Time scales of magma transport and mixing at Kīlauea Volcano, Hawai‘i

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ABSTRACT

Modeling of volcanic processes is limited by a lack of knowledge of the time scales of storage, mixing, and final ascent of magmas into the shallowest portions of volcanic plumbing systems immediately prior to eruption. It is impossible to measure these time scales directly; however, micro-analytical techniques provide indirect estimates based on the extent of diffusion of species through melts and crystals. We use diffusion in olivine phenocrysts from the A.D. 1959 Kīlauea Iki (Hawai‘i, USA) eruption to constrain the timing of mixing events in the crustal plumbing system on time scales of months to years before eruption. The time scales derived from zonation of Fe-Mg in olivines, combined with contemporaneous geophysical data, suggest that mixing occurred on three time scales: (1) as much as 2 yr prior to eruption in the deep storage system; (2) in a shallow reservoir, between incoming hot melts and resident melt for several weeks to months prior to eruption; and (3) in the conduit and summit reservoir, between the resident magma and cooled surface lava, draining back into the vent on time scales of hours to several days during pauses between episodes. Synchronous inflation of the shallow reservoir with deep earthquake swarms and mixing suggests an intermittently open transcrustal magmatic system.

INTRODUCTION

Determining the time scales of pre-eruptive and syn-eruptive magmatic processes is a primary objective of modern volcanology. Time scales of magma movement through the lithosphere prior to eruptions are difficult to resolve unequivocally with geophysical techniques, yet understanding these time scales is critical for eruption forecasting. Swarms of earthquakes at a range of depths often occur prior to eruptions and are inferred to be caused by magma movement. It has not been possible to state with certainty whether these earthquakes are linked with the magma that eventually erupts. However, the chemistry and microtextures of crystals may be used as rate meters of magma mixing (e.g., Costa et al., 2009; Kahl et al., 2011; Martin et al., 2008; Ruprecht and Plank, 2013). Analysis of the chemical stratigraphy of crystals, using time scales from diffusion chronometry (e.g., Costa et al., 2003, 2008, 2009; Costa and Chakraborty, 2004; Costa and Dungan, 2005; Morgan et al., 2004; Morgan and Blake, 2005; Nakamura, 1995), provides constraints on magma ascent rates and crystal residence times that may be compared with contemporaneous geophysical data acquired prior to and during a volcanic eruption (e.g., Kahl et al., 2013).

We apply this method to the 1959 eruption of Kīlauea Iki, Kīlauea Volcano, Hawai‘i, USA (Fig. 1), the type example of a powerful Hawaiian fountaining eruption. It included the highest fountaining ever observed at Kīlauea (Richter et al., 1970) and was the first eruption at Kīlauea that was rigorously geophysically monitored (Eaton and Murata, 1960; Eaton et al., 1987). The magma budget is well estimated by tilt measurements (Eaton et al., 1987), direct observation (Richter et al., 1970), and geochemical studies (Helz, 1987; Anderson and Brown, 1993; Sides et al., 2014). The eruption presents an excellent opportunity to retrospectively constrain the timing of magma ascent and mixing with respect to eruption triggering. It was preceded by significant seismicity and ground deformation linked to magma movement (Eaton et al., 1987) and involved 17 episodes of eruption (Richter et al., 1970). Geophysical and geochemical observations suggest that magma stored in a shallow reservoir was mixed, during and between episodes, with primitive magmas from depth as well as with cooler, outgassed lava that had drained back from a lava lake formed in episode 1 (Murata and Richter, 1966; Richter and Murata, 1966; Wright, 1973; Eaton et al., 1987; Helz, 1987; Loewen, 2013; Sides et al., 2014).

Our aim is to constrain the timing of magma mixing events prior to and during the A.D. 1959 eruption of Kīlauea Iki through the characterization of Mg-Fe zonation in olivine crystals. These time scales are then compared with the timings of deformation and seismicity recorded during the eruption. We seek to understand time scales of magma storage and transport to better constrain our understanding of the significance of seismic swarms that traverse the mantle and crust prior to eruptions at Kīlauea Volcano.

METHOD

When a crystal, in equilibrium with a melt, experiences a change in intrinsic parameters of

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Figure 1. The location of the Kīlauea Iki crater and samples (for details, see the Data Repository [see footnote 1]). Based on Sides et al. (2014) and Stovall et al. (2010).
TABLE 1. MODELING PARAMETERS

<table>
<thead>
<tr>
<th>Episode</th>
<th>Temperature (°C)</th>
<th>Oxygen fugacity (JANNO)</th>
<th>Pressure (kbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>1</td>
<td>1170 ± 10</td>
<td>1259 ± 10</td>
<td>-1.7</td>
</tr>
<tr>
<td>3</td>
<td>1170 ± 10–1170 ± 10</td>
<td>1284 ± 10–1287 ± 10</td>
<td>-0.5</td>
</tr>
<tr>
<td>5</td>
<td>1135 ± 10–1155 ± 10</td>
<td>1250 ± 10–1252 ± 10</td>
<td>1 ± 1</td>
</tr>
<tr>
<td>8</td>
<td>1147 ± 10–1170 ± 10</td>
<td>1255 ± 10–1279 ± 10</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1180 ± 10</td>
<td>1310 ± 10</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1140 ± 10–1160 ± 10</td>
<td>1256 ± 10–1292 ± 10</td>
<td></td>
</tr>
</tbody>
</table>

Note: Each crystal was assigned temperature conditions independently; the ranges indicate the minimum and maximum temperature by episode. NNO—Ni-NiO buffer.

RESULTS

The composition of the olivine cores is typically more magnesium (forsterite, Fo) rich than the rim, i.e., they are normally zoned. Olivine cores typically contain ~87 mol% Fo but range between 82.7 and 88.2 mol% Fo. Rim and intermediate compositions are more variable, from 80 to 88 mol% Fo, with a broad peak at ~82.5 mol% Fo. There is a paucity of olivine compositions of 84–86 mol% Fo (Fig. 2).

DISCUSSION

The distribution of compositions of the olivine cores and rims, combined with the zoning patterns, suggests a complex petrogenetic history for the crystal cargo of this eruption. The wide range of olivine core compositions (Fig. 2) has been linked to crystal mush disaggregation supplying primitive olivines, with fractionation during shallow storage producing the olivines with the lower Fo cores (Clague et al., 1995).

There are several possible causes of the zoning identified here. In all crystals diffusion acts due to disequilibrium across the crystal face, thus the diffusion is caused by changes in the intrinsic properties of temperature, pressure, oxygen fugacity, and/or melt composition. Of these, temperature and melt composition are most significant for changing the equilibrium chemistry of olivine (Roeder and Emslie, 1970; Ford et al., 1983). Cooling, or a decrease in MgO content, causes normal zoning while sub-liquidus heating, or an increase in MgO content, causes reverse zoning.

Approximately 60% of the mixing events recorded by the olivines took place after the onset of shallow (<10 km) seismicity (Fig. 4). The number of mixing events increases rapidly with time up to the eruption onset, paralleling the increasing frequency of upper crustal seismicity from 50 events/day initially to more than 1000 events/day by ~14 days (Eaton et al., 1987). The mixing events and seismicity in the upper crust over the few weeks prior to eruption plausibly represent the intrusion of melts from depth into a shallow summit reservoir. We are unable to distinguish between the south caldera and Halema‘uma‘u reservoirs as the location of mixing, but it is clear that magmas were hosted, albeit briefly, and mixed in one of the reservoirs.
implying the mixture of different composition and/or temperature melts, each bearing their own crystal cargoes, i.e., a hot, mantle-derived, MgO-rich magma bearing high-Fo olivines mixing with cooler, MgO-poor magmas bearing low-Fo olivines. Although the deep earthquake swarms cannot be linked individually to any particular magma mixing event as recorded in the olivine, there is a suggestion that mixing occurred sporadically at depth, associated with seismicity, prior to the Kilauea Iki eruption. The time scales calculated here are consistent with estimates of time scales between melt segregation from the mantle and eruption based on U-series disequilibria suggesting a maximum of 7 yr (Girard et al., 2012). It is critical, however, that the shallow magma reservoir beneath the summit exhibited periods of inflation from ~800 to ~350 days, and from ~150 days until the eruption (Eaton et al., 1987). This suggests that deep intrusions were supplying magma via an open system (generating little seismicity) throughout this period. This analysis implies that the time scales for magma ascent from 45 to 65 km depth might be significantly less than 800 days and may be as short as weeks to months. These short time scales would be consistent with other studies showing rapid ascent of magmas from mantle depths to the surface (Ruprecht and Plank, 2013). Furthermore, the occurrence of deep swarms of earthquakes after the start of the eruption might indicate that magmas were drawn up from depth on the time scale of the eruption, similar to the downward-propagating seismicity observed during the Eyjafjallajökull (Iceland) eruption in 2010 (Tarasewicz et al., 2012).

The volume of magma intruded into the shallow reservoir declined as the eruption continued (to near zero by episode 8; Eaton et al., 1987), while drainback volumes remained fairly constant throughout the eruption. Several of the diffusion zones indicate mixing events after episode 8; it therefore seems likely that these zones were a result of mixing between the magma in the shallow reservoir and the drainback lava, which may have driven further vesiculation and new episodes of fountaining. The return of drained-back lavas to the shallow storage reservoir is supported by melt inclusion geochemistry (Sides et al., 2014; Wallace and Anderson, 1998).

This study provides the first geochemical constraint on the time scales of magma residence and mixing through the mantle and crust
at Kilauea. The 1959 Kilauea Iki eruption was triggered by magma mixing in the shallow crust, synchronous with shallow seismicity in the weeks leading up to the eruption. Mixing occurred up to 800 days before eruption, consistent with the timing of sporadic swarms of deep earthquakes, which probably mark the intrusion of mantle-derived melts into the deep Kilauea plumbing system. Magmas migrated up into the shallow system rapidly and quasi-continuously during the ~2 yr preceding the eruption. Approximately 60% of the mixing events analyzed took place <100 days prior to and during the eruption, caused by magma movement in the upper crust and by drainage processes during the eruption. The link to the deep mantle was maintained even after the start of the eruption.

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