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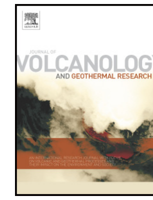

Thermobarometry of Whangarei volcanic field lavas, New Zealand: Constraints on plumbing systems of small monogenetic basalt volcanoes

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ABSTRACT

The intra-plate, basaltic Whangarei volcanic field (WVF) is a little-studied cluster of Quaternary monogenetic volcanoes in northern New Zealand. Clinopyroxene-melt equilibria provides an insight to the ascent and storage of the magmas that is not evident from whole-rock-scale geochemistry. Basalts from two of the younger volcanoes contain a population of equilibrium and disequilibrium clinopyroxene phenocrysts. Many of the crystals are resorbed, and are characterised by diffuse, patchy zoning, and low MgO (Mg#70–80) and Cr_2O_3 contents. Such crystals also occur as relic cores in other phenocrysts. These grew in a magma that was more evolved than that of the host rock composition. Equilibrium clinopyroxenes are enriched in MgO (Mg#83–88) and Cr_2O_3 (~0.4–0.9 wt%), and occur as reverse-zoned crystals, and rim/mantle overgrowths on relic cores of other crystals. These crystals and rim/mantles zones nucleated in magma with a composition similar to that of the host rock. The textural relationships demonstrate that a mafic magma intruded a more silicic resident magma, resulting in crystal-exchange and entrainment of antecrysts. Clinopyroxene-melt equilibria indicate that the crystallisation occurred at temperatures in the range 1135–1195 °C, and pressures in the range 290–680 MPa. The dominant pressure mode (400–550 MPa) equates to depths of about 15–19 km which coincides with a present-day body of partial melt in the crust. Higher pressures indicated by subordinate crystal populations indicate staged ascent and crystallisation above the Moho (~26 km depth). Thus, the magmatic system is envisaged as a crystal mush column through the lower and mid crust. Such crystallisation histories are perhaps not expected in low flux, monogenetic magma systems, and reflect the importance of the crustal density structure beneath the volcanoes. Future activity could be preceded by seismic events in the lower crust as the magmas intrude localised crystal mush bodies.

1. Introduction

An important aspect of monitoring volcanoes is recognising and interpreting precursor phenomena. Geophysical data such as seismicity, gravity, ground deformation and gas release provide insight to magma ascent and intrusion, and are variously used to model the crustal structure beneath the volcano. Such modelling requires a knowledge of magma temperature and pressure. Temperature has a strong control on the seismic velocities, and viscosity which controls ability of magma to flow in conduits. Magma pressure provides insight to depth and hence the location of the magma body. At active and dormant basalt volcanoes, petrological data such as clinopyroxene-melt equilibria (e.g., Putirka, 2008) in previously erupted rocks is commonly the only source of information on the magma pressure and temperature in the deep crustal setting.

Fields of monogenetic, continental basalt volcanoes are perhaps one of the more difficult volcanic settings to monitor. Geophysical data acquisition is limited by the infrequency of the eruptions (~10^{-4} to 10^{-5}/yr), and their short duration, typically lasting months to a few years (e.g., Wood, 1980). From a petrological perspective, the small extrusive volumes of such events suggest that conduits are unlikely to be thermally viable for a prolonged time (e.g., Walker, 1993). This necessitates rapid magma ascent through the crust and minimal magmatic interactions on the journey (e.g., Valentine and Perry, 2007; McGee et al., 2013; Rasoazanamparany et al., 2015). The aphyric or finely porphyritic rocks commonly produced are not always optimal for crystal- and sub-crystal scale geochemical investigations, although clinopyroxene-melt thermobarometry has been applied to such basaltic fields in the western United States (e.g., Putirka and Condit, 2003; Mordick and Glazner, 2006; Browne et al., 2017).

This work focuses on the intra-plate basaltic Whangarei Volcanic Field (WVF), a cluster of Quaternary volcanoes in northern New Zealand (Smith et al., 1993; Huang et al., 2000) (Fig. 1). Scant attention has been given to the WVF despite its youth and location near regional settlements. In contrast, the neighbouring and contemporaneous Auckland Volcanic Field (AVF) has been extensively investigated because of its proximity to a large urban area (e.g., Bebbington and Cronin, 2011;

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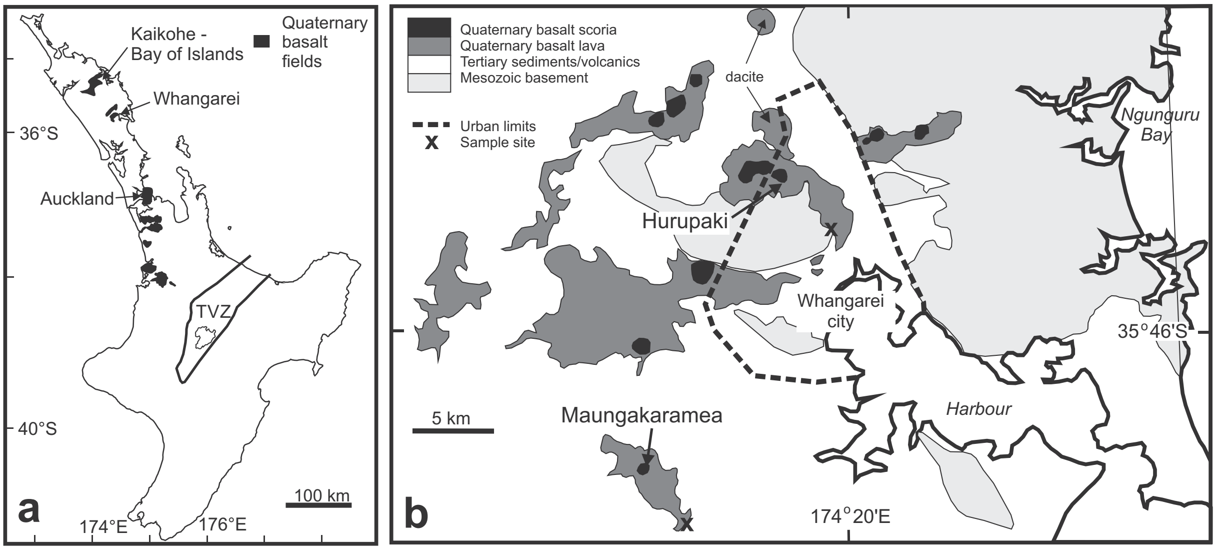

Fig. 1. (a) The location of Quaternary intraplate basaltic fields (black) and the subduction-related Taupo Volcanic Zone (TVZ) in North Island, New Zealand. (b) Simplified map of the Whangarei volcanic field based on Edbrooke and Brook (2009).

McGee et al., 2013; Linnell et al., 2016). A significant difference between the two volcanic fields is the presence of a low-velocity seismic zone in the crust beneath the WVF, interpreted to be a body of partial melt (Horspool et al., 2006). This means mantle-sourced magmas must stall in the crust to cause melting. Clinopyroxene phenocrysts in WVF basalts provide an opportunity to investigate the thermobarometry of the magmas and thus, assess the origin of the crystal cargo and examine the relationship between the seismic structure of the crust and magma ascent/storage. The magma ascent histories also have implications for the likelihood and type of detectable precursor phenomena in future eruptions.

2. Whangarei Volcanic Field (WVF) and samples studied

The Whangarei Volcanic Field (WVF) is one of several Quaternary intra-plate basalt volcanic fields in northern, New Zealand (Fig. 1a). They are located on continental crust, away from the convergent plate margin (Taupo Volcanic Zone) that runs through the central North Island. Basalt volcanism commenced in the WVF during the late Pliocene, but the stratigraphy is poorly established. The Quaternary part of the WVF covers an area of about 500 km^2. During the last ~1 Ma, at least 10 basalt volcanoes erupted, including individual scoria cones or amalgamated clusters of 1–3 cones; and isolated small shields (Smith et al., 1993) (Fig. 1b). In addition, two dacite domes mapped as Quaternary in age are located in the field (Edbrooke and Brook, 2009). The alignment of some vents has been interpreted as fault control of magma conduits (Smith et al., 1993). The volcanoes are described as monogenetic on the basis of their morphology, however, detailed stratigraphy of the individual volcanoes is lacking. The WVF basalts and those of other fields in the region have a broadly similar ocean island basalt (OIB)-like, and/or mid-ocean ridge basalt (MORB)-like mantle source (e.g., Huang et al., 2000; Hoernle et al., 2006). There is no geophysical evidence for plume-like structures beneath the fields, and the spatio-temporal pattern of volcanism is not consistent with a fixed plume or extensional rift. Some workers suggest the basalts originated from decompression melting of the mantle that was caused by delamination of over-thickened lithosphere (e.g. Hoernle et al., 2006). Huang et al. (2000) note that WVF basalts generally have rare earth element (REE) patterns and Sr-Nd isotope ratios typical of MORB, but also a negative Nb anomaly and elevated radiogenic Pb isotope ratios that indicate a subduction influence in mantle source. Any such subduction contamination must be a relic feature because subduction ceased in the region at the end of the Miocene (e.g., Booden et al., 2011). Geochemical data for WVF dacites have not been published.

Based on seismic data, Horspool et al. (2006) interpreted the depth to the Moho to be 26 ± 1 km beneath the WVF, and additionally identified a low velocity (<3 km/s) zone at ~12–18 km in the crust. This crustal body extends to the north under the adjacent Kaikohe-Bay of Island volcanic field, but does not occur beneath the AVF some 180 km to the south (Fig. 1a). High ^{3}He/^{4}He ratios in gas from the WVF area is consistent with mantle melting beneath the field (Hoke and Sutherland, 1999). The sub-surface geology of the WVF is poorly known. Within the boundaries of the field, Permian-Triassic greywacke and argillite (Waipapa terrane) outcrop as fault-controlled blocks (Fig. 1b). Elsewhere allochthonous Cretaceous and early Tertiary sediments and rocks of ophiolite origin, interbedded with autochthonous sediments are exposed. Eroded edifices of Miocene andesite arc volcanoes occur along the eastern margin of the field. Schistose mafic inclusions in Miocene andesite lavas (Booden et al., 2011) could represent deeper facies of the greywacke terrane that underlies the WVF.

Lava from two volcanoes were selected for investigation on the basis of their non-weathered outcrops, size of phenocrysts, and presence of clinopyroxene. The two volcanoes are the youngest in the field, and thus, are potentially more representative of future volcanism. (1) Hurupaki volcano is a ~100 m high scoria in a cluster with 3 smaller cones, and a lava field with an area of ~12 km^2 (Fig. 1b). A lava flow that extends some 10 km to the southeast is dated by K-Ar at 0.26 ± 0.12 Ma (Smith et al., 1993), and ^{40}Ar-^{39}Ar at 0.32 ± 0.06 Ma (P Shane, unpublished data). This lava was sampled in this study from an outcrop on State Highway 1 (NZTopo50 series maps, 1:50000 Q07, grid reference 296089). (2) Maungakaramea volcano consists of a single scoria cone ~150 m in elevation, and has an associated lava field of ~10 km^2 area extending up to 5 km from vent. Smith et al. (1993) reported two K-Ar ages of 0.29 ± 0.05 Ma and 0.31 ± 0.06 Ma for the lava field. Lava in a quarry was sampled in this study (Map Q07, grid reference 210914).

3. Analytical methods

Thin sections of lava from Hurupaki and Maungakaramea volcanoes were examined to characterise their mineralogy. A minimum of 300 crystals were point-counted in each sample. Backscatter electron (BSE) imaging of clinopyroxene and olivine in polished thin sections were used to investigate zonation patterns of crystal populations, and select crystals for geochemical analysis. Quantitative spot analyses