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Olivine xenocryst diffusion reveals rapid monogenetic basaltic magma ascent following complex storage at Pupuke Maar, Auckland Volcanic Field, New Zealand

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ABSTRACT

Monogenetic basalts are spatially and temporally unpredictable and are commonly interpreted to rise extremely rapidly and directly from their mantle source, increasing their potential hazard. The assumption of rapid ascent is commonly based upon the presence of xenocrysts and xenoliths as well as generally short OH and elemental diffusion profiles at the margins of xenocrystic material. We show that small-volume monogenetic basalts may also have complex multi-stage deep mantle magma storage prior to rapid ascent, using coupled diffusion modelling of major and trace elements and OH within olivine xenocrysts. The xenocrysts and crystal clusters were extracted from a tuff ring in Auckland City (New Zealand), within the Late Pleistocene–Holocene 100 km^2 Auckland Volcanic Field. Forsterite-rich olivine xenocrysts ($Fo\#_{89.5–91.7}$) have undergone Fe–Mg (Fo#), Ca, Ni and Mn element diffusion that extends up to ~200 μm from their rims. Major and minor element diffusion at frozen melt–xenocryst interfaces was modelled using crystallographically oriented grains. These profiles show that the host basalt collected most of the olivine xenocrysts and xenoliths over approximately 1 month. The narrow OH diffusion profiles in the olivine suggests late-stage degassing over <1 day (i.e., not extremely rapid ascent rates). Some olivine crystals have diffusion profiles requiring step function initial conditions; these indicate that magma resided in the mantle for up to one year and accumulated from multiple batches of mixed magmas. Our results show that primitive magmas in small volume monogenetic volcanoes may have complex lithospheric magmatic histories, but they may suddenly rise to eruption, with seismic detection providing less than a week of warning.

1. Introduction

Monogenetic volcanoes often erupt chemically and petrographically simple small-volume basaltic magmas apparently directly ascending as near-primary mantle-derived melts (McGee and Smith, 2016). In these magmas, the absence of shallow crystallising phases (e.g. plagioclase), or large and complexly-zoned crystals, coupled with the presence of mantle xenoliths, are interpreted as evidence for lack of crustal stalling (Albert et al., 2016; Jankovics et al., 2015; Re et al., 2017). This has led to a model of monogenetic basaltic magmas rising to eruption rapidly from a source area in the mantle shortly after their generation through partial melting (McGee et al., 2012). The uncertain nature of eruptive events in both time and space within a typical volcanic field, coupled with the likely short unrest times of even a small volcanic eruption give rise to great public uncertainty and potentially vast hazard implications. These include impacts to urban infrastructure and landscape (e.g., Heimaey, Iceland), global air travel (e.g., Eyjafjallajökull), or chronic health and agriculture implications for long eruptions (Cronin and Sharp, 2002). Cities such as Mexico City (Mexico), Portland (Oregon), Auckland (New Zealand) and Jeju (Korea) all have populations of >1 million people on or near intraplate monogenetic basaltic fields. Lack of magma storage within the crust in these settings limits ongoing monitoring possibilities,

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leading to a key question: if magma is geophysically detected as it rises through the crust beneath a monogenetic volcanic field, how quickly could an eruption ensue?

Magma ascent processes and magma residence times have been estimated using a range of techniques, including: U–Th–Ra isotopic disequilibrium in magma (Condomines and Tanguy, 1995), seismicity before eruptions (Okada and Yamamoto, 1991), and the physics of dense xenoliths carried within magma (Spera, 1984). However, the analysis of reaction rims in olivine xenocrysts is a promising technique for recording magma ascent rates because diffusion of major and minor elements (Mg, Fe, Ni, Mn, Ca; Coogan et al., 2005; Holzapfel et al., 2007) as well as H_2O (Demouchy and Mackwell, 2006) are well constrained in olivine (Dohmen et al., 2017). Models based on different diffusion methodologies, however, vary by several orders of magnitude in their estimates (Denis et al., 2013; Peslier et al., 2015) and require careful interpretation. Previous workers have compared magma ascent rates based on different methodologies (cf. Fig. 7 in Peslier et al., 2015) and have inferred a degree of consistency (Dohmen et al., 2017) despite ranges of several orders of magnitude (<0.1–$10\ m\,s^{-1}$). In order to produce robust hazard estimates, it is necessary to consider an array of techniques to determine the processes controlling chemical disequilibrium.

In this work we integrate major, minor and trace element and OH diffusion data to model the different stages of entrainment and evolution of olivine xenocrysts in tephra within the tuff ring beside the Pupuke Maar in the Auckland Volcanic Field (AVF), New Zealand. This is the first such study on a maar volcano system, and the diffusion results reveal a complex magmatic history with implications for understanding pre-eruption magma assembly in monogenetic fields, along with the interpretation of the widely ranging magma ascent rates modelled using different techniques and the resulting implication for hazard and warnings.

2. Geology of Pupuke Maar

Pupuke Maar is a basaltic volcano in the northern part of the AVF, comprising a complex succession of phreatomagmatic, strombolian and effusive deposits (Spargo, 2007). It is one of the older volcanoes of the field and was recently dated at ~200 ka (Leonard et al., 2017). The eruption produced four main stratigraphic units erupted in two separate episodes. Three vents in the southern part of the complex initially produced lava flows, capped by localised pyroclastic deposits (including the units sampled for this study). Following an unknown period of quiescence marked by a weathering and erosion surface, vents in the northern and central part of the volcanic complex began by erupting lava flows toward the north. Later, maar formation in the central area produced the uppermost pyroclastic (base surge) deposits, forming a near-concentric tuff ring. The two episodes of eruption have similar petrography, but different chemical compositions, with the southern group showing greater silica undersaturation (basanite to alkaline basalt) compared to the northern group (alkaline to transitional basalt) (Spargo, 2007) (Fig. A1 in Electronic Appendix A).

The southern (early episode) pyroclastics sampled here begin with ~4 m of 0.2–0.5 m beds of fall-bedded, well-sorted scoria lapilli with rare bombs. These contain common free olivine xenocrysts (2–20 mm) and olivine/pyroxene xenoliths (2–3% of the 2–6 mm fraction based on sorting of 2–4 kg sub-samples). This passes gradually up to a sequence of ~4 m of more poorly sorted beds, 0.1–0.5 m thick of mixed ash to lapilli (lapilli tuffs), with at least 50% of dense basalt lava clasts and scoria. These units also have obvious free olivine xenocrysts (2–3% of 2–6 mm fraction). The lapilli tuff beds are interspersed with 0.05–0.2 m beds of indurated, poorly sorted fine-coarse ash (tuff) showing common cross-bedding and dune forms, accretionary lapilli and fine-grained vesiculated tuff. The sequence passes up to weathered lapilli tuff and to an unconformity with the overlying maar-sourced base-surge deposits of the second episode of volcanism.

Xenocrysts and xenoliths for this study (Fig. 1) were collected from the lowermost scoria (~40% vesicularity, Fig. 1c, d) lapilli fall unit, which has basanite to alkaline basalt composition. In addition to the free, coarse xenocrysts and xenoliths, the dominant phenocryst is olivine (typically <15 vol.%) forming subhedral crystals up to 0.4 mm in diameter with compositions in the range Fo# [100*molar Mg/(Mg + Fe)] 73 (phenocryst rims and groundmass) to Fo#85 (phenocryst cores) and with CaO 0.2–0.7 wt% (Fig. 2b) (Spargo, 2007). Clinopyroxene phenocrysts (diopside–augite) are less abundant (~5 vol.%) and smaller (<0.2 mm diameter). The groundmass consists of plagioclase (andesine–labradorite) microlites (<200 μm) and clinopyroxene with subordinate olivine and minor iron–titanium oxide.

3. Methodology

To characterise xenocrysts compositions, electron microprobe analysis was carried out on a Cameca SX100 at the Research School of Earth Sciences, Australian National University, with accelerating voltage of 15 kV, a current of 20 nA and a focused beam diameter of 1 μm. Analytical precision was monitored using a series of international standards and is estimated as <3% (σ) for elements present in abundances >1%. The full dataset of analyses is available as Electronic Appendix A.

Olivine xenocryst orientations were determined by Electron Back-Scattered Diffraction (EBSD) at the Otago Centre for Electron Microscopy, University of Otago, using a Zeiss Sigma VP FEG-SEM. Maps covering the majority of each crystal consisted of >2000 points spaced ~10 microns apart. Crystal axes orientations were determined graphically based on the pole figures extracted from the EBSD measurements using the software AZtec. The angle of the traverse on the crystal plane was determined graphically and via "Stereonet 9.5" software (Allmendinger et al., 2011), and used to measure the angles between the three crystal axes and the analysed traverse (Table C2 in Electronic Appendix C).

Trace elements were measured using laser-ablation inductively-coupled-plasma mass-spectrometry (LA-ICP-MS) at the Research School of Earth Sciences, The Australian National University. The setup consisted of a Coherent COMPexPro 110excimer laser (193 nm) and fast washout, two-volume ablation cell coupled to an Agilent 7700 series mass spectrometer. Samples were ablated in a helium atmosphere, and the aerosol fed into the mass spectrometer in a dilute stream of helium and argon. An ablation frequency of 5 Hz was used, and laser fluence directly above the sample surface was estimated to be 5–6 J/cm^2. The ablation technique consisted of a moving slit with dimensions 10 × 100 μm that was angled parallel to the crystal edge and moved at a constant speed of $1\ \mu m\,s^{-1}$ in a perpendicular direction towards the diffusion interface. The total integration time for the analysed elements (Si, Li, Na, Mg, Al, P, Ca, Sc, Ti, V, Cr, Mn, Fe, Ni) was approximately 8 s, thus giving an effective chemical resolution of 8 μm along the travel direction. The length and shape of these diffusion profiles match closely high-resolution (2 μm step) microprobe traverses, showing that there are no smoothing effects in the laser data (Electronic Appendix B2). Samples consisted of olivine separates, mounted in epoxy. Analyses were run in batches of 10–15 using NIST610 glass (Jochum et al., 2011) at the beginning and end of each batch as the primary calibration standard. A secondary standard BCR-2g was also run with each batch to monitor analytical performance. Fifteen repeat analyses of standard BCR-2g indicate precision of <4% (RSD) and accuracy better than 5% at the 95% confidence level for most elements. Results are reported in Electronic Appendix B.