



Prolonged ascent and episodic venting of discrete magma batches at the onset of the Huckleberry Ridge supereruption, Yellowstone

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ABSTRACT

How exceedingly large, volcanic supereruptions begin provides crucial information on the storage, ascent and release of silica-rich magma in catastrophic events. Initial fall deposits of the 2.08 Ma, 2500 km³ Huckleberry Ridge eruption are multiply bedded and in several places contain reworked intervals, indicating time breaks in the opening phases of the eruption. A 2.5 m section of these fall deposits was sampled at nine levels below the earliest ignimbrite (member A) at Mount Everts (Mammoth, Wyoming). We analyzed major and trace elements and volatiles in quartz-hosted melt inclusions (MIs), reentrants (REs; unsealed melt inclusions) and associated obsidian pyroclasts (thick-walled shards) to establish quartz crystallization and storage depths and melt compositional groupings. Systematic relationships between Rb and other incompatible elements (U, Cl, B) indicate ~55% fractional crystallization between the least and most evolved glass compositions. In contrast, H₂O concentrations in MIs show scattered relationships with trace elements and are interpreted to reflect variable loss of H₂O by diffusion through the quartz host during magma ascent. The wide H₂O variations (1.0–4.7 wt.%) in MIs from individual fall horizons imply as much as ~14 days of diffusive loss, reflecting highly variable and surprisingly slow decompression conditions. Water and CO₂ gradients in reentrants, however, are consistent with final ascent times of <1 to 4 h (ascent rates of ~0.3–1.5 m/s), similar to those represented by MIs that we infer to have experienced little to no diffusive H₂O loss. The wide range of ascent rates for co-erupted crystals mirrors that of intermittent explosive activity at Mount St. Helens in summer 1980, and implies that the Huckleberry Ridge magma body was not strongly overpressured at eruption onset. Restored entrapment pressures and geochemical data for MIs provide evidence for six distinct populations of quartz that originally crystallized in geochemically distinct magma domains. The compositions of REs and obsidian pyroclasts, by comparison, show that by the onset of eruption, the quartz had been brought together into three discrete magma bodies, which we interpret to have been cupolas on the roof of the main magma body. These cupolas were erupted sequentially and episodically from separate vents to generate the fall deposits before escalating activity led to generation of voluminous pyroclastic flows, and this pattern of activity suggests that tectonic triggering may have destabilized multiple magma bodies. Supereruptions as large as the Huckleberry Ridge event may start hesitatingly if the parental magma bodies are not strongly overpressured, with small-scale episodic activity that is modulated by external controls that may leave no other geological evidence for their presence.

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1. Introduction

Caldera-forming silicic eruptions are among the most devastating natural events on Earth, with the largest (supereruptions) disgorging vast quantities of material on geologically instantaneous timescales (Mason et al., 2004; Self, 2006). However, the mechanisms and timescales associated with eruption onset remain un-

clear. Do such eruptions start vigorously, then escalate (Wilson and Hildreth, 1997), or can there be episodicity (Wilson, 2001), and what might cause an explosive eruption to stop once initiated? Although most researchers agree that overpressure due to magma recharge or volatile exsolution is a common triggering mechanism in small-volume chambers (Roche and Druitt, 2001; Jellinek and DePaolo, 2003; Gregg et al., 2012), there remains controversy about its role in larger, caldera-forming eruptions (see Gregg et al., 2015). In the latter case, there is also debate as to

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whether buoyancy is central to the initiation (Caricchi et al., 2014; Malfait et al., 2014) or if an external mechanism, such as roof destabilization or tectonic rifting, is a requirement for mobilization (Gregg et al., 2012, 2015; de Silva and Gregg, 2014). This controversy is exacerbated by a scarcity of geochemical data on the very earliest deposits from supereruptions that could constrain how they start. However, discriminating between these mechanisms is possible (e.g. Allan et al., 2012) if the state and behavior of magma at eruption onset could be assessed. In particular, because magma ascent rates reflect the extent of overpressure in the magma chamber (e.g., Melnik and Sparks, 1999), determining ascent rates for the earliest erupted materials can reveal whether or not internal triggering by overpressure in the source magma body was important.

Here we address these issues by combining field evidence with evaluation of magma ascent timescales derived from diffusive H₂O losses from enclosed melt inclusions (MIs) and H₂O and CO₂ loss from reentrants (REs; unsealed melt inclusions), all preserved in quartz phenocrysts. We take advantage of the inferences that significant diffusive loss of H₂O species from MIs through their host phenocryst can occur on timescales of hours to days during magma rise (Severs et al., 2007), and from REs on even shorter timescales associated with the final stages of magma ascent (Liu et al., 2007; Humphreys et al., 2008; Lloyd et al., 2014). We couple our timescale information with micro-scale geochemistry to examine magma chamber conditions and conduit processes shortly before and during the opening stages of the Huckleberry Ridge supereruption.

2. Geological background

The Huckleberry Ridge Tuff (HRT) is the product of the oldest and largest (2.08 Ma; 2500 km³) of the three caldera-forming eruptions at the Yellowstone Plateau volcanic field (Christiansen, 2001; Fig. 1). The HRT consists of initial fall deposits overlain by three voluminous welded ignimbrite units [members A, B and C], with minor additional fall deposits beneath member C. Here we focus on the initial fall deposits beneath member A, which consist of multiple bedded layers, including several that are normally graded up to fine ash tops. This grading implies that the eruption plume stopped and restarted several times, reflecting episodicity during the opening explosive phases. In addition, there is evidence in these deposits for reworking in their lower parts at multiple stratigraphic levels, observed in widely-spaced stratigraphic sections (Fig. 1b, c and Supplementary Fig. 1). A lack of wholesale reworking or significant gullying of the fine-grained ash-rich beds, however, precludes time periods of months to years for any single hiatus, but rather requires pauses in deposition on the order of days (see also Supplementary Fig. 1).

3. Methods

Nine individual layers were sampled from the lowest 1.8 meters of the 2.5 m thick, largely unconsolidated fall deposits preserved beneath the welded base of ignimbrite member A on the western rim of Mt. Everts near Mammoth, Wyoming, north of the inferred eruptive source (Fig. 1a). The nine sampled layers were chosen to bracket horizons of reworking and to be distributed over changes in grain size (Fig. 1b). At higher levels than those sampled, the fall deposits are baked or fused by the overlying welded ignimbrite, the matrix glasses are darkened and MIs devitrified; this material was not used in this study. Samples were sieved to 500 μm and picked for loose, but glass-coated, quartz crystals. Individual crystals were mounted and doubly polished to expose glassy, bubble-free MIs and REs (Fig. 2). Size, glass color, and distance from the

nearest crystal rim were recorded for each MI (Online Supplementary Table 1) and cathodoluminescence images of the quartz hosts were acquired (Supplementary Fig. 2). We report data only from those samples with pristine and glassy MIs, which are thus inferred to have quenched rapidly on eruption, preserving information about their entrapment and ascent histories. Black obsidian shards to micro-pyroclasts (<1 mm across) from each layer were also sampled, and mounts prepared and analyzed in a similar manner to the MIs and REs.

Water and CO₂ concentrations were measured using a Thermo Nicolet Nexus 670 Fourier transform infrared (FTIR) spectrometer interfaced with a Continuum IR microscope at the University of Oregon. Absorbances measured were converted to H₂O and CO₂ concentrations using the Beer–Lambert law ($c_i = M_i \cdot A / \rho \cdot d \cdot \varepsilon$), where c_i is the concentration of the absorbing species, M_i is the molecular weight of the species (g/mol), A is the absorbance (height) of the relevant vibration band, ρ is the glass density (g/L), d is the thickness of the wafer analyzed (cm) and ε is the molar absorption coefficient (L/mol cm). In rhyolitic compositions, ρ and ε strongly depend on total H₂O concentration. This requires the use of an iterative process to converge on appropriate values [Eq. (1) Skirius, 1990 and Eq. (2) Leschik et al., 2004]:

$$\rho = 2350 - 12.6 C_{\text{H}_2\text{O}} \quad (1)$$

$$\varepsilon = 80 - 1.36 C_{\text{H}_2\text{O}} \quad (2)$$

where $C_{\text{H}_2\text{O}}$ is the concentration of total dissolved H₂O in wt.%. Final densities using Eq. (1) range from 2295–2336 kg/m³, and final ε values using Eq. (2) are between 73 and 79 L/mol cm. Total H₂O concentration was calculated using the 3570 cm⁻¹ peak, which required that thicknesses for the quartz wafers be between 30 and 70 μm. For thicker wafers, total H₂O was calculated using the near IR peaks (5230 cm⁻¹ and 4520 cm⁻¹; Zhang et al., 1997). The absorption coefficient (ε) for molecular CO₂ (2350 cm⁻¹) in rhyolitic glass is 1214 L/mol cm (Behrens et al., 2004). Peak heights were calculated using a straight-line background correction (Dixon et al., 1995). Thicknesses were measured using both a digital micrometer (± 2 μm) and the reflectance interference fringe method (Wysoczanski and Tani, 2006). Agreement between the two methods is within 4 μm.

After FTIR analysis, the quartz and obsidian pyroclast wafers were set in a 1-inch epoxy mount for analysis of major elements using a Cameca SX-100 electron microprobe (EPMA) at University of Oregon. Operating conditions were 15 kV and 10 nA sample current for Si, Ca, Na, Fe, Al, and K, and 50 nA current for Cl, F, Mg and Ti. A beam size of 5–10 μm was used for all analyses. Sodium, K, Si, and Al were measured first, and their concentrations were calculated using a time-dependent intensity correction in Probe for Windows (Donovan et al., 2007). Glasses were then analyzed for trace elements by Laser-Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) at Oregon State University using a 50 μm spot size, with five glass standards (GSD-1G, BHVO, ANTO, NIST-612, and BCR) for calibration, ²⁹Si as an internal standard, and GSD-1G as a check standard throughout the run. Major, trace, and volatile element concentrations, along with their associated errors, can be found in Online Supplementary Table 1 (MIs and REs) and Online Supplementary Table 2 (obsidian pyroclasts).

4. Results

All quartz-hosted MIs and REs from the nine stratigraphic levels sampled are high silica rhyolite (SiO₂ = 75–77 wt.%, volatile-free). The data show a negative correlation between SiO₂ and Al₂O₃, consistent with compositional control dominated by feldspar crystallization (Fig. 3a). Concentrations of U (6–10 ppm), Cl (1200–2000 ppm), and B (9–20 ppm) produce continuous arrays

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