Eruptions of basalt volcanoes in the Kaikohe-Bay of Islands field (16/U733)

Principal Investigator/s, Organisation/s
Assoc Prof Phil Shane, University of Auckland

Research team
Alisha Coote (PhD student), University of Auckland

Key words
Magma ascent, eruption precursor phenomena, Basalt, Monogenetic volcanoes

Summary
Late Quaternary basalts erupted in the Kaikohe-Bay of Islands area provide an opportunity to explore the ascent history of small volume magmas in an intra-continental monogenetic volcano field, and hence, improve our understanding of potential future precursor phenomena. To achieve this goal, we investigated the formation and growth history of phenocrysts (crystals) in the basalts. The plagioclase phenocrysts represent a diverse crystal cargo. Most of the crystals have a rim growth that is in equilibrium with the host basalt rock. The resorbed cores of the crystals variously formed in more differentiated or more primitive melts. The relic cores have 87Sr/86Sr ratios that are either mantle-like (~ 0.7030) or crustal-like (~ 0.7040 to 0.7060), indicating some are antecrysts formed in melts fractionated from plutonic basaltic forerunners, while others are true xenocrysts from greywacke basement and/or Miocene arc volcanics.

Clinopyroxene phenocrysts also record magma mixing and crystal entrainment in the crust. Like the accompanying plagioclase, many have a rim overgrowth which is in equilibrium with the host rock, but have a resorbed core that crystallised in a more silicic magma. These crystals record mafic recharge, presumably the trigger to eruption. Crystal-melt equilibria indicate that the clinopyroxene formed at a narrow temperature range (1095-1200 ºC), but wide pressure range (150-870 MPa). Most formed at 300-600 MPa (~11-23 km depth), and a subordinate population formed at 700-900 MPa (>27 km depth). These depths coincide with major seismic velocity contrasts at a zone of partial melt (10-19 km) and the Moho (~28 km) inferred from geophysical data. Thus, buoyancy or rheology contrasts in the crust temporarily slow magma ascent and promote periods of melt crystallisation and the assimilation of antecrystic and xenocrystic components.

It is envisaged that intrusive basaltic forerunners produced a zone where various degrees of crustal assimilation and fractional crystallization occurred. The erupted basalts represent subsequent mafic recharge of this system. This crystallization history contrasts with traditional concepts of low-flux basaltic systems where rapid ascent from the mantle is inferred. From a societal perspective, staged magma storage and crystallisation beneath some basalt intra-plate fields increases the likelihood of detecting pre-eruption geophysical phenomena that could act as signals to pending eruptions.

Introduction
Monogenetic basaltic volcanoes are small volume edifices such as scoria cones or maars, associated with lava flows. In intra-continental settings, they form a field of numerous edifices of wide geographic extent. During historic eruptions, the individual volcanoes emit a small volume of magma (10^2–10^9 m^3) in a short-lived interval lasting only days to years. In thick, cold continental crust, such low magma supply rates require rapid ascent to prevent magmatic freezing before eruption, and it is unlikely that a thermally viable conduit is maintained

following eruption. As a result, eruption precursor phenomena would have limited duration or may be undetectable by geophysical methods, and future activity is likely to occur in a new location. Thus, such eruptions are difficult to forecast and monitor. Petrological studies of ancient deposits are, in some cases, the only insight to likely future magmatic ascent. Recent petrological and geophysical studies of monogenetic basalt eruptions in high-flux magmatic systems on oceanic islands indicate that shallow (5-15 km depth) crustal magma storage zones can also occur. Less is known about their low-flux counterparts in continental settings such as New Zealand.

Here we examine porphyritic basalts erupted in the Quaternary Kaikohe-Bay of Islands (KBI) volcanic field, an intra-continental field of monogenetic volcanoes in northern New Zealand. The occurrence of large plagioclase phenocrysts in the rocks indicates staged magmatic crystallization. Micro-analysis of the phenocrysts provides an opportunity to investigate the geochemical changes, including variations in Sr isotopic composition, which occurred during magma evolution and the origin of the crystals. We demonstrate that the phenocrysts result from a range of magmatic differentiation, mixing and assimilation events involving both mantle and crustal sources. Multi-stage magmatic ascent and storage is inferred. This contrasts with inferences made about relatively aphyric basalts erupted in other contemporary intra-plate fields in New Zealand (e.g., Auckland volcanic field), and elsewhere.

Objectives

The overall objective was to improve the eruption hazard and warning scenario models for basalt volcanoes in Northland, and by comparison, Auckland. This would be achieved by studying the formation and growth of crystals in basalts erupted from the KBI field to determine how the magmas ascended through the crust.

Conclusions and key findings

Based on geochemical and isotopic zonation, most the plagioclase and clinopyroxene crystals in the Kaikohe-Bay of Islands basalts are a diverse cargo. Sr-isotope ratios demonstrate various mantle and crust sources for the crystals. Clinopyroxene-melt equilibrium demonstrates periods of crystallisation at depths of about 15 km and >27 km. Many of the crystals comprise a relic core formed in a basaltic forerunner magma or from country rock, surrounded by a rim zone that grew from new ascending magma. We found that ascending magmas interact or mix with earlier magmas residing in the crust, and some magmas fail to erupt. This is a remarkable contrast to the traditional models for small-volume intra-plate basalt volcanoes (e.g. Auckland volcanic field) that assume rapid formation and ascent of magmas to eruption without significant crustal interaction. We envisage the magma system to be a mush column through the crust where magmas stall at various depths. This petrological model fits well with geophysical data that suggests a low-velocity zone of partial melt occurs beneath the volcanoes at 10-19 km, and the Moho occurs at >27 km.

Our studies highlight that during future activity, periods of temporary magma storage and crystallisation could occur at rheology barriers in the crust, thus prolonging the interval of eruption precursor activity, and increasing the potential for detecting seismic or degassing events. Future magma eruptions and failed eruptions (intrusions) at the Kaikohe-Bay of Islands volcanic field could be associated with seismicity at 10-19 km and ~28 km, where the major crustal rheology contrasts occur. The likelihood of intrusion unaccompanied by eruption may also be greater than previously expected for such volcanoes.

Impact *(ie, how this research reduces the impact of natural disaster on people and property)*

There is a paucity of direct observations of continental intra-plate basalt eruptions, and they have not occurred in New Zealand during recorded history. Thus, hazard scenarios are based on the assumption of rapid magma ascent from the mantle and a short period of precursor phenomena, perhaps lasting days to weeks (for example Auckland Volcanic field models).

However, one style of magmatism and volcanism may not apply to all volcano fields. As highlighted by our studies, periods of temporary magma arrest and crystallisation at rheology barriers in the crust could prolong the interval of eruption precursor activity, and thus, increase the potential for detectable seismic or degassing events. Future magma eruptions and failed eruptions (intrusions) at the Kaikohe-Bay of Islands volcanic field could be associated with seismicity at 10-19 km and ~28 km where the major rheology contrasts occur. The likelihood of intrusion unaccompanied by eruption may also be greater in such magmatic systems.

Future work

Magma ascent histories may differ greatly beneath fields of monogenetic volcanoes. Thus, crystal histories and melt equilibria should be investigated at other fields such as Auckland volcanic field and South Auckland volcanic field. This would contribute to up-dating hazard scenarios.

Acknowledgements

This work was funded by Earthquake Commission Post-Graduate Research Programme Grant 16/U733. Valuable assistance with the electron probe was provided by Ian Schipper at Victoria University of Wellington. Ian Smith kindly provided some whole-rock analyses. Claudine Stirling, Malcolm Reid and Michael Palin at University of Otago assisted with isotope data acquisition and reduction.

Outputs and Dissemination -

Results from this project were presented at the International Association of volcanology & chemistry of Earth's interior Scientific Assembly, Portland, Oregon August 2017.
Abstract: Coote A, Shane P, Stirling C, Reid M (2017). Origin of of plagioclase phenocrysts and crystal cargos in small volume intraplate basalt magmas. International Association of volcanology & chemistry of Earth's interior Scientific Assembly, Portland, Oregon August 2017, ME43C-038.

Results were published in a peer-reviewed science journal:
Coote, A., Shane, P., Stirling, C., Reid, M. 2018. The origin of plagioclase phenocrysts in basalts from continental monogenetic volcanoes of the Kaikohe-Bay of Islands field, New Zealand: implications for magmatic assembly and ascent. Contributions to Mineralogy and Petrology (2018) 173, https://doi.org/10.1007/s00410-018-1440-y

Links to publications/theses

Coote, A., Shane, P., Stirling, C., Reid, M. 2018. The origin of plagioclase phenocrysts in basalts from continental monogenetic volcanoes of the Kaikohe-Bay of Islands field, New Zealand: implications for magmatic assembly and ascent. Contributions to Mineralogy and Petrology (2018) 173, https://doi.org/10.1007/s00410-018-1440-y

List of key end users

DeVORA and Auckland Council
GNS Science
Far North Regional Council