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NanoSIMS results from olivine-hosted melt embayments: Magma ascent rate during explosive basaltic eruptions

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ABSTRACT

The explosivity of volcanic eruptions is governed in part by the rate at which magma ascends and degasses. Because the time scales of eruptive processes can be exceptionally fast relative to standard geochronometers, magma ascent rate remains difficult to quantify. Here we use as a chronometer concentration gradients of volatile species along open melt embayments within olivine crystals. Continuous degassing of the external melt during magma ascent results in diffusion of volatile species from embayment interiors to the bubble located at their outlets. The novel aspect of this study is the measurement of concentration gradients in five volatile elements (CO_2, H_2O, S, Cl, F) at fine-scale (5–10 μm) using the NanoSIMS. The wide range in diffusivity and solubility of these different volatiles provides multiple constraints on ascent timescales over a range of depths. We focus on four 100–200 μm, olivine-hosted embayments erupted on October 17, 1974 during the sub-Plinian eruption of Volcán de Fuego. H_2O, CO_2, and S all decrease toward the embayment outlet bubble, while F and Cl increase or remain roughly constant. Compared to an extensive melt inclusion suite from the same day of the eruption, the embayments have lost both H_2O and CO_2 throughout the entire length of the embayment. We fit the profiles with a 1-D numerical diffusion model that allows varying diffusivities and external melt concentrations as a function of pressure. Assuming a constant decompression rate from the magma storage region at approximately 220 MPa to the surface, H_2O, CO_2 and S profiles for all embayments can be fit with a relatively narrow range in decompression rates of 0.3–0.5 MPa/s, equivalent to 11–17 m/s ascent velocity and an 8 to 12 minute duration of magma ascent from ~10 km depth. A two stage decompression model takes advantage of the different depth ranges over which CO_2 and H_2O degas, and produces good fits given an initial stage of slow decompression (0.05–0.3 MPa/s) at high pressure (>145 MPa), with similar decompression rates to the single-stage model for the shallower stage. The magma ascent rates reported here are among the first for explosive basaltic eruptions and demonstrate the potential of the embayment method for quantifying magmatic timescales associated with eruptions of different vigor.

1. Introduction

A critical parameter governing the style and intensity of volcanic eruptions is the rate at which magma ascends from the storage region to the surface. The decompression of ascending magma drives the exsolution of dissolved volatile components from the melt into a separate vapor phase, which increases the buoyancy of the magma and creates a driving force for further ascent and eruption. The interaction of the rate of ascent with the kinetics of bubble nucleation, growth, and coalescence is also an important factor controlling the development of permeability in magmas and therefore how magmas degas and ultimately erupt (Gonnermann & Manga, 2007; Cashman and Sparks, 2013). Although several factors and feedbacks may affect the style in which magmas erupt, magma ascent rate is fundamental to the dynamics of eruption. However, it is a parameter that has proved difficult to determine, with current estimates limited to a few well-documented eruptions (Rutherford, 2008).

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Many approaches have been employed to quantify magma ascent rates, including but not limited to: fluid dynamical simulations, seismicity, decompression crystallization and bubble nucleation experiments, crystal reaction kinetics, elemental diffusion during ascent, or a combination of these techniques (e.g. Spera, 1984; Endo et al., 1996; Geschwind and Rutherford, 1995; Rutherford and Devine, 2003; Proussevitch and Sahagian, 2005; Szramek et al., 2006; Toramaru, 2006; Castro and Dingwell, 2009; Ruprecht and Plank, 2013). These approaches have revealed magma ascent rates that vary over orders of magnitude (0.1–30 m/s) for volcanism with a diversity of magma composition and viscosity, eruption explosivity, and depth resolution from source to vent (i.e. some techniques are sensitive in the shallow crust, while others may provide deeper constraints). Here, we pursue an approach, in which we make use of the preservation of chemical zonation in crystals or glass, and then apply time-dependent diffusion models to obtain the duration of magma ascent (e.g., Demouchy et al., 2006; Peslier and Luhr, 2006; Liu et al., 2007; Ruprecht and Plank, 2013). Our study focuses on hydrous mafic arc volcanism, for which few previous estimates of ascent rate exist.

A petrologic approach that holds much promise for constraining ascent timescales involves the analysis of chemical zonation of volatile species in melt embayments that are found within phenocryst phases (Anderson, 1991; Liu et al., 2007; Humphreys et al., 2008). Essentially melt inclusions (MIs) that have failed to become fully enclosed, melt embayments have also been termed hourglass inclusions, melt pockets, melt tubes, and re-entrants. With the exception of hourglass inclusions that are connected to the exterior melt via a very narrow neck of glass (Anderson, 1991), all of these other features refer to some crystal growth defect that fills with melt and remains connected to the external melt through a wide outlet on the crystal face. While most fully-enclosed melt inclusions preserve magma compositions prior to degassing (Metrich and Wallace, 2008), embayments inevitably experience diffusive volatile loss due to the direct connection to the host melt during ascent and degassing. In some cases this volatile loss is only partial and compositional gradients within the embayment may constrain the timescales of diffusive re-equilibration, which can be related to the decompression rate.

The key assumptions in this approach are that the chemical species of interest within the embayment attempt to remain in equilibrium with an external melt undergoing equilibrium degassing and that the resultant diffusion profile can be spatially resolved to extract meaningful time scales. As near-surface magma ascent is rapid for explosive eruptions, only fast-diffusing volatiles, such as H_2O, CO_2 and S, capture the ascent process. In a pioneering study, Liu et al. (2007) measured H_2O and CO_2 by FTIR in quartz-hosted embayments. However, the large FTIR beam size limited the analysis to two to three spots, and such coarse spatial resolution compromises the temporal resolution. Humphreys et al. (2008) later utilized the embayment technique with plagioclase-hosted embayments, correlating H_2O concentration with gray scale values measured by electron back-scatter (EBS) for a highly spatially resolved profile. Although they achieved better spatial resolution especially in the critical region near the outlet, the EBS method is unable to quantify the additional constraint on ascent and pressure provided by CO_2.

Here we attempt to improve upon prior work by utilizing the unique analytical capabilities of the NanoSIMS (Hauri et al., 2011), which allows for a spatial resolution (<0.1 to 10 μm raster size) approaching that of the EBS technique, while enabling the analysis of multiple volatile species (H_2O, CO_2, S, Cl, F). We focus on the well-documented October 1974 eruption of Volcán de Fuego (Rose et al., 1978), which was meticulously sampled and includes a comprehensive melt inclusion record (Roggensack, 2001; Berlo et al., 2012; Lloyd et al., 2013). In this study, we model the diffusion of multiple volatile species within melt embayments in olivine to determine magma decompression rate and its relationship to volcanic explosivity.

2. Background

This study utilizes the same airfall samples of the Volcán de Fuego October 1974 eruption as in our previous study on melt inclusions (MIs) and the timescales of volatile loss (Lloyd et al., 2013). Four sub-Plinian eruptions (VEI 4) occurred between October 14 and October 23, 1974, producing ~0.1 km^3 of porphyritic, H_2O-rich, high-aluminum basalt (Rose et al., 2008). A comprehensive sample suite was collected by S. Bonis during each eruptive phase. Here we focus on samples erupted on October 17, 1974, to ensure that the analyzed embayments underwent similar ascent, eruptive, and depositional histories, and not the shifts in eruptive behavior often observed during multi-day eruptions (e.g. 2010 Eyjafjallajokull, Gudmundsson et al., 2012). The October 17 phase of the eruption was the most explosive of the 4 main phases and produced about 40% of the total erupted material (Rose et al., 1978). Furthermore, this phase exhibited a sustained eruptive sequence that does not include the complexities associated with the initiation or cessation of the eruption (Carr and Walker, 1987).

The October 17 phase has been described as a sub-Plinian eruption with major ash flows and extensive airfall from an eruption column that reached stratospheric heights (~15 km, Rose et al., 1978). Intense explosions with a one-minute periodicity were observed near the vent. The pulsating explosions and bimodal grain size distribution of the tephra suggest that a comminution or milling process could be occurring post-fragmentation in the upper conduit and vent during the eruption (Rose et al., 2008). After the 1974 eruption, the main surface vent of Fuego was observed to be greater than 20 m in radius and was hypothesized to be connected to the source region by a vertical conduit (Rose et al., 1978).

The extensive prior work on MIs from the October 17 phase of the eruption provides a useful starting point for understanding the pre-eruptive conditions and decompression path during magma ascent. Shifts in bulk ash geochemistry (Rose et al., 1978), changes in the size and modal proportions of phenocrysts (Roggensack, 2001), and MI heterogeneity (Berlo et al., 2012) have all been presented as evidence for the hybridization of distinct magmas during this 10-day long eruption. It has been speculated that the 1974 eruption either tapped a vertically stratified magma chamber (Rose et al., 1978), or that magma ascent was preceded by mixing of magmas, which fractionated at different depths (Roggensack, 2001; Berlo et al., 2012).

Our work on Fuego MIs erupted on October 17 indicates that a simpler magma system was associated with this phase of the eruption. The linear variation in K_2O–SiO_2, as well as consistent trace-element ratios, reflect degassing-induced crystallization of a single parental magma (Lloyd et al., 2013). This could reflect a fresh influx of basaltic melt preceding the explosive October 17 eruption, whereas the other, less explosive eruptions may have included residual magma that stalled within the plumbing system (Berlo et al., 2012). In Lloyd et al. (2013), we analyzed MIs from multiple pyroclasts of different sizes (ash, lapilli, and volcanic bombs) and discovered systematically lower (~1 wt.%) H_2O concentrations in MIs from both the core and the rim of two 6 cm bombs, compared to those in ash and lapilli samples. We interpreted this to reflect diffusive H_2O-loss through the olivine host during post-eruptive cooling, on a timescale of approximately 10 min. However, because H_2O-loss from ash and lapilli hosted MIs could not be accounted for by post-eruption cooling alone, we considered the possibility that some H_2O-loss also occurred during ascent, and estimated magma ascent rates on the order of 10 m/s. Once the MIs were corrected for post-entrapment diffusive re-equilibration, the volatile concentrations conformed to a closed-system degassing path, indicating that the MIs were trapped at various depths prior to and during ascent. Here, we use this closed-system degassing path and the associated range of MI entrapment pressures to define initial and external boundary conditions for embayment formation and ascent. By exploiting the differences in solubility and diffusivity of five volatile species, this embayment study provides independent constraints on