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The role of melt-fracture degassing in defusing explosive rhyolite eruptions at volcán Chaitén

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ABSTRACT

Explosive volcanic eruptions of silicic magma often evolve towards non-explosive emissions of lava. The mechanisms underlying this transition remain unclear, however, a widely cited idea holds that shear-induced magma fragmentation plays a critical role by fostering volatile loss from fragmentary magma and through ash-filled cracks termed tuffisite. We test this hypothesis by measuring H_2O concentrations within glassy tuffisite from the 2008–2011 rhyolitic eruption at volcán Chaitén, Chile. We show that while H_2O concentrations decrease next to tuffisite veins and at the margins of obsidian fragments, the depletions cannot account for the disparity in H_2O between explosively and effusively erupted rhyolite. Tuffisite vein lifetimes derived from diffusion modeling (min to h) imply degassing rates that are too slow to effectively degas magma, unless the magma was entirely fragmented to mm or smaller particles. This level of brecciation may locally develop near conduit margins, but is unrealistic for entire conduits. The primary role of melt fracturing may therefore be to provide gas-escape pathways for more efficient degassing of permeable vesicular magma in the conduit interior.

1. Introduction

The broad range of volcanic eruption styles, bound by explosive and effusive eruptions, is underpinned by magma's ability to shed its volatiles whilst rising to the surface. Magma loses its dissolved volatiles via *degassing*, a two-part process involving firstly, short-path-length (10's to 100's μm) diffusive transfer of volatile components into an area of lower chemical potential (e.g., a melt–bubble interface) and then advective transport of those exsolved volatiles to the surroundings, such as the conduit margins and atmosphere (Eichelberger, 1995). The common progression of explosive to effusive eruption requires that magma degassing become more effective with time such that magma loses most of its volatiles during transit from storage to the surface. This can happen if, for example, syneruptive gas escape occurs through permeable magmatic foam that after releasing its vapor, collapses to form dense lava (Eichelberger et al., 1986; Taylor et al., 1983; Westrich et al., 1988; Westrich and Eichelberger, 1994; Eichelberger, 1995). The critical part of this degassing mechanism is that coherent magma behaves as a chemically open system (Newman et al., 1988), and the "opening" of the system occurs through the development of bubble permeability (e.g., Westrich and Eichelberger, 1994; Klug and Cashman, 1996; Okumura et al., 2009) and flow of exsolved volatiles upward and out of permeable conduit walls (Jaupart and Allègre, 1991; Woods and Koyaguchi, 1994).

A recent hypothesis (Gonnermann and Manga, 2003) posits that effective, open-system degassing of magma can happen in response to shear-induced fracturing of melt (Stasiuk et al., 1996; Rust et al., 2004; Rust and Cashman, 2007; Tuffen et al., 2003; Cabrera et al., 2011; Yoshimura and Nakamura, 2010). According to this hypothesis, strain-rate dependent brittle failure of the magma prompts diffusive degassing of cm-sized fragments combined with gas flow through cracks, thereby causing the "inhibition of explosive behavior" (Gonnermann and Manga, 2003). Cabrera et al. (2011) discovered evidence of this degassing mechanism in the form of H_2O-concentration depletions around a healed microfault in an obsidian bomb and suggested that these signatures reflect an efficient degassing mechanism that could explain the transition from explosive to effusive eruption in silicic volcanoes. Does shear fracturing of silicic magma really play such an important role in syn-eruptive magma degassing and forcing

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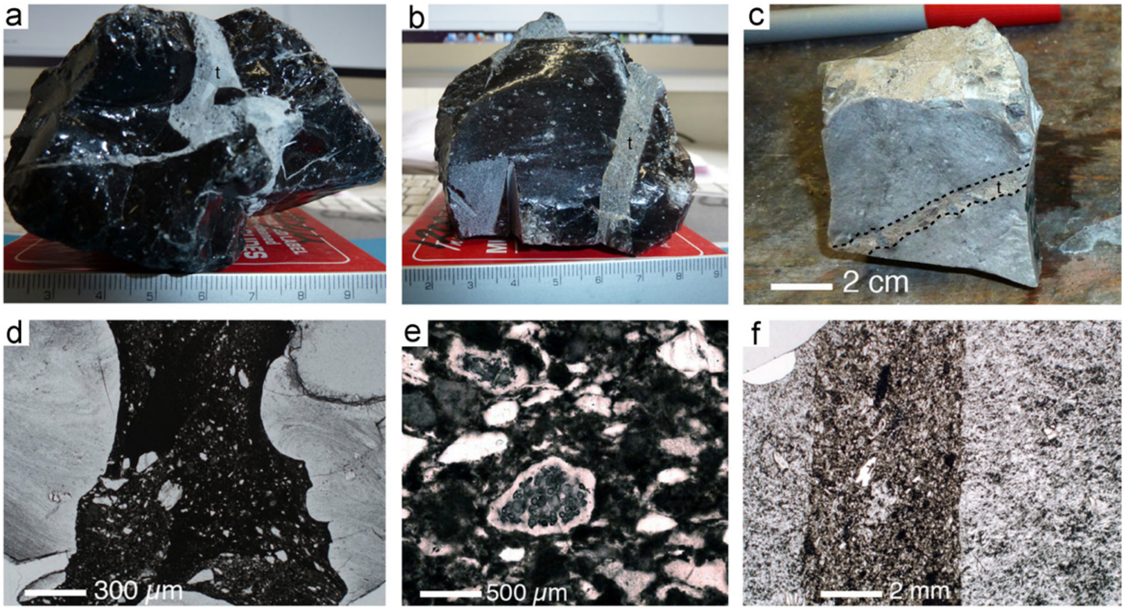

Fig. 1. Tuffisite-bearing bombs collected from volcán Chaitén. Bombs are typically dense and glassy like (a) and (b), but some are vesicular as shown in (c) (sample ChR-FT-1). Frames d–f give photomicrographic views of three superjacent frames and show the tuffisite-vein-filling material and fine structure of the fracture margin. Note the lobate wall structures in (d); these indicate flowage of melt into the vein after it had formed from brittle deformation, and therefore signals the formation of the vein above the calorimetric glass transition possibly due to shear-induced fracturing. Note also the microvesicular grain in (e), which also indicates viscous deformation following initial fragmentation. Frame f shows a thin tuffisite vein transecting a pumiceous bomb (sample ChR-FT-1) containing roughly 32 percent irregular shaped vesicles by volume.

eruptive transitions? If so, the fractures and fragments should show evidence of degassing at their margins and should have “lifetimes” that allow significant release of vapor on the timescale of magma ascent and eruption. The fracturing process, furthermore, would have to repeat through cycles that allow progressively more gas to bleed off the rising magma (Chouet et al., 2005), either through upward flow or migration through permeable conduit walls (Jaupart and Allègre, 1991).

Until now, testing the melt-fracture degassing hypothesis has been hampered by a lack of observed eruptions that could provide fresh samples and a timeline for the explosive-to-effusive transition. The 2008 eruption of volcán Chaitén provides both, the stringent explosive-to-effusive timeline, and fresh glassy samples spanning the entire eruption interval. On early 2 May 2008, volcán Chaitén explosively erupted hydrous pumice, and 10 days later, began to rapidly effuse ($\sim$20–100 $m^3 s^{-1}$; Pallister et al., 2010) chemically identical lava concurrently with tephra emissions (Lara, 2008) and sporadic large explosions (Smithsonian Insitution, 2008). The lava shed more than 90% of its water by the time it emerged (initial H_2O $\sim$4 wt%; Castro and Dingwell, 2009). Moreover, the large effusive flux (Pallister et al., 2010) suggests a conduit-scale process was acting to degas magma, rather than a localized mechanism near the conduit margins (Gonnermann and Manga, 2003; Rust and Cashman, 2007).

Here we evaluate the role shear fracturing played in fostering magma degassing and the explosive–effusive transition at Chaitén. Shear fracturing is manifested as tuffisite veins in obsidian (Fig. 1), which form when the stress exceeds a critical threshold for viscous flow (Gonnermann and Manga, 2003; Tuffen et al., 2003). We have analyzed H_2O-concentrations on tuffisite veins in order to assess the amount and rates of degassing of magma that would erupt effusively at volcán Chaitén.

2. Samples and methods

Tuffisites are non-welded to completely welded clastic materials filling veins in the country rock surrounding silicic conduits and in the conduit-filling lavas themselves (Stasiuk et al., 1996; Tuffen et al., 2003; Heiken et al., 1988; Tuffen and Dingwell, 2005). Juvenile tuffisites are common at Chaitén volcano, where they occur as ubiquitous blocks (5–50 cm) on the crater rim and flanks (Fig. 1). Their position atop both the Plinian fall and column-collapse surge deposits suggests the bombs were ejected as early as the waning stages of Plinian activity in the second week of May 2008 (Pallister et al., 2010; Lara, 2008). At this time, lava extrusion had begun and was punctuated by large explosions from the same vent that fueled effusive and ash-venting activity (La Penna, 2009, pers. comm.); these explosions likely reflect vent-clearing blasts that mined out parcels of dense tuffisite-bearing magma within the conduit. Tuffisite veins in these bombs (cm’s to dm’s in length) contain moderately welded fine ash and fine glassy lapilli. The vein walls often have lobate structures along their margins signaling secondary flowage of melt into the vein after it had formed (Fig. 1d). Such textural evidence supports the interpretation that the veins formed in response to shear-induced failure of magma (Tuffen et al., 2003).

Of 35 bombs examined on Chaitén’s rim, 28 were bore tuffisite veins. Of these, five were selected for H_2O analysis using synchrotron FTIR. We also analyzed H_2O in obsidian from the following deposits so that tuffisite degassing could be related to the early and later eruptive phases: (1) Plinian-fall, (2) pyroclastic cone formed during simultaneous sub-Plinian explosive and effusive activity, and (3) lava formed in early May, 2008.

We measured the water concentrations in and around tuffisite veins by SFTIR at the Infrared Microspectroscopy Beamline at the Australian Synchrotron (AS) and Beamline 1.4.3 at the Advanced Light Source (ALS), USA. Measurements were made on spots (3–10 μm diameter), along line traverses, and as 2D maps. Experiments were performed in transmission mode on doubly polished wafers ranging in thickness from 30 to 570 μm with IR microscopes (Bruker at the AS and NicPlan at ALS) having MCT detectors. Wafers were cut perpendicular to the orientation of fracture walls and the tuffisite vein was held intact by impregnation in epoxy. Background spectra comprising the signal of a sample-free aperture were collected every 5 min. All experiments were collected with 16 to 128 scans and at