



Lithium diffusion in olivine records magmatic priming of explosive basaltic eruptions

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ABSTRACT

The short duration (e.g., hours to days) of magmatic processes leading up to volcanic eruptions are challenging to characterize using conventional petrologic and geophysical methods. This is especially true for eruptions that occurred prior to the implementation of seismic and geodetic monitoring (mid-20th century). We present a new application of diffusion chronometry that utilizes lithium zoning in olivine phenocrysts to investigate the timing of late-stage, pre-eruptive magma mixing at Kilauea Volcano (Hawai'i). The diffusive re-equilibration of sub-ppm changes in lithium concentration are modeled in rapidly quenched, well-oriented olivine from six eruptions during a dominantly explosive period (1500–1820 CE). Lithium timescales reveal repeated intrusion of primitive composition magma into Kilauea's shallow (~2–6 km) reservoir system typically only a few days prior to each eruption. These timescales are shorter than the weeks to years retrieved from modeling Fe–Mg and Ni zoning in the same olivine crystals, which record earlier magma mixing events. The short Li timescales indicate that an intrusion primed the shallow magma reservoir potentially only hours to a few days before an eruption. Late-stage intrusions and mixing events should thus be investigated at other basaltic volcanoes to better understand pre-eruptive processes, so that eruption scenarios can be better constrained.

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1. Introduction

1.1. Priming volcanic eruptions

A fundamental challenge of mitigating volcanic hazards is identifying the magmatic processes that occur right before eruptions (National Academies of Sciences, Engineering, and Medicine, 2017). The timing of such events is often difficult to detect and characterize with current geophysical, petrologic and geochemical methods (e.g., Kahl et al., 2011; Patanè et al., 2013). Many volcanic eruptions are thought to be initiated by intrusion of hot, primitive magma into an existing reservoir within the volcanic plumbing system (e.g., Sparks et al., 1977; Aiuppa et al., 2017). The timing and storage duration of these intrusions are usually poorly known, especially for pre-historic eruptions. Geophysical evidence of such a magma mixing event may be absent or give ambiguous results.

For example, magma mixing may occur aseismically (e.g., Klein et al., 1987; Johnson, 1992) and increases in tilt that are normally attributed to magma influx may be related to excess gas rather than the arrival of magma to a shallow reservoir system (e.g., Johnson, 1992; Aiuppa et al., 2017). Consequently, developing new tools that document short-lived events is crucial to understanding the timing of the magmatic processes that precede and possibly trigger volcanic eruptions.

Olivine is a common phenocryst in basaltic magmas. Studying its chemical zoning patterns has proven invaluable for gaining a better understanding of the timescales of magmatic processes operating in diverse tectonic settings (e.g., Costa and Dungan, 2005; Ruprecht and Plank, 2013; Shea et al., 2015a; Bouvet de Maisonneuve et al., 2016; Lynn et al., 2017). For example, timescales of weeks to years that broadly correspond to periods of volcanic unrest (e.g., Kahl et al., 2011; Albert et al., 2015) are now routinely determined by modeling diffusion-controlled concentration gradients of major and minor elements in olivine (Fe–Mg, Ni, Mn, Ca; Fig. 1). These elements are typically used to characterize pre-eruptive magmatic processes that operate over weeks to centuries in mafic volcanic systems (Fig. 1). Longer timescales (years to

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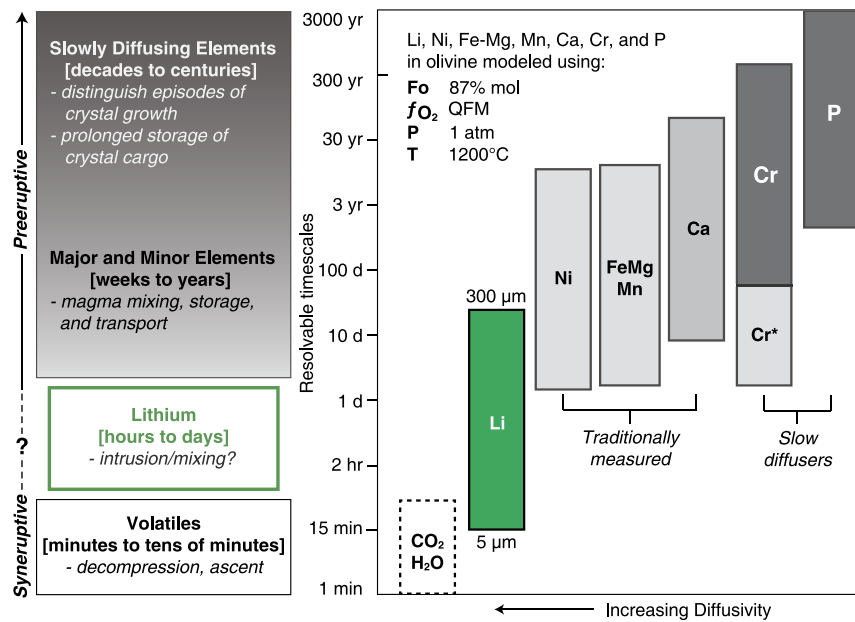


Fig. 1. Lithium is a rapidly diffusing trace element in olivine (green box; vacancy mechanism of ${}^7\text{Li}$ from Dohmen et al., 2010) that provides a unique view into the pre-eruptive processes operating on timescales of a few hours to a few days. Timescales of syneruptive processes operating over as little as a few minutes have recently been proposed using CO_2 and H_2O diffusion through phenocryst-hosted melt embayments (dashed box; Lloyd et al., 2014; Ferguson et al., 2016). Pre-eruptive magmatic processes such as magma mixing, storage, and transport are characterized using the diffusion of traditionally measured major (Fe–Mg, light grey box; Dohmen and Chakraborty, 2007a, 2007b) and minor elements (Ni, Mn, Ca, Cr^* , light grey boxes; Petry et al., 2004; Coogan et al., 2005; Holzapel et al., 2007; Cr^* is a faster D_{Cr} value from Jollands et al., 2018). The oldest histories of crystal growth and/or prolonged storage are usually inferred from slowly diffusing trace elements, such as Cr and P (dark grey boxes; Ito and Ganguly, 2006; Watson et al., 2015). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

decades) representing episodes of crystal growth and storage can be inferred from trace elements, typically Cr and P, that are more slowly modified by diffusion (e.g., Bouvet de Maisonneuve et al., 2016; Fig. 1).

Timescales of minutes to tens of minutes correspond to syneruptive processes such as degassing and magma ascent (Fig. 1). The decompression and rapid diffusion of CO_2 and H_2O in glasses from mineral-hosted melt embayments (Lloyd et al., 2014; Ferguson et al., 2016) and the diffusive loss of hydrogen from olivine (e.g., Demouchy et al., 2006) have been modeled to access short timescales of syneruptive processes. However, embayments are rare and measuring and interpreting hydrogen concentrations in olivine is challenging, resulting in large analytical uncertainties. Thus, there remains a critical pre-eruptive period of hours to days that is largely inaccessible using traditional geospeedometers. Characterizing the magmatic processes operating in this enigmatic window of time remains a fundamental challenge for modern petrology and volcanology.

1.2. Lithium chronometry

Lithium is a rapidly diffusing trace element in olivine that can provide a unique perspective on magmatic processes that occur over hours to days in basaltic magma (Fig. 1; Dohmen et al., 2010). Lithium is moderately incompatible (e.g., $K_{\text{Li}}^{\text{ol/melt}} = 0.1\text{--}0.2$; Grant and Wood, 2010), and its partitioning behavior apparently does not strongly depend on pressure, temperature and mineral composition (Seitz and Woodland, 2000). The rapid diffusion of Li (Fig. 1) results in the complete re-equilibration of olivine crystals <1 mm in diameter after only a few months at temperatures near 1200°C (Tomascak et al., 2016). Thus, Li zoning is expected to be unrelated to the longer-term magma mixing history preserved by Fe–Mg, Ni, and Mn (Fig. 1), and potentially records additional information about short-lived processes. Lithium diffusion in olivine can occur via two mechanisms: a vacancy-controlled, ‘slower’ mode, and an interstitial ‘faster’ mode (Dohmen et al., 2010). Signif-

icant mass-dependent diffusive fractionation of ${}^6\text{Li}$ and ${}^7\text{Li}$ can occur in olivine with high Li contents (e.g., 10s or 100s of ppm in doped experiments and natural samples; Dohmen et al., 2010; Weyer and Seitz, 2012; Richter et al., 2017). However, at concentrations of only a few ppm and high temperatures typical of basaltic systems (e.g., near 1200°C), it is thought that the diffusion of Li concentrations may be modeled using the slower vacancy mechanism of ${}^7\text{Li}$ (Dohmen et al., 2010).

In this study, lithium concentrations in volcanic olivine are modeled in basalts from Kīlauea Volcano. Rapidly quenched tephra from the recent prehistoric (1500 to ~ 1820 CE) Keanakāko’i Tephra (KT) explosive eruptions were chosen for this study because little is known about the physical or chemical controls on the eruption dynamics during this time, and Li diffusion can help to identify processes occurring shortly before and potentially during these eruptions. The basaltic pumice in these deposits are ideal for Li diffusion because they contain fresh, glass-coated olivine produced during a period of exceptionally low magma supply ($\sim 2\%$ of average output during the historical period after 1823; Swanson et al., 2014). These glass and olivine are among the most primitive sub-aerial deposits at Kīlauea (glass MgO up to 11.2 wt.% and forsterite values of 89%; Lynn et al., 2017; Garcia et al., 2018). The heterogeneous glasses (e.g., 6.5–11.0 wt.% MgO) in several KT units were interpreted to reflect inefficient mixing and little or no storage of the high-MgO magma in the reservoir system (Helz et al., 2015; Garcia et al., 2018). Thus, these more primitive eruption products may not have been stored for years to decades in a shallow magma chamber like Kīlauea’s historical lavas (Garcia et al., 2003; Pietruszka et al., 2015).

Basaltic deposits from six eruptions, three from phreatomagmatic and three from high lava-fountaining eruptions within the Keanakāko’i Tephra are utilized because their rapid quenching (seconds to minutes) preserves information relevant to magmatic processes by avoiding the longer cooling histories (hours to days) following eruption that are typical of effusive lava flows (e.g., Hon et al., 1994). These samples are ideal for applying the lithium

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