage conditions of silicic magma at Hekla, we neglect the hybridized parts of the deposit responsible for the chemical zoning in our study. Pumice samples from the lower and middle part of the deposit, which were used in this study, contain a mineral phase assemblage comprising plagioclase > fayalitic olivine + clinopyroxene > titanomagnetite + ilmenite, as well as minor apatite and zircon (Fig. 1). Whole rock pumice and matrix glass analyses of the studied samples are provided in Table 1.

All studied samples are crystal-poor (<10 vol.%), and show a highly vesicular texture and homogeneous rhyolitic groundmass glass composition (72.59 ± 0.53 wt.% SiO_2). The groundmass glass is microlite free in all samples, implying that no crystallization occurred upon rapid ascent of the magma. Plagioclase ($An_{31–48}Ab_{54–68}Or_{1–2}$) is the most common phenocryst phase and occurs as subhedral fragments or euhedral crystals (100 and 1000 μm). The second most common mineral is eu- to subhedral fayalitic olivine ($Fo_{12–13}Fa_{83–84}Te_3$). Clinopyroxene ($Wo_{35–42}En_{24–35}Fs_{36–45}$) is present in similar amounts and size to fayalite in the analyzed samples. The grains are typically subhedral fragments but euhedral crystals also occur.

Faceted crystal faces are observable on all of the analyzed mineral phases, whereas resorption surfaces or mineral breakdown reaction coronas are sparse in these samples. This textural evidence indicates that the phase assemblage grew from magma at equilib-