Final Report

Earthquake Commission University Post-Graduate Research Programme

Reconstructing Rangitoto volcano from a 150-m-deep drill core (project 14/U684)

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Technical abstract

A 150-m-deep hole was drilled through the upper western flank of Rangitoto volcano, Auckland, in February 2014. The core comprises about 128 m of lavas from the main shield-building phase overlying marine sediments with intercalated lava and pyroclastics. All of the volcanic deposits in the drill core classify as transitional basalts, and display a relatively narrow range in major element composition (SiO_2 ~48-49 wt % and Mg# ~0.60 to 0.64). The rocks comprise at least four chemical affinities which relate to stratigraphic sequence. Variations in incompatible trace elements and uniformity of radiogenic isotope compositions are best explained by the magmas representing discrete batches reflecting different degrees of partial melting in the mantle. The uniformity in isotopic composition and lack of crustal signal indicates all magmas shared a common source region and experienced minimal crustal contamination during ascent or storage. An important implication is that magma ascent was sufficiently rapid to preclude assimilation of country rock. Thus, potential future eruptions could display limited precursor activity.

Organic materials dated by the ^{14}C method produce a coherent stratigraphic sequence from ~7,400 years at 139.38 m to 3,800 years at 128 m depths. However, ages of ~1,000 years at 135.39 m and 1,500 years at 133.11 m are stratigraphically inverted, and discordant with ages above and below. This is likely to reflect fluidized extrusion of pyroclastics into the core barrel. Ages of ~5,900 and 6,800 years bracket the oldest lava flow at 137 m depth, thus providing an age for the earliest volcanism. Traditionally it was thought that Rangitoto volcano had formed in one or two brief episodes about 550 years ago, based on ages associated with ash layers on Motutapu Island. However, ages from the drill core suggests the ash layers are a late phase of activity that post-date most of the volcano’s construction. This is further supported by the lack of alkalic rock compositions in the drill core that would match the North Scoria Cone at the summit of the volcano. Thus, implying pyroclastic activity post-dating main edifice construction. The prolonged and perhaps episodic activity is consistent with the studies of microscopic ash from Rangitoto preserved in sediments at Lake Pupuke. Future modeling should consider the possibility of repeat eruptions from volcanic centers in the Auckland Volcanic Field and prolonged activity. The socio-economic impact would differ from that resulting from short-lived phenomena

Laypersons abstract

Investigation of a 150-m-deep core drilled into Rangitoto volcano, Auckland, reveals a volcanic history extending farther back in time than previously known. The oldest lava flow has been dated by radiocarbon ages on wood and shell from enclosing estuarine sediments at about 6000 years old. Most of Rangitoto is made of a pile of lava flows and these post-date 3800 years ago. Traditionally it was thought that Rangitoto volcano had formed in one or two brief episodes about 550 years ago. However, the rocks in the drill core suggests this was a late phase of activity that post-dates most of the volcano’s construction. The prolonged and perhaps episodic activity is consistent with the studies of microscopic ash from Rangitoto preserved in sediments at Lake Pupuke. The composition of magma erupted from Rangitoto has changed with time due to processes of melting in the mantle. However, there no evidence of interaction between the rising magmas and Earth’s crust. This implies the magmas ascend fast and there would be limited warning times in any future eruptions. The prolonged life of Rangitoto means that future eruptions could potentially occur at Rangitoto, in addition to other sites around Auckland.

Preamble

This investigation focused on using rock core recovered from a deep drill hole through the edifice of Rangitoto volcano, in the Auckland Volcanic Field, New Zealand, to determination of magmatic evolution of the volcano and inprove its chronology. The main objectives of this work were:

Objective 1. Determine the characteristics of magma ascent and storage. Magma formation and transport history can be modelled from geochemical data.

Objective 2. Determine the longevity and frequency of past eruptions at Rangitoto.

Details of the drilling and the lithological aspects of the core, along with the overview of the entire project will be presented in the final report of EQC biennial grant 14/U676. This report summarizes the laboratory analytical work funded by grant 14/U638.

Background

Rangitoto Island is the youngest volcano in the Auckland region, having erupted as recently as about 550 yrs ago. The volcano represents about half the known magma erupted in the region over the last 250,000 yrs. Auckland city is New Zealand's largest city, and local volcanic eruptions would have a nation-wide economic impact. Our recent volcanic ash studies have shown that the volcano erupted intermittently, starting about 1500 yrs ago, and lasted for a duration of about 1000 yrs (Shane et al., 2013). Previously, it was thought that these types of small basaltic volcanoes are short-lived (months to a few years) and erupt only once or twice. It is difficult to assess the history of the volcano because of the lack of deep erosional dissection and hence rock outcrops on the island. Thus, we investigated the history of Rangitoto by drilling a deep (150 m) well into the flank of the volcano to obtain a continuous core of deposits. From lithological studies of the core, we hoped to determine the styles of volcanism recorded, such as effusive lava events versus explosive scoria fall and pyroclastic flow events. The lithological continuity of the deposits (presence or absence of hiatuses, such as erosion surfaces and fossil soils) will provide insight to the magnitude and frequency of individual eruption events within the larger episode of activity. We hope to delineate cone-building stages from lava field stages in the volcano's history. The core also allowed us to thoroughly investigate the volcano's magmatic evolution via geochemistry and petrography of the deposits. This provided insight to whether different magma batches were involved in prolonging the eruption episode or making it intermittent. We also investigated the core for material that can be used in radiometric dating. Hence, we hope to gain a greatly improved assessment of future eruption scenarios and associated hazards. This will allow hazard and risk end-users to significantly improve models of future activity.

A 150-m-deep hole was drilled through the upper western flank of the edifice (Fig. 1) in February 2014, which provided excellent core recovery (>95%). The core comprises about 128 m of lavas from the main shield-building phase overlying marine sediments with intercalated lava and pyroclastics. Miocene sediments were encountered at ~150 m. The early phase of the eruptions were represented by a thin lava flow and pyroclastic lapilli. These are interbedded with fossiliferous muds that were the target for ^{14}C dating. In the laboratory each lava flow unit was sampled and the rocks (n=70) were analysed to obtain a record of geochemistry for the volcano.

Major element analysis of the rocks were determined using a PANalytical Axios 1 kW wavelength dispersive XRF spectrometer with an Rh tube at the University of Auckland. Trace and rare earth elements were analysed using the quadropole LA-ICP-MS at the Australian National University, Canberra, which included an Excimer LPX120 and an Agilent 7500CS spectrometer. Radiogenic isotopes were analysed at the School of Earth Science, Geology and Meteorology at the University of Melbourne under the supervision of Dr. Roland Maas. Radiocarbon analyses were carried out by the Rafter Radiocarbon Laboratory at the National Isotope Centre, GNS Science. Full datasets and technical methods are available from the authors.

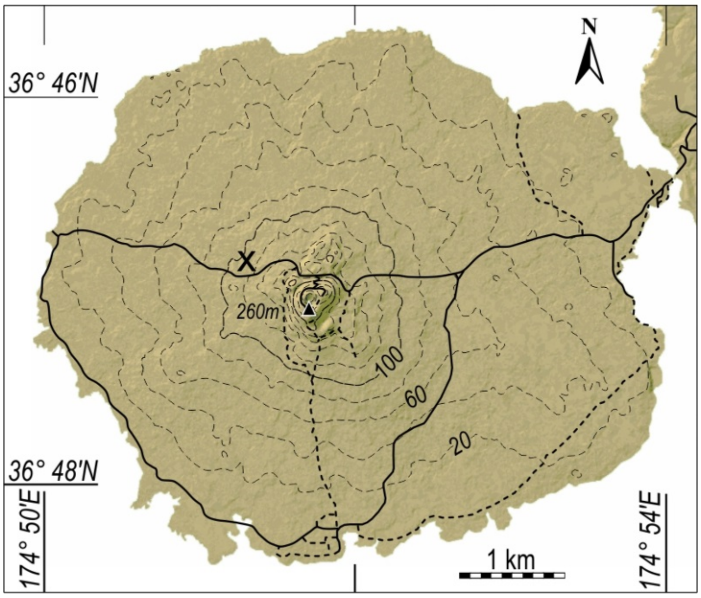

Figure 1. Map of Rangitoto Island showing the location of the drill site (marked by X).

Geochemistry of lava flows and pyroclastic deposits

All of the volcanic deposits in the drill core classify as transitional basalts, and display a relatively narrow range in major element composition (Fig. 2). Compositions are in the range SiO_2 ~48-49 wt % and Mg# (Mg/Mg+Fe) ~0.60 to 0.64. However, within these ranges, compositional groups are evident on binary variation diagram (Fig. 2), and these discrete groups are related to stratigraphic depth. The youngest flows (0-25 m depth) are particularly distinguishable by their lower Mg# values, as are the lowermost lavas (95-137 m depth) that are characterized by lower SiO_2 and higher Mg# (Fig. 2). This lower group includes pyroclastic deposits at 128-135 m and the isolated oldest flow at ~137 m. Lavas in the intervening depths can be broadly divided into compositional groups at 26-67 m and another at 69-93 m depth. These latter two groups are somewhat more variable in composition.

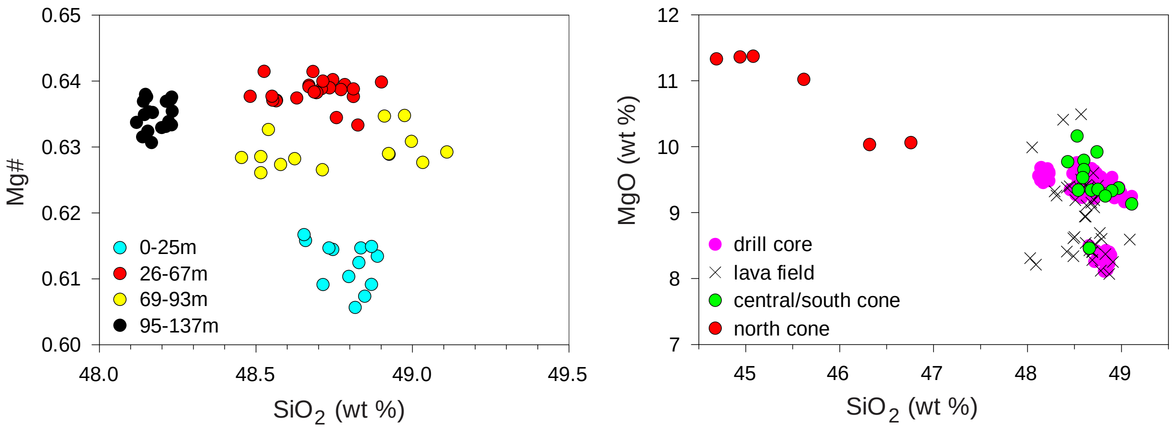

Fig. 2. Major element composition of lavas in the Rangitoto drill core showing groupings that related to stratigraphic depth (left). Comparison to surface lava and scoria on Rangitoto (right).

The basalts display enriched light rare earth element (LREE) chondrite-normalized patterns similar to late Cenozoic intra-plate basalts in northern New Zealand (e.g., Huang et al., 1997; Cook et al., 2005) (Fig. 3). Relative enrichment in high field strength elements (HFSE) Th, U, Pb, Nb and Ta on primitive mantle-normalized multi-element plots and lack of negative Nb and Ta anomalies (Fig. 3), are consistent with an intra-plate mantle source that lacked slab-derived fluids.

Trace element compositions reflect the compositional groups revealed in the major element compositions. In addition, some trace elements (e.g., Sr, Nb) define distinct temporal trends of depletion and enrichment (Fig. 4). This particularly evident in the core interval 26-93 m, characterized by upward trends of depletion in incompatible element abundance. There is little change in Mg# in this interval, other than a slight enrichment near the top of the sequence.

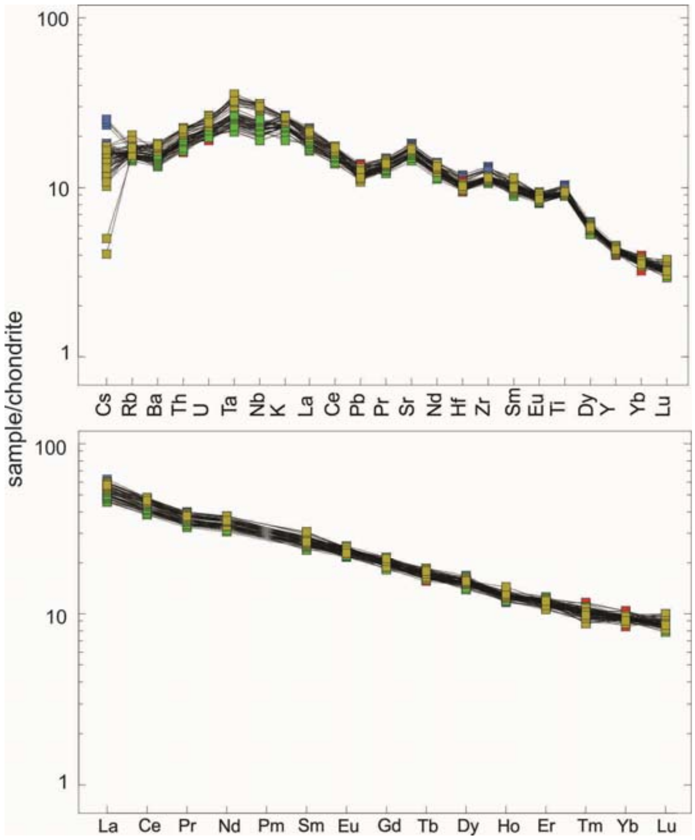

Fig. 3. Trace element composition of basalts in the Rangitoto core. Trace element compositions normalized to primitive mantle (top), and rare earth elements normalized to chondites (bottom). Normalized compositions are from Sun and McDonough (1989).

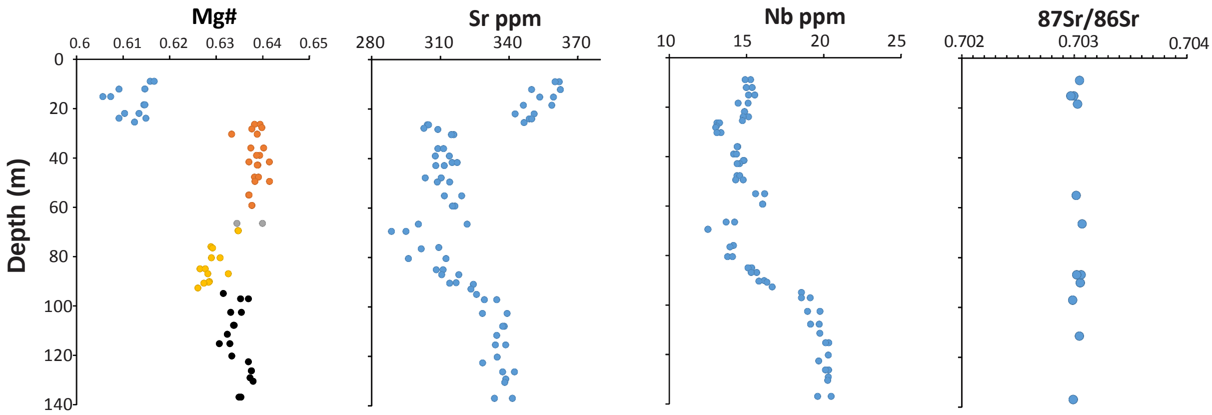

Fig. 4. Selected trace element and isotopic composition of basalts in the Rangitoto core plotted against stratigraphic depth.

Eleven samples representing the range of stratigraphic depths were selected from the core for radiogenic isotope analysis of 87Sr/86Sr (Fig. 4), 143Nd/144Nd, 206/204Pb, 207/204Pb, and 208/204Pb ratios to investigate potential variation in source and crustal contamination during ascent. As a reference frame for crustal compositions, we selected 3 xenoliths (country rock) from the neighboring St Heliers volcano that included schistose lithologies of a mafic protolith, and one sample of greywacke from Motutapu Island. The lava flows represent one uniform compositional group with variation within analytical uncertainty (Fig. 4, 5). The isotopic compositions are similar to those previously reported by McGee et al. (2013) for surface lavas on Rangitoto. The uniformity in isotopic composition indicates all magmas shared a common source region in the mantle. In addition, the lava flows lack elevated radiogenic signals indicating minimal crustal contaminated by the lithosphere during ascent or storage. Such contamination would drive the Sr ratio to higher values and Nd ratio to lower values, similar to those shown by the reference greywacke sample analysed. An important implication of this data is that magma ascent was sufficiently rapid to preclude assimilation of country rock. Thus, potential future eruptions could display limited precursor activity. Thus, compositional variations in the lavas represent modification processes such as various degrees of melting at the source and fractional crystallization in conduit.

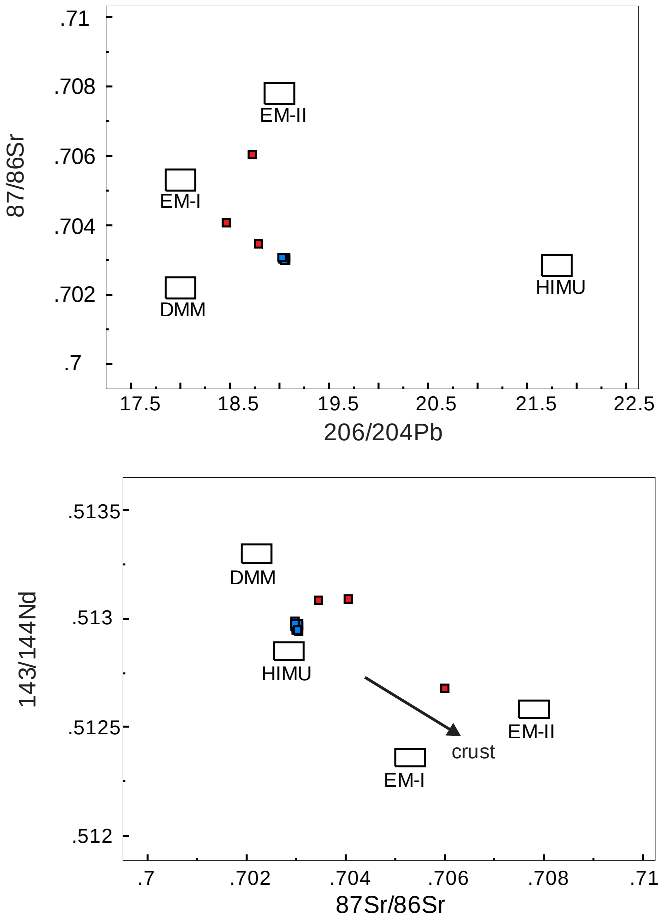

Fig. 5 Plot of radiogenic isotope ratios for lavas in the Rangitoto core (blue squares) and three xenoliths (red squares) selected to represent crustal components. The Rangitoto lavas are compositionally uniform and distinct from xenolith samples. The lava do not display compositional affinities with the crust. DMM etc represent mantle compositional end-members recognized globally.

The lavas in the core are compositional similar to those exposed at the surface of Rangitoto, collected from various sectors around the volcano (Fig. 6) (Needham et al., 2011). The core sequence is similar to the lava field and the Central and Southern Scoria cones. The North Scoria Cone is compositional distinct being characterized by more primitive compositions (lower SiO2 and higher MgO). Thus, the core sequence captures much of the eruptive sequence, but not that associated with North Cone. Surface lavas can be broadly matched to the stratigraphic compositional groups in the core. Surface lavas that compositionally match core lava at depths of 26-138 m are mostly found in the eastern sectors of the island (Fig. 6), while the youngest lava group in the core (0-25 m depth) dominate the distal flank locations on the western half of the island (Fig. 6). This suggests the final episode of lava outpouring was mostly west directed.

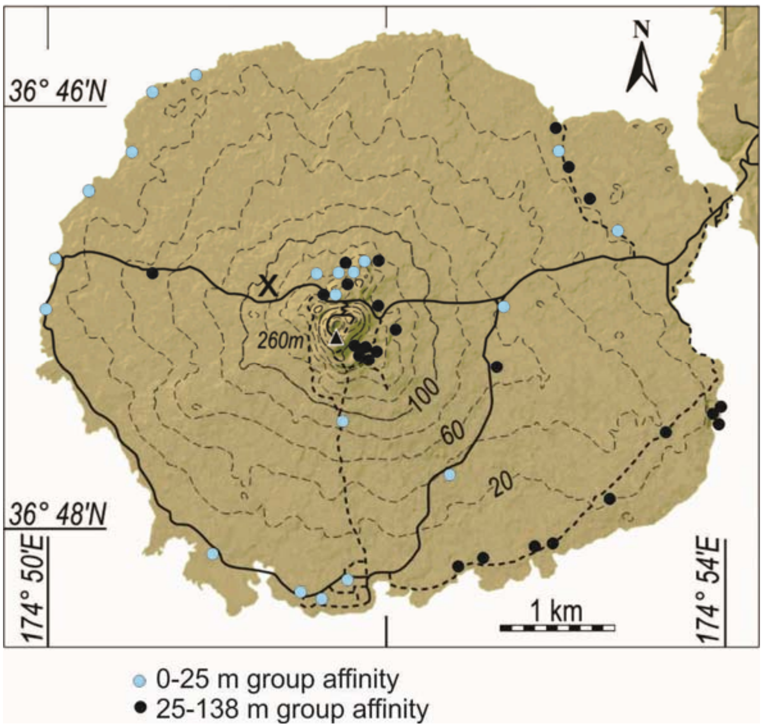

Fig. 6. Map of Rangitoto showing the location of surface samples analysed by Needham et al. (2011), and classified as chemically matching either young lava flows in the drill core (0-25 m) or older flows (26-138 m).

Chronology

Nine samples of organic material were selected for dating via the ^{14}C AMS technique (Fig. 7; Table 1). The study was restricted to the core interval 128-139 m because that part of the core contained organic material. No organic material was observed in the overlying 128 m of lava flows, while sediments beneath about 139 m are very old (Miocene Waitemata Group) and thus would not constrain the age of the volcano. The organic materials were contained within estuarine mud. Six ages were obtained from Mollusca fragments (each sample is a single fragment), one sample was wood and two were obtained from complete gastropod shells. Ages discussed here are converted to calibrated years before AD1950.

Table 1. Accelerator mass spectrometry results for shell material Rangitoto core. Calibration via OxCal 4.2 online, using SHCal13. Note the cal ages are +/- 2 sigma

Sample ID	Core depth (m)	Age ID NZA	Radiocarbon age (yrs BP)	error (yrs)	d13C (‰)	error	Calibrated age (yrs BP)	error (yrs)
R1-009	128	57098	3875	23	-1.59	0.2	3811	72
R1-009b	128.10	58368	3962	23	1.7	0.2	3933	72
R1-063	133.11	57100	2010	20	-0.22	0.2	1551	64
R1-064	135.39	57101	1429	20	1.18	0.2	960	54
R1-068	136.5	57103	5591	25	2.37	0.2	5968	64
R1-068b(w)	136.5	58337	5190	19	-27.0	0.2	5896	55
R1-067b	137.26	58367	6401	26	0.7	0.2	6852	67
R1-067	137.84	57102	6411	27	0.72	0.2	6864	69
R1-035	139.38	57099	6927	28	2.56	0.2	7416	51

Each sample is a Mollusca shell fragment, except R1-068b (wood); and R1-009b and 067b (single gastropod)

With the exception of two ages (at depths 133.11 and 135.39 m), the dated materials produce a coherent stratigraphic sequence from ~7,400 years at 139.38 m to 3,800 years at 128 m (Fig. 7). Close sampling for duplicate age determinations produced concordant ages. Concordant ages included shell fragments versus whole gastropods, and shell fragments versus wood, at various depths. However, ages of ~1,000 years at 135.39 m and 1,500 years at 133.11 m are stratigraphically inverted, and discordant with ages above and below (Fig. 7). The cause of this anomaly is uncertain. However, the mud from which these ages were determined are contained in the pyroclastic deposits which presented considerable drilling difficulties in recovery. Fluidized extrusion of pyroclastics into the core barrel occurred several times preventing depth penetration, and requiring frequent flushing of the core. This could have resulted in disruption of the stratigraphic sequence. Although, it is difficult to explain the older ages of~3,800 years (at 128 m) above the pyroclastic deposits and immediately below the main lava sequence by coring disruption (Fig. 7). It is also possible that the thin mud layers in the pyroclastic sequence and immediately above it are not in situ, and were excavated and emplaced by the pyroclastic eruption. In that case, the age of the pyroclastic deposits would not be older that the youngest age determined (~1 ka). Beneath the pyroclastic sequence, the ^{14}C ages are in stratigraphic sequence, and there is no lithological indication of disruption. Ages of ~5,900 and 6,800 years bracket the oldest lava flow at 137 m depth, thus providing an age for the earliest volcanism recorded in the core. Miocene Waitemata sediments occur a short distance beneath the sequence, and thus older volcanic units do not occur at the drill location.

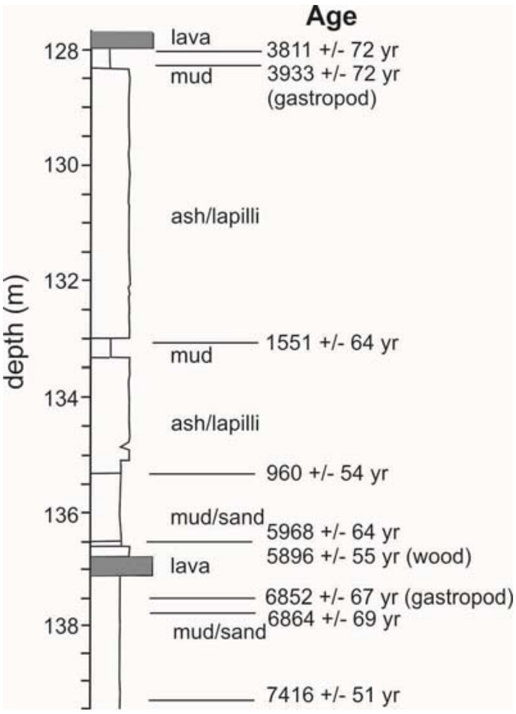

Fig. 7. Stratigraphic log of the lower part of the Rangitoto core showing the location and ages of organic material dated by radiocarbon. Ages are on shell fragments except where indicated.

Discussion

Interferences from basalt geochemistry

1. Lava flows in the drill core can be grouped into at least four chemical affinities which relate to stratigraphic sequence (Fig. 2). Variations in incompatible elements and uniformity

of isotopic compositions are best explained by the magmas representing discrete batches reflecting different degrees of partial melting of a common source.
2. The compositional affinities can be somewhat correlated to lava flow samples from the surface of Rangitoto. On this basis, the youngest lava flows in the core are widely dispersed to the western half of the island, while older lava flows dominate the eastern half. The drill core thus provides the potential to add a temporal dimension to volcano construction.
3. The uniformity in isotopic composition indicates all magmas shared a common source region in the mantle. In addition, the lava flows lack elevated radiogenic signals indicating minimal crustal contamination by the lithosphere during ascent or storage. An important implication is that magma ascent was sufficiently rapid to preclude assimilation of country rock. Thus, potential future eruptions could display limited precursor activity.

Chronology of Rangitoto volcano

The timing and duration of activity at Rangitoto volcano have been extensively reviewed (Nichol, 1992; Lowe et al., 2000; Lindsay et al., 2011; Shane et al., 2013). A limited paleomagnetic investigation of lava flows (Robertson, 1986) revealed some scatter in the demagnetized remnant directions, but much of the data is within wide error limits preventing conclusive interpretation of eruption duration. The commonly cited radiocarbon ages for Rangitoto volcano (around 550–500 cal yrs BP) are from organic material associated with tephra layers on the neighboring Motutapu Island. This episode of tephra dispersal is what previous workers equate to the construction of the volcano in one relatively short episode. Hence, the Rangitoto was considered monogenetic, produced in the brief episode and not likely to erupt again. However, some of ages associated with tephra on Motutapu Island do not conform to their stratigraphic order (Shane et al., 2013), raising uncertainty over their accuracy. The only radiocarbon determinations associated with lava flows on Rangitoto Island produced widely disparate ages of 214 ± 129 cal yrs BP for wood beneath a lava flow and 1161 ± 72 cal yrs BP for marine shells in mud baked by a (different) lava flow. These were dismissed by Nichol (1992) as representing young tree roots penetrating the lavas, and relict shells pre-dating the eruption, respectively. However, the ~1,100 year age on shells is in the range of ages on shell material and wood obtained the basal sequence of the Rangitoto core (Fig. 7). Thus, the ages on shell can be interpreted as constraining volcanism that commenced prior to the deposition of tephra layers on Motutapu Island. In particular, several ages in stratigraphic sequence bracketing the oldest lava flow in the core indicate an age of about 6,000 years (Fig. 7) for the commencement of volcanism. Such older ages are consistent with an investigation of microscopic glass shards preserved in lake sediments of Lake Pupuke, west of Rangitoto Island. Shane et al. (2013) found microscopic basaltic ash layers, chemically similar to Rangitoto deposits, extending back to 1498 ± 140 cal yrs BP, and suggested an extended life-span for the volcano of at least 1000 years.

There are two macroscopic basalt tephra layers in Lake Pupuke sediments that post-date the Kaharoa eruption of 636 ± 12 cal yrs BP (Shane et al., 2013). The composition of the upper macroscopic layer matches that of Central and South scoria cones on Rangitoto. This supports the concept that summit cones on Rangitoto volcano represent a late-stage eruptive episode. In contrast, the lower macroscopic tephra in Lake Pupuke and ash layers on Motutapu Island do not chemically match any of the scoria cones on Rangitoto volcano (Shane et al., 2013). This indicates that the volcanic landforms do not record the entire pyroclastic history of the volcano. The more alkalic North Scoria Cone has no compositional match to either glass in the ash deposits (Shane et al., 2013) or whole rock compositions of lavas in the Rangitoto core (this study). This further points to a multi-stage history of the volcano, rather than the previously proposed short-lived construction.

Implications of Rangitoto volcano's longevity

The new perspective that volcanism at Rangitoto may have started as early as 6,000 years ago, and continued intermittently until about 500 years ago shows it is not a monogenetic volcano, and future eruptions in the Auckland volcanic field (AVF) could conceivably occur on the volcano. On the broader scale, the prolonged longevity of Rangitoto supports the concept of changing volcanic style and tempo in the AVF over short durations (10^3–10^4 year). Previous studies suggest that multiple, small volcanic centers were contemporaneously active across the field at around 30,000 years ago (Cassidy, 2006; Cassata et al., 2008; Molloy et al., 2009). In contrast, there have been few eruptions in the more recent history of the field. Well-constrained evidence for activity in the interval 10,000 to 20,000 years ago interval is scarce (Molloy et al., 2009; Lindsay et al., 2011), and a scoria cone and tuff-ring complex were produced at ~10 ka (Mt Wellington center, Shane and Zawalna-Geer, 2011). Thus, the relatively voluminous Rangitoto volcano, perhaps representing over 1000-6000 years of activity, reflects a dramatic regime change to central vent volcanism or a focusing of activity location in the field. This has significant implications for AVF hazard/risk models that have focused on a short-lived eruption (~1 year) from a site that has not experienced recent volcanism. Future modeling should consider the possibility of repeat eruptions from volcanic centers and prolonged activity. The socio-economic impact would differ from that resulting from short-lived phenomena.

Future research recommendations

1. A study of the paleomagnetic inclination and intensity recorded in the lava flows of the Rangitoto core would provide insight to the duration of flow emplacement. This would clarify whether activity has been intermittent. We are current collaborating on such an investigation.

2. An additional deep drill core on the eastern flanks would allow a more complete reconstruction of the volcano history.

Acknowledgements

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