Convection in a volcanic conduit recorded by bubbles

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ABSTRACT
Microtextures of juvenile pyroclasts from Kilauea’s (Hawai'i) early A.D. 2008 explosive activity record the velocity and depth of convection within the basaltic magma-filled conduit. We use X-ray microtomography (µXRT) to document the spatial distribution of bubbles. We find small bubbles (radii from 5 µm to 70 µm) in a halo surrounding larger millimeter-size bubbles. This suggests that dissolved water was enriched around the larger bubbles—the opposite of what is expected if bubbles grow as water diffuses into the bubble. Such volatile enrichment implies that the volatiles within the large bubbles were redissolving into the melt as they descended into the conduit by the downward motion of convecting magma within the lava lake. The thickness of the small bubble halo is ~100–150 µm, consistent with water diffusing into the melt on time scales on the order of 10−1 s. Eruptions, triggered by rockfall, rapidly exposed this magma to lower pressures, and the haloes of melt with re-dissolved water became sufficiently supersaturated to cause nucleation of the population of smaller bubbles.

The required supersaturation pressures are consistent with a depth of a few hundred meters and convection velocities of the order of 0.1 m s−1, similar to the circulation velocity observed on the surface of the Halema'uma'u lava lake.

INTRODUCTION
Lava-filled conduits are complex systems where degassing, cooling, and crystallization of magmas may generate convection. Measured magmatic gases, thermal imagery of heat flux, as well as the surface expression of convection on lava lakes and filled conduits all confirm that conduit convection occurs (e.g., Witter et al., 2004; Harris et al., 2005; Palma et al., 2008, 2011; Oppenheimer and Yirgu, 2002).

Since A.D. 2008, an active lava lake has been hosted within the “Overlook” vent, located in Halema'uma'u crater, which in turn is located within the summit caldera of Kilauea Volcano, Hawai'i (Fig. 1). Rockfalls of the conduit and vent walls into this lava lake have triggered heightened degassing, ash production, and at times, explosive eruptions (Orr et al., 2013). The eruptions at Halema'uma'u provide a unique opportunity to study an active lava lake as the erupted pyrocoes sample magma from a range of depths. Volatile solubility in magmas is primarily pressure dependent and at depths of a few hundred meters or less; the predominant volatile species dissolved in the melt is water (Dixon et al., 1995; Newman and Lowenstern, 2002; Papale et al., 2006). Because bubbles nucleate and grow in response to decreasing pressure as magma rises toward the surface, we use the microtextures of the 9 April 2008 pyrocoes along with a model for water diffusion and bubble nucleation to estimate the depths and rates of magma convection in the shallow Halema'uma'u conduit.

EXPLOSIVE ERUPTIONS OF THE OVERLOOK VENT
Although lava within the vent was not visible until 5 September 2008, volatile fluxes in great excess of background levels and semicontinuous eruption of juvenile ash and lapilli indicate that magma was degassing at shallow levels. The first appearance of juvenile tephra was on 23 March 2008, and eruptive activity continues to the present (September 2012). Throughout this time, several hundred shallow conduit-wall and vent collapses (Orr et al., 2013) have triggered explosive eruptions that produced lapilli with high number densities of small bubbles (Carey et al., 2012). Disruption of the lava-lake surface by rockfalls caused short-lived but rapid magma decompression, which we infer resulted in the nucleation of high numbers of small bubbles (Carey et al., 2012).

9 APRIL 2008 EXPLOSIVE ERUPTION AND EJECTA
On 9 April, an area of ~200 m2 collapsed into the vent and triggered a small explosive eruption that lasted ~14.5 s (Fee et al., 2010). The pyroclastic deposit geometry and isosass data imply that ~1.3 × 104 kg of magma and wall-rock lithics were erupted. Following the eruption, 100 juvenile pyrocoes were collected for analysis. From macroscopic clast observations and clast density, nine representative casts were selected for thin-sectioning, synchrotron Fourier transform infrared spectroscopy (FTIR) analysis, and X-ray microtomography (µXRT) at the Advanced Light Source, Lawrence Berkeley National Laboratory (California, United States). The April ejecta was macroscopically and microtexturally heterogeneous (Fig. 2). Three textural types were observed: (1) fluidal, fluted dense clasts containing spheroidal bubbles 1–4 mm in diameter; (2) dense spinoce clasts with a bubble-poor (<10 vol%) outer margin up to 1 cm thick, and a more coarsely vesicular interior composed of predominantly millimeter-diameter bubbles with spheroidal shapes; and (3) highly vesicular and microvesicular, golden-colored clasts with complexly shaped bubbles up to 4 mm across. One representative clast from each type was selected for µXRT.

All clasts show an unusual texture; large millimeter-sized bubbles that are surrounded by up to 150-µm-thick haloes containing high numbers of small isolated round bubbles of between 5 µm and 70 µm in diameter (Fig. 3). This texture is the focus of our study; however, clast type 2 has a higher density, which permits measurement of haloes (and vesicles contained in the haloes)....
within) with greater accuracy. Synchrotron FTIR analyses of the glass, including the small bubble haloes, showed uniform water concentrations of <0.1 wt% with no volatile gradients. This likely reflects the initial low water concentrations of the magma, the high diffusion rates of water in basaltic magmas, and the detection limits of the FTIR instrument.

The high number densities of small bubbles within the haloes reflect high nucleation rates and little time for bubble coalescence after nucleation (Carey et al., 2012). Furthermore, this unusual texture suggests that water concentrations were high enough only within the haloes to produce high rates of bubble nucleation. Watkins et al. (2012) identified a similar halo of small bubbles around large bubbles in rhyolite obsidian, where water concentration profiles show an enrichment of water adjacent to the large bubbles, equivalent to a pressure increase of ~10 MPa prior to eruption. As proposed by Watkins et al. (2012), this observation implies that the water within the large bubbles was resorbing back into the melt prior to eruption.

**CONDUIT CONVECTION MODEL**

The textures observed in Figure 3 can be used to constrain conduit dynamics. Specifically, the thickness of the haloes of small bubbles defines a diffusion length associated with bubble resorption during convection, whereas bubble number densities can provide estimates for water supersaturation, and thus, depth. Consequently, we consider a convecting lava lake with volatiles (water) exsolving during magma ascent, and then dissolving back into the melt around bubbles as the magma circulates back down the conduit. This process was interrupted when rockfalls impacted the lava, causing rapid decompression (Carey et al., 2012) and bubble nucleation in the water-enriched haloes.

**Resaturation of Melt**

Time variations in pressure (P) during convective cycling can be approximated as

$$P(t) = P_0 + \Delta P \sin(2\pi t/\tau),$$  

(1)

where $t$ is time, $P_0$ and $\Delta P$ are the mean and change in pressure, and $\tau$ is the period of one convective overturn (circulation). Water diffusion in and out of the melt around individual bubbles creates a concentration boundary layer, the halo, over which water concentration changes by a factor of $e$ with thickness ($\delta$), where $\delta = \sqrt{D\tau}$ and $D$ is the diffusivity of water. The diffusion of water in and out of bubbles is affected, however, by their expansion and contraction as they move up and down within the conduit, stretching and thickening the boundary layer, respectively. Existing analytical solutions (e.g., Fyrillas and Szeri, 1994) do not account for the nonlinearity of water solubility in basaltic melts nor the nonlinear change in radius with respect to pressure. We thus solve numerically for the thickness of the boundary layer upon bubble resorption for different bubble sizes, mean pressures ($P_0$), changes in pressure ($\Delta P$), and periods of circulation ($\tau$). The diffusivity depends on pressure and water content (Zhang et al., 2007), and water solubility is based on the model of Dixon (1997). We use an algorithm for bubble growth and volatile diffusion based on the formulation of Prousevitch et al. (1993) and viscosity based on the formulations of Hui and Zhang (2007) and Lensky et al. (2001). Steady-state boundary-layer thicknesses are reached after a few cycles of circulation, and we find that all cases are well described by

$$\delta = \sqrt{D\tau/\delta \bar{c}},$$  

(2)

(see Fig. DR1 in the GSA Data Repository1).

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1GSA Data Repository item 2013109, Figure DR1 (scaling analysis) and Figure DR2 (nucleation rate as a function of supersaturation pressure), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
Microtextural analyses of three-dimensional (3-D) tomographic images indicate that melt shells with relatively high bubble number densities typically extend to δ ≈ 100–150 µm around larger bubbles. Decompression during eruption will have thinned the boundary as the large bubble expanded. Neglecting diffusion during the eruption and assuming the magma is not permeable, so that all the gas remains in the large bubble, expansion from a pressure of 3 MPa (equivalent to a depth of 150 m for a density of 2000 kg m⁻³; see below) to 0.1 MPa would thin δ by a factor of up to 10. In addition, the nucleation growth of small bubbles in the halo thickens the boundary layer by a factor of ~2. Thus, at depth δ may have been up to ~5 times thicker, or between 100 and 500 µm. Using $D = 1.3 \times 10^{-10}$ m² s⁻¹ for basaltic magma at 1165 °C (Zhang et al., 2007), the calculated time scale $\tau$ for this length scale of diffusion is $-0.4 \times 10^9$ s to $1 \times 10^9$ s. Owing to the high permeability of vesicular basaltic magma (Saar and Manga, 1999), we suggest that there may have been little expansion of the large bubbles post-fragmentation, in which case $\tau$ would be near the lower end of this range.

**Nucleation During Eruption**

The unusual texture with small bubbles surrounding large ones has three requirements: (1) a mechanism to produce a water-enriched region around bubbles (here attributed to an increase in pressure due to downward convection); (2) the mean pressure $P_m$ prior to eruption must be small enough that there is insufficient supersaturation for bubble nucleation outside of the haloes; and (3) $\Delta P$ must be large enough to create sufficient supersaturation for bubble nucleation within the haloes. For the clasts that erupt from well supersaturated during the eruption, both in the upper range corresponds to the case with limited post-fragmentation expansion of bubbles.

**TIME AND LENGTH SCALES OF MAGMA CONVECTION**

A combination of internal and external factors unique to Kīlauea’s volcanic system provides a rare window into degassing and convection processes in a basaltic lava-filled conduit. In a convective cycle (Fig. 4), pressure cycling drives volatiles either to exsolve from or to resorb back into the melt (Fig. 4B). Bubble nucleation within the melt around millimeter-sized bubbles records magma circulation and pressure cycling. Using models for water diffusion and bubble nucleation in basaltic magma and the measured length scale of the bubble haloes, we estimate the depth to which magma is recycled in the shallow conduit (100–300 m), the time scales of convection (0.4 × 10⁶ s to 1 × 10⁸ s), and the convective velocities (0.02–0.8 m s⁻¹). The latter prediction is testable, and the range of our calculated vertical convective velocity is similar to that observed on the surface of the Halema‘uma‘u lava lake (0.1–0.3 m s⁻¹).

**GAS-MELT COUPLING IN CONVECTING CONDUTS**

The microtextural observations described in this paper confirm that bubbles can be carried by the convecting magma to depths in excess of 100 m. We can calculate the critical size for bubbles to decouple from the magma, which occurs when their ascent speed owing to buoyancy is greater than the downward velocity of the convecting magma. The Stokes velocity of a bubble is

$$U_s = \frac{1}{3} \frac{\Delta P}{\mu} g R_b^2,$$  

where $\Delta P$ and $\mu$ are the pressure difference and viscosity of the melt, respectively, and $R_b$ is the bubble radius.
where $\Delta \rho$ is the density difference between the melt and gas, $\mu$ is the fluid viscosity, $g$ is gravitational acceleration, and $R$ is bubble radius. The ratio of $U$ to the speed of convection $U_c$ is called the Stokes number and it determines the degree of coupling between the bubble and the melt. A bubble with Stokes number greater than $\sim 1$ indicates that the bubble largely ignores the fluid flow, whereas a bubble with Stokes number smaller than $\sim 1$ is coupled to the flow and is carried as a tracer. Choosing Stokes number $U/U_c = 1$ to separate coupled and decoupled flow, we have $U/U_c = 1$ from which we obtain an expression for critical bubble radius $R_c$:

$$R_c = \sqrt{3 \frac{U_c}{\mu g \Delta \rho}}. \tag{5}$$

Using convective velocities observed on the surface of the Halema‘uma‘u lava lake, a bubble needs a diameter $\sim 10$ cm to decouple from the magma and readily reach the surface. Vigorously convecting lava lakes like Halema‘uma‘u will lose their gas less efficiently than those that are convecting more slowly, as only the very large bubbles can escape from the flow. They therefore maintain enough potential energy in the form of exsolved water to react explosively to rockfalls. The bubbles preserved in the erupted clasts thus preserve a record of circulation depth, convection velocity, and the separation of bubbles from the melt in the conduit.

**CONCLUSIONS**

The minimum depth to which the Halema‘uma‘u lava lake overturns convectively can be estimated from pyroclast microtextures. As bubbles are advected downward by the convecting magma, water diffusively resorbs, creating boundary layers (haloes) with high water concentration. Short-lived and rapid decompression of the convecting magma, triggered by rockfalls into the lava lake, results in water supersaturation and high rates of bubble nucleation within these haloes. The width of the haloes constrains the characteristic diffusion time scale, whereas the bubble number density (assuming classical nucleation theory) constrains water concentrations, and hence, depth. The combination of depth and diffusion time yield convective velocities, compatible with measured surface velocities of the Halema‘uma‘u lava lake. The analyzed textures thus provide a rare but intriguing insight into the upper parts of the highly vigorous magmatic plumbing system of the most active volcano on Earth, where outgassing is likely never complete.

**ACKNOWLEDGMENTS**

This research was supported by National Science Foundation grants EAR-1049662, EAR-0810332, and EAR-1145187, and U.S. Geological Survey grant SV-ARRA-0004. We would like to thank Jocelyn McPhee, Derek Sahagian, Ed Llewelyn, Roger Dentlinger, and two anonymous reviewers for editing a previous version of the manuscript. The FTIR and XRT analyses were conducted at the Advanced Light Source (ALS) at the Lawrence Berkeley National Laboratory in Berkeley, California, USA. We wish to thank the S.3.2 and 1.4.3 ALS Beamline scientists Alastair McDowell, Dula Parkinson, Michael Martin, and Hans Bectel for all their helpful advice and technical assistance.

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Manuscript received 29 May 2012
Revised manuscript received 3 October 2012
Manuscript accepted 11 October 2012
Printed in USA