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Magma transport and olivine crystallization depths in Kīlauea's east rift zone inferred from experimentally rehomogenized melt inclusions

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Abstract

Concentrations of H_2O and CO_2 in olivine-hosted melt inclusions can be used to estimate crystallization depths for the olivine host. However, the original dissolved CO_2 concentration of melt inclusions at the time of trapping can be difficult to measure directly because in many cases substantial CO_2 is transferred to shrinkage bubbles that form during post-entrapment cooling and crystallization. To investigate this problem, we heated olivine from the 1959 Kīlauea Iki and 1960 Kapoho (Hawai'i) eruptions in a 1-atm furnace to temperatures above the melt inclusion trapping temperature to redissolve the CO_2 in shrinkage bubbles. The measured CO_2 concentrations of the experimentally rehomogenized inclusions ($\leqslant$590 ppm for Kīlauea Iki [$n = 10$]; $\leqslant$880 ppm for Kapoho, with one inclusion at 1863 ppm [$n = 38$]) overlap with values for naturally quenched inclusions from the same samples, but experimentally rehomogenized inclusions have higher within-sample median CO_2 values than naturally quenched inclusions, indicating at least partial dissolution of CO_2 from the vapor bubble during heating. Comparison of our data with predictions from modeling of vapor bubble formation and published Raman data on the density of CO_2 in the vapor bubbles suggests that 55–85% of the dissolved CO_2 in the melt inclusions at the time of trapping was lost to post-entrapment shrinkage bubbles. Our results combined with the Raman data demonstrate that olivine from the early part of the Kīlauea Iki eruption crystallized at <6 km depth, with the majority of olivine in the 1–3 km depth range. These depths are consistent with the interpretation that the Kīlauea Iki magma was supplied from Kīlauea's summit magma reservoir (~2–5 km depth). In contrast, olivine from Kapoho, which was the rift zone extension of the Kīlauea Iki eruption, crystallized over a much wider range of depths (~1–16 km). The wider depth range requires magma transport during the Kapoho eruption from deep beneath the summit region and/or from deep beneath Kīlauea's east rift zone. The deeply derived olivine crystals and their host magma mixed with stored, more evolved magma in the rift zone, and the mixture was later erupted at Kapoho.

Keywords: Volcanology; Melt inclusions; Geochemistry; Kīlauea; Hawaiian geology

1. INTRODUCTION

Melt inclusions provide a window into magmatic systems at depth by providing information on melt compositions, including volatiles, at the time of trapping. Melt inclusion studies at Hawaiian volcanoes have been used

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to investigate a variety of problems, from shallow magmatic processes during individual eruptions (Anderson and Brown, 1993; Wallace and Anderson, 1998; Edmonds et al., 2013; Thornber et al., 2015) to studies of mantle plume geochemistry and mantle heterogeneities (Hauri, 2002; Sobolev et al., 2011). These studies have improved our understanding of the eruption of high lava fountains (Sides et al., 2014a,b) and the details of Kīlauea's magma plumbing system (Edmonds et al., 2013, 2015; Rowe et al., 2015). At other oceanic islands such as La Réunion, olivine-hosted melt inclusions have also been used to constrain the size and shape of the magma plumbing system (Bureau et al., 1998a,b) and to understand individual eruptions (Vigouroux et al., 2009).

Melt inclusions that are rapidly quenched and naturally glassy are ideal for studying volatile concentrations (e.g., Johnson et al., 1994; Lloyd et al., 2013). In particular, the CO_2 and H_2O concentrations in melt inclusions can be used to infer olivine crystallization pressures and thus provide a tool for estimating magma storage depths (Anderson and Brown, 1993; Roggensack et al., 1997; Newman et al., 2000). However, determining the total volatile content of melt inclusions is complicated by the formation of shrinkage bubbles during post-entrapment cooling and crystallization (Anderson and Brown, 1993; Esposito et al., 2011; Steele-MacInnis et al., 2011; Hartley et al., 2014; Mironov et al., 2015; Moore et al., 2015; Wallace et al., 2015). Low solubility volatiles, like CO_2, partition strongly into these bubbles, depleting their concentration in the melt. As a result, the CO_2 measured in the glass by Fourier Transform Infrared Spectrometry (FTIR) or ion microprobe (SIMS) can greatly underestimate the amount of CO_2 that was present at the time of trapping (Esposito et al., 2011; Steele-MacInnis et al., 2011; Hartley et al., 2014; Mironov et al., 2015; Moore et al., 2015; Wallace et al., 2015).

A shrinkage bubble is formed during post-entrapment cooling and crystallization because of the negative volume change caused by crystallization of olivine along the inclusion-host interface and the fact that the melt in the inclusion contracts more than its crystalline host (Anderson, 1974; Roedder, 1979). This shrinkage causes a drop in pressure in the inclusion that leads to nucleation and growth of a vapor bubble (e.g., Lowenstern, 1995). During eruption, the shrinkage bubble will continue to expand with continued cooling, as the melt continues to contract more than the olivine host (Roedder, 1979; Anderson and Brown, 1993; Riker, 2005). Experimental heating of melt inclusions can redissolve the shrinkage bubble, returning some or all of the CO_2 to the glass (Wallace et al., 2015; Mironov et al., 2015). The main goal of our study was to investigate the use of a 1-atm furnace for heating of melt inclusions to redissolve CO_2 from bubbles. Our experimental results can be compared with other methods (micro-Raman and computational approaches) for assessing the extent of CO_2 loss to bubbles The second goal was to use the restored CO_2 contents of melt inclusions to calculate the pressures at which the inclusions were trapped in the olivine, thus providing information on crystallization depths beneath Kīlauea Volcano. Olivine crystallization depths can be used to constrain the depths of magma storage and transport, enabling a way to test magma plumbing models based on geophysical data.

1.1. Background on Kīlauea volcano and eruptions studied

1.1.1. Kīlauea's magma plumbing system

Kīlauea's magma plumbing system has been studied using geophysical (e.g. Eaton and Murata, 1960; Ryan et al., 1981; Poland et al., 2014) and geochemical (e.g. Wright and Fiske, 1971; Wright, 1973; Pietruszka and Garcia, 1999; Garcia et al., 2003; Thornber et al., 2003; Pietruszka et al., 2015) approaches to define the size, shape, and location of the summit magma body(s) and the interconnectedness between the summit and shallow rift zones (Eaton and Murata, 1960; Tilling and Dvorak, 1993). Most magma beneath the summit is currently stored in two reservoirs, one ca. 1–2 km deep near Halema'uma'u Crater and the larger ca. 2–5 km deep in the south caldera (Ryan et al., 1981; Ryan, 1988; Poland et al., 2014). These reservoirs have likely coexisted since at least the mid twentieth century (Wright and Klein, 2014; Pietruszka et al., 2015). Magma from summit storage is injected into the east rift zone 2–4 km below the surface (Poland et al., 2014), where it may be stored or later erupted (Wright and Fiske, 1971). Seismic data suggests that the rift zones are not likely deeper than 4–5 km, but the east rift zone has been proposed to extend to a depth of 6–9 km (Ryan, 1987; Delaney et al., 1990; Cayol et al., 2000; Wright and Klein, 2014).

Alternative rift zone models have been proposed in which dike injection occurs directly into the shallow rift zone from the mantle (Garcia et al., 2000) or from the décollement that marks the boundary between the volcanic pile and ocean floor (Clague and Denlinger, 1994; Vinet and Higgins, 2010). These alternatives are based in part on the primitive character of some lava erupted on the submarine lower east rift zone (Clague et al., 1995). At present, observations from the long-lived Pu'u 'Ō'ō eruption confirm the link between the summit and shallow rift zone, because rift zone tilt and inflation-deflation cycles closely follow those of the summit magma reservoir (Poland et al., 2014). Delaney et al. (1990) suggest that the summit and rift zone may be underlain by a thick, near vertical, dike-like magma system at a depth of 3–9 km, and Clague et al. (1995) proposed that the shallow and deep portions of the rift zone are interconnected by a series of bladed dikes that allow olivine to settle and accumulate across a large range of depths to form dunitic cumulate bodies.

1.1.2. Kīlauea Iki and Kapoho

The 1959 Kīlauea Iki eruption was unusual in many regards. It erupted outside the topographic summit caldera (see Supplementary Material, Figs. A.1 and A.3), produced the highest lava fountains ever recorded (ca. 600 m) at Kīlauea (Richter et al., 1970), contained abundant olivine (up to 20 wt.%) and MgO-rich glasses (up to 10 wt.%, indicating high eruptive temperatures up to 1192 °C; Murata and Richter, 1966; Wright, 1973; Helz, 1987; Pietruszka et al., 2015), and carried several different populations of olivine (deformed, megacrystic, reversely