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Contrasting plagioclase textures and geochemistry in response to magma dynamics in an intra-caldera rhyolite system, Okataina volcano

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ABSTRACT

The changing magmatic dynamics of the rhyolite caldera volcano, Okataina Volcanic Centre, New Zealand, is revealed in plagioclase growth histories. Crystals from the ~0.7 ka Kaharoa eruption are characterized by resorbed cores displaying a cellular texture of high-An (>40) zones partially replaced by low-An (<30) zones, surrounded by a resorption surface and a prominent normal-zoned rim ($An_{50–20}$). Elevated An, Fe, Mg, Sr, and Ti follow the resorption surface and display rimward depletion trends, accompanied by Ba and REE enrichment. The zonation is consistent with fractional crystallization and cooling. The cores display wide trace element diversity, pointing to crystallization in a variety of melts, before transport and mixing into a common magma where the rims grew. Plagioclase from the ~36 ka Hauparu eruption display several regrowth zones separated by resorption surfaces, which surround small resorbed cores with a spongy cellular texture of variable An content ($An_{40–50}$). The crystals display step-wise regrowth of successively higher An, Fe, Mg, and Ti content, consistent with progressive mafic recharge. Two crystal groups are distinguished by trace element chemistry, indicating growth in separate melts and co-occurrence via magma mingling. For plagioclase in both eruption deposits, partition coefficients (D) estimated from crystal rim-groundmass glass analyses, produce melt compositions similar to the array of rock and glass compositions erupted and are consistent with the processes of fractional crystallization and recharge. However, *D* values estimated from some published formulations based on An content and temperature produce unrealistic melts. The contrasting zoning patterns in plagioclase correspond to the evolutionary history of magmatism at Okataina. Emptying of the magma reservoir following caldera eruption at 46 ka reduced barriers to mafic magma ascent. This is recorded by the frequent resorption and recharge episodes in Hauparu crystals. Subsequent redevelopment of a more silicic reservoir zone (post-26 ka) dampened thermal and mass perturbations, resulting in simpler growth histories of the Kaharoa crystals. The plagioclase lack features associated with rapid decompression events that are common in andesite systems. This reflects the rapid ascent of the rhyolite magmas and lack of precursory eruptions that could decompressed the system.

1. Introduction

Textural and geochemical zoning in phenocrysts of volcanic rocks can be recorders of the magmatic conditions that lead to eruption, including temperature, pressure, melt composition, and other parameters (e.g., Davidson and Tepley, 1997; Ginibre et al., 2007). These conditions reflect the processes of magmatic ascent, fractionation, recharge, or contamination. Such data are significant in reconstructing the magmatic state of dormant volcanoes that display repose periods of hundreds or thousands of years, thus providing little opportunity for day-to-day technological sampling or monitoring.

The major and trace element composition of plagioclase has been widely utilized to reconstruct upper crustal, pre-eruption magmatic dynamics. Plagioclase is commonly the most abundant phase in silicic magmas, the systems capable of the most catastrophic explosive eruptions. It is stable over a wide range of magmatic conditions, and due to relatively slow atomic diffusive exchange within the crystals, compositional zonation patterns are preserved (Grove et al., 1984). Studies of the geochemical zoning patterns in plagioclase have focused on andesitic and dacitic magmas in arc settings (Singer et al., 1995; Ginibre et al., 2002; Browne et al., 2006; Berlo et al., 2007; Ginibre and Worner, 2007; Ruprecht and Worner, 2007; and many others). In contrast, plagioclase in rhyolitic magmas have received less attention (Smith et al., 2010).

Rhyolites erupted from the Okataina Volcanic Centre (OVC) in New Zealand provide an ideal system for the investigation of plagioclase zonation in the more silicic arc magmas. The OVC has been the site of frequent intra-caldera volcanism over the last 46 ka, and the petrological and chronological framework of the volcano is well established (Nairn, 2002; Shane et al., 2008; Cole et al., 2014). Recent crystal-based studies have focused on zircon, demonstrating the presence of a periodically active, long-lived (10^4–10^5 yr) magmatic reservoir beneath OVC (Storm et al., 2012). However, there is little correlation between periods of

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zircon crystallization and eruption events. Most, if not all, eruptions at OVC have been triggered by rapid basaltic recharge (Shane et al., 2008). The robust zircons with very slow atomic diffusion rates can potentially survive magmatic recharge (e.g., Schmitt, 2011), limiting their utility in recording near-eruption events. In contrast, plagioclase have the potential to record volcanic timescales of a few thousand years to even days, depending on the spatial resolution of analytical technique employed (e.g., Saunders et al., 2014). Ideally, minerals of a variety of diffusion timescales are employed to reconstruct the entirety of a magma history.

A fundamental feature of post-caldera activity at OVC is a change in magma composition and eruption styles starting at 26 ka (Smith et al., 2005). The interval ~46–32 ka was characterized by smaller volume, high-temperature rhyodacite magmas. Post-26 ka, there was a change to a lower tempo of activity involving larger volume, low-temperature, rhyolite magmas. Differences in magmatic dynamics could be expected to accompany these changes. A more open system immediately following the caldera formation may have reflected the emptying of the silicic reservoir that acted as a density barrier to mafic magma ascent and recharge. To investigate the change in magma dynamics, the textural and compositional characteristics of zoned plagioclase in two eruption deposits representing these two time intervals are examined. The plagioclase growth histories reveal contrasting conditions leading to eruption, reflecting the different states of post-caldera magma evolution. They demonstrate the potential of using plagioclase archives for assessing magmatic change in large, infrequently active rhyolite volcanoes.

2. Geologic setting and eruption deposits

OVC is part of the Taupo Volcanic Zone, the on-land continuation of the Tonga–Kermadec arc, formed at the convergent plate boundary between the westerly subducted Pacific Plate and the partly continental Australian plate. The eruptive history of OVC extends back to at least 600–700 ka (Cole et al., 2014). The most recent caldera-forming event (Rotoiti eruption) occurred at ~46 ka and was followed by a sequence of intra-caldera eruptions. During the interval 46–32 ka, at least 13 small to moderate-sized (mostly <5 km^3 magma) rhyodacite plinian and sub-plinian eruptions occurred (referred as Mangaone Group). The vents are now buried. The older eruptions produced crystal-poor deposits with an orthopyroxene–clinopyroxene ± hornblende mineralogy and display high eruption temperatures (~850–950 °C). The younger deposits of this group are mostly rhyolite magmas. These display an orthopyroxene-hornblende mineralogy, and eruption temperatures of ~800–850 °C (Smith et al., 2005; Shane and Smith, 2013). Post-26 ka activity occurred along two linear vent zones (Nairn, 2002), comprising nine caldera-infilling lava and pyroclastic episodes, each with magma volumes of about 10 km^3. Haroharo volcano erupted mostly cummingtonite-bearing rhyolites, and Tarawera volcano erupted mostly biotite-dominant rhyolites (e.g., Smith et al., 2005). Most post-26 ka rhyolites were high-SiO_2 (>74 wt%) and display low eruption temperatures (mostly 750–800 °C).

The ~0.7 ka Kaharoa (Nairn et al., 2004) and the ~36 ka Hauparu (Shane et al., 2005) eruption deposits were selected for investigation because their petrology has been well investigated, and they represent petrological end-members of intra-caldera magmas erupted. Kaharoa deposits erupted from the Tarawera vent zone, comprise sub-plinian fall deposits, lava domes, and associated pyroclastic flows with magma volume of 9.1 km^3 (Sahetapy-Engel et al., 2014). The rhyolite lavas and pumice contain an average of 11% crystals, comprising plagioclase (40–45%), quartz (40–45%), biotite (<5%), cummingtonite (<2%), Fe-Ti oxides (<2%), and trace hornblende, in a vitric groundmass. Fe-Ti oxide equilibrium imply temperatures of about 750 °C (Shane and Smith, 2013). Juvenile clasts are high-SiO_2 rhyolites (SiO_2 = 76–77 wt%: groundmass glasses >77 wt%, water-free). An assortment of subordinate rhyodacite to basaltic andesite ejecta also occurs, representing magma-mixing between the rhyolites and a mafic end-member (Nairn et al., 2004). Samples examined here were obtained from a block and ash flow sourced from the Whanga dome, representing late-stage T2 magma of Nairn et al. (2004). An additional sample represents pumiceous pyroclastic flow deposits (Hpdc unit) that display evidence of basaltic-rhyolitic magma mingling.

Hauparu eruption deposits comprise plinian fall deposits with magma volume of 3.9 km^3 (Jurado-Chichay and Walker, 2000). The samples examined here were collected from late-stage T2 magma pumice fall deposits (Shane et al., 2005). These are poorly vesicular and crystal-poor (15%). They have a modal mineralogy of 70% plagioclase, 21% hornblende, 6% Fe-Ti oxides, 2% clinopyroxene, and 1% orthopyroxene. Fe-Ti oxide equilibrium provides temperature and fO_2 estimates of ~880C and NNO + 1.5, respectively (Shane et al., 2005). Whole rock compositions contain 67–68 wt% SiO_2, while groundmass glasses have >77 wt% SiO_2.

3. Methods

The crystal-poor, vesicular, and soft lithology of the samples rendered thin sections impractical for investigation. Instead, crystals were liberated by crushing. Many of the crystals display fractures, prior to laboratory processing. Larger crystals (>0.5 mm) were hand-picked with preference for those with intact rims and adhering glass. The crystals were embedded in epoxy blocks and exposed by polishing. Following reconnaissance backscatter electron (BSE) imaging of selected crystals to characterize textural groups, approximately 150 crystals per sample were imaged at lower magnification to assess abundance and diversity. The textural types documented here are the most common, but it is acknowledged a greater diversity of subordinate types are present.

Plagioclase zonation was examined by BSE imaging using a JEOL JXA-8230 SuperProbe at Victoria University of Wellington. The BSE intensity increases with An content. Electron microprobe analysis (EMA) of elements Si, Al, Ca, Na, K, Fe, Mg, and Ti on spots were determined using a 15 kV acceleration voltage, 20 nA current, and a beam size of 1–2 μm. Peak counting times were 60 s for Fe and Mg, and 30 s for the remaining elements. Analyses were monitored by analyzing plagioclase standard NMNH 115900. Replicate analyses on this standard give indication of precision and accuracy (see supplementary material). Uncertainties are mostly < ±4% of abundance, except for Ti (~27%).

Trace element concentrations were determined by laser ablation inductively coupled mass spectrometry (LA-ICPMS) at the Australian National University. Techniques are outlined by Park et al. (2013). Analytical spots were chosen along the crystal traverse lines from EMA data. The system comprises a Lambda Physik Complex 110 excimer laser (k = 193 nm) and an ANU-designed HelEx ablation cell, coupled to an Agilent 7500 ICPMS, with He as the laser ablation carrier gas. Analyses were performed using a laser pulse rate of 5 Hz and spot size of 28 μm, comprising 15 s of background measurement followed by 40 s of sample ablation. Concentrations of single trace elements were calculated employing ^{43}Ca as an internal standard relative to the USGS glass standard BCR-2G. Analyses of BCR-2G indicate that analytical precision (1σ) of about 5% for all elements, except for Pb (8%). The measured value for BCR- 2G is consistent with the reference values within 10% for most of the elements. BCR-2G and NIST 610 standards were analyzed periodically as a monitor for drift. A complete data set can be found in supplementary material.

4. Types of plagioclase

4.1. Kaharoa

The plagioclase are euhedral to subhedral stubby laths up to 2 mm μm long. BSE imaging reveals about 70% of crystals have cores displaying boxy-cellular textures surrounded by a normally zoned rim (Ka-03, 31, 33 in Fig. 1). The cellular core display a chess-broad-like