Article

Shining a light on Auckland's volcanic monster under the bed

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If you asked a person to draw a volcano, generally they would draw a triangle shape, not unlike Mt Taranaki, with either steam coming out of the top, or lava flowing down the sides. What they would not draw is lots of little apparent hills and lakes, but this is what Auckland's volcanoes are like. The Auckland volcanic field (AVF) is made up of lots of individual volcanoes that generally only erupt once, and are hence called 'monogenetic'. Globally, monogenetic volcanic fields are poorly understood, and whilst these little single eruptions may seem less threatening to human life than a large imposing volcano like Mt Ruapehu or Mt Taranaki, the frightening thing is that the location of the next eruption is completely unknown. When you couple this unknown with a large urban population and nationally dependent infrastructure, the potential threat to humans of a future eruption dramatically increases. In order to reduce the unknowns, reconstructing the past eruptive history of the entire field can allow patterns or trends in eruptions to be uncovered, and allow better-informed predictions about a future eruption to be made.

Background

Monogenetic volcanic fields exist globally, exhibiting a range of characteristics. Individual eruptions are relatively small scale (usually 0.0001 to 4 km^3; Guilbaud *et al*. 2012), leading to eruptions that may only last from a few days to months (Connor & Conway 2000). As a result of this, the magma ascent pathways do not remain a favoured route for continued activity, and subsequent eruptions occur in isolation from the previous vent site. Volcanic fields generally contain 10–100 vent sites (Connor & Conway 2000), with the current count in the AVF at 53 centres covering an area of 360 km^2 (Hayward *et al*. 2011; Fig 1). However, some fields can be considerably larger, for example the Michoacán-Guanajuato field in Mexico, contains evidence for over 1000 eruptions and covers >40,000 km^2 (Connor 1990). In comparison to other volcanic systems, monogenetic eruptions have a very low magmatic output, but cumulatively a field's total eruptive products can be comparable to polygenetic systems (Németh 2010). The lifespan and productivity of volcanic fields is also highly variable. For example, the 53 centres of the AVF have erupted over the last c. 200,000 years. In comparison, Cima volcanic field, California, has approximately 70 centres formed over the last 4.5 million years (Dohrenwend *et al*. 1986). Eruptive activity is, however, rarely constant, with periods of heightened activity and periods of quiescence, commonly identified where full field studies have been undertaken (e.g. Leonard, G. pers. comm.).

Most commonly monogenetic fields are found within intraplate settings (away from plate boundaries) with basaltic products, like the AVF (Valentine & Gregg 2008). However, fields are found linked to subduction-related upwelling (e.g. Ortega-Gutiérrez *et al*. 2014) to plume-like rifting environments (e.g. Shaw 2004), with siliceous andesitic to rhyolitic complexes identified (Tanaka *et al*. 1986). Despite variability in the geological settings, there appears to be a common relationship between the local structural environment and the orientation of monogenetic centres. For example, individual centres can be located along known fault lines (e.g. Springerville Volcanic field, Arizona; Condit & Connor 1969), or can migrate relative to plate movements (e.g. San Francisco Volcanic field, Arizona; Tanaka *et al*. 1986). Another commonality at the global scale is the eruptive products that form as a result of the interaction between the upwelling magma and local water (ground or surface). If there is interaction with water, the eruption will be explosive (phreatomagmatic), likely leading to pyroclastic density surges (e.g. Brand *et al*. 2014), ash fall (e.g. Hopkins *et al*. 2015), and the production of a maar-diatreme crater and tuff ring (e.g. Fig 2A). In comparison, if the ascending magma does not encounter water, a dry eruption will ensue, comprising fire fountaining and the production of a scoria cone and lava flows (e.g. Fig 2B-C; Hayward *et al*. 2011). In the AVF, individual centres generally show evidence of a progression from explosive wet eruptions to effusive dry eruptions, as any surface water is used up before cone building ensues.

The AVF is not unusual in its location close to a high-density urban population (e.g. Michoacán-Guanajuato in Mexico City; or Harrat Rahat, Al-Madinah in Saudi Arabia), and therefore more recent studies have begun to focus on the hazard and risk implications of a future eruption scenario. Unlike with a polygenetic cone, where the source vent of the next eruption is obvious, monogenetic eruptions are much harder to predict because of the unknown location of a future vent. Investigations have therefore focussed on reconstructing the eruption history of

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Jenni Hopkins is a Postdoctoral Researcher currently working in collaboration with GNS Science, the DEVORA project, and Victoria University of Wellington. Originally from England, Jenni came to Wellington after completing an MSc in geochemistry to undertake a PhD in geochemical volcanology in 2011. Her thesis focused on reconstructing the evolution of the Auckland Volcanic Field through developing new geochemical correlation techniques in tephrochronology. Her current research is focussed on further developing geochemical and radiometric dating techniques on New Zealand ash deposits, with application to hazard and risk management strategies in the event of future eruption scenarios.

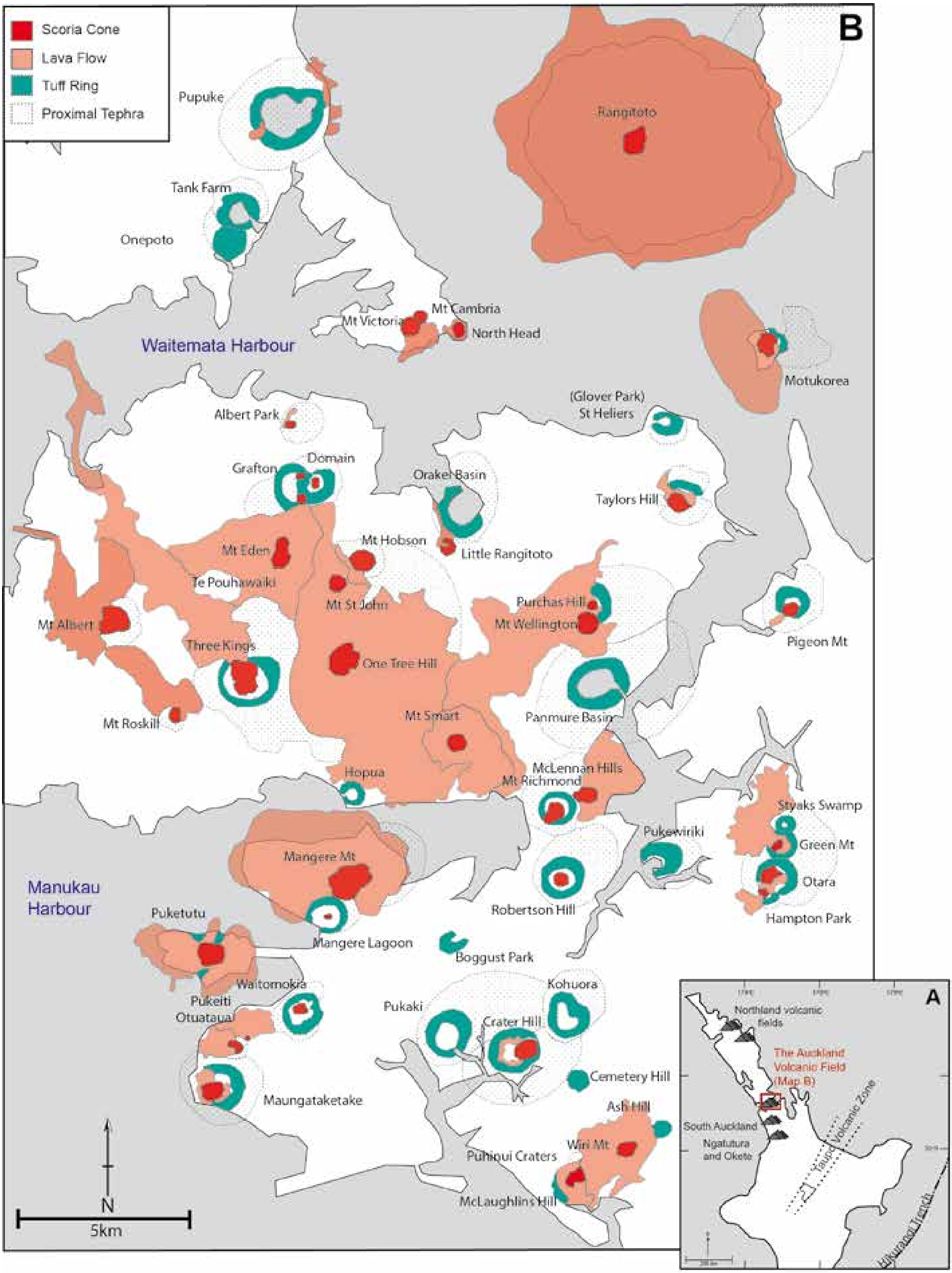

Figure 1. A. Location of the AVF, New Zealand; included are other monogenetic volcanic fields also found on the North Island.
B. Location of the centres of the AVF, and their key physical characteristics.

Figure 2. Examples of the differing volcanic landforms seen in the AVF: (A) The maar crater and tuff ring of Orakei Basin created through explosive wet eruptions; (B) the scoria cone of Mt Eden created through dry eruptions; and (C) Motukorea Island which shows both tuff ring, scoria cone, and some minor lava flows. Pictures taken from Hayward *et al.* (2011) accredited to Alastair Jameson.

monogenetic fields in order to find patterns in vent distribution, recurrence rates and geochemical signatures. For Auckland, the DEVORA project (Determining Volcanic Risk in Auckland) was set up in 2008 to do just this, and as a result the AVF is now one of the best studied volcanic fields globally.

AVF specifics

AVF is actually the youngest in a series of intraplate volcanic fields that run along the west coast of the North Island, New Zealand (Fig. 1A). Okete is the southernmost and oldest field (2.69–1.8 Ma; Briggs *et al.* 1994), followed by Ngatutura (1.83–1.54 Ma; Briggs et al. 1994), South Auckland volcanic field (SAVF) (1.59-0.51 Ma; Cook et al. 2004), and finally Auckland volcanic field (Fig 1). Based on the characteristics of the AVF compared with the South Auckland VF, which has approximately 98 centres erupted over about 1 million years (Cook *et al*. 2004), some authors have suggested that the AVF is still in its eruptive infancy (e.g. Hayward *et al*. 2011).

Current data suggest the total output from the field is about 1.7 km^3, just under half of which is linked to the eruption(s) of Rangitoto (Kereszturi *et al*. 2013). These volumes are relatively small when compared to cumulative eruptive volumes of some of the other volcanoes in New Zealand (e.g. Ruapehu ~ 110 km^3, Gamble *et al*. 2003; or the largest eruption from Taupo, the Oruanui, ~ 1170 km^3, Wilson 2001). In the AVF the erupted volumes have recently been linked back to the original mantle source characteristics (McGee *et al*. 2013). These characteristics can be understood using the geochemistry of the erupted products. Recent work by Lucy McGee and co-authors highlighted that many of the centres showed slightly differing geochemical signatures, especially within their trace element compositions. They concluded that the variations observed in the eruptive products were reflective of the mixing of three different mantle sources, each with differing geochemical signatures, and, as a result it was suggested that each centre had the potential to have a unique geochemical signature, with varying magma volumes. A connection was therefore made between mantle source, the size of the magma body formed, and the eruption style at the surface.

Morphostratigraphic constraints (for example, where ash or lava from one eruption is found overlapping another) allow the relative ordering of some volcanoes to be determined, but these relationships are not prevalent across the field, and a full field order cannot be reconstructed in this manner. Radiometric techniques have been used with varying success in the AVF. In 2011, a review of the ages of each individual eruption concluded that of the 53 centres, only three (Rangitoto, Mt Wellington, and Three Kings) were 'reliably and accurately dated', with a further eight 'reasonably reliably dated' (Lindsay *et al*. 2011). This lack of understanding of the eruption order and repose periods (time between eruptions) significantly reduces our ability to forecast future eruptions. A recent study combines improved methodologies in $^{40}Ar/^{39}Ar$ techniques in order to report new ages for an additional 23 centres (Leonard, G. pers. comm.). However, uncertainties associated with these radiometric techniques (e.g. $^{40}Ar/^{39}Ar$ analysis) make them unable to resolve the small repose periods for the eruptions of the AVF (Fig 3). For example, where multiple eruptions have overlapping ages, neither their relative nor their absolute eruption order can be identified.

Tephrochronology and its applications

Tephrochronology is a stratigraphic method that uses tephra deposits to synchronise, date and link geological events, for example individual volcanic eruptions (Lowe 2011). The term 'tephra' relates to all unconsolidated, explosively erupted material of all grain sizes, whereas 'ash' refers to a size fraction of this material <2 mm in diameter.

The maar craters that form from phreatomagmatic eruptions (e.g. Fig 2A) not only preserve the eruption and provide evidence of the centre itself, but also provide a depositional environment for tephra deposits from the surrounding successive eruptions. In addition, because the deposits are layered within the lake sediments they provide a mostly well-preserved relative order of eruptive events.

The basaltic tephras are punctuated with well-correlated and dated rhyolitic tephras from eruptions in the central North Island, e.g. from Taupo. These rhyolitic deposits give absolute age constraints to the ages of the intervening basaltic deposit (e.g. Molloy *et al*. 2009). The rhyolitic ages also allow sedimentation rate estimates to be calculated. These sedimentation rates can then be used to assign approximate ages to the basaltic tephra deposits themselves.

Prior to our work, the basaltic tephra deposits from the AVF had not been used to their full potential, their sources were unknown, and therefore their usefulness in reconstructing the eruptive history of the field's centres was limited. The aim of our work was therefore to develop a method to link the proximal tephra deposits found within the maars back to their source centres. This would allow the relative and absolute ages for the AVF eruptions to be resolved.

In order to collect the tephra samples from within the maar lakes, long sediment cores were retrieved (typically between 30 and 80 m long). In many cases these cores drill down to where the lacustrine sediments end and where dense volcanic deposits are found, indicating the volcanic crater itself has been reached. From the length of the core, we could therefore estimate the age of the centre, as well as the tephra horizons preserved within it. Our improved methodology began at the initial analysis of the cores themselves.

Dark coloured basaltic tephra deposits, especially when they are particularly fine-grained, are very difficult to identify through visual observation alone. We therefore exploited their geochemical properties in order to make their identification much easier. Products of basaltic eruptions will generally have a higher proportion of magnetic minerals (e.g. Mg, Fe) and be slightly denser, in comparison to the lake sediments. Therefore, if the magnetic susceptibility of the core is measured, the basaltic horizons will general show a spike in the readings, and in addition, an X-ray density scan of the core will reveal the basaltic tephra horizons as much lighter in colour on an X-ray (e.g. Fig 4; Hopkins *et al*. 2015). This method of core analysis highlighted even the thinnest of basaltic horizons, and in addition allowed us to identify areas of reworked tephra within the core, allowing just the primary deposits to be taken into account for our reconstructions.

Geochemical analysis of the tephra horizons showed that each one had a relatively distinct signature and could therefore be geochemically fingerprinted. This allowed our team to accurately correlate the tephra deposits across 6 different cores (from north to south in Fig. 1: Pupuke, Onepoto, Glover Park, Orakei, Hopua, and Pukaki centres), covering an estimated age range from the present to approximately 200,000 years ago. Once the tephra horizon chronology was developed, the next challenge was to work out how to accurately correlate these tephra deposits to their source centres.

In traditional tephrochronology, the geochemistry of the distal tephra deposits (far from source) are linked to their proximal (near source) counterparts. However, in Auckland there are minimal proximal tephra deposits and often lots of potential source centres. As a result, linking even proximal tephra deposits to their source is difficult, and therefore linking distal to proximal tephra to find the origin of the distal tephra is practically impossible. We therefore developed a new method to correlate the distal tephra to the proximal whole rock deposits (e.g. lava or scoria), because proximal whole rock deposits are much more easily linked to their source, and are a lot more common in the AVF. This method exploited the geochemical variance in the deposits of the AVF but also used age, locational, and volumetric constraints to allow the tephra horizons to be accurately correlated. Of the 29 tephra horizons found within the AVF cores, 26 were correlated to a source centre. The outcome of these correlations not only allowed the relative eruption history of 48 of the 53 centres to be put in order, but also allowed the tephra dispersal patterns of the AVF eruptions to be rationalised.

Key research outcomes

The reconstruction of the relative and absolute eruption order of the AVF highlights some patterns within the temporal spacing of the eruptions. Our current understanding indicates Pupuke was the first eruption, occurring between 190,000 and 200,000 years ago. From this point until around 50,000 years ago, another 18 centres erupted, with an average repose period during this time of around 8000 years. The remaining centres erupted

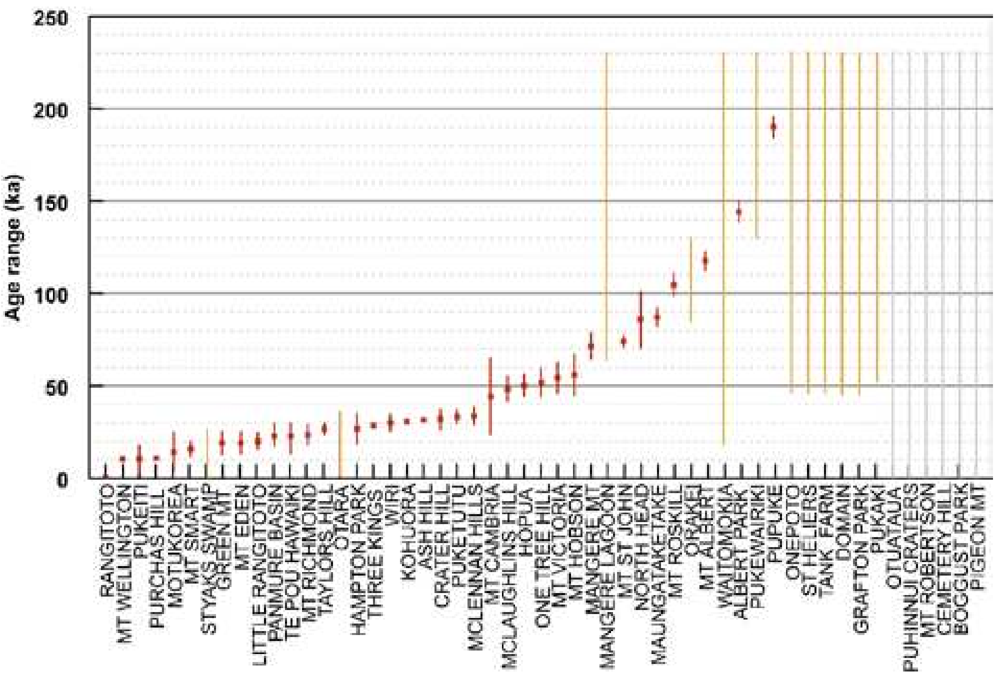

Figure 3. Proposed ages for the centres of the AVF. Those in red are $^{40}Ar/^{39}Ar$ (from Leonard, G. pers. comm.) or ^{14}C ages (from Cassata *et al.* 2008 and Lindsay *et al.* 2011) with their mean ages shown by the markers and the errors on these ages shown by the lines. Those in orange have their ages based only on morphostratigraphy, and those in grey have no ages associated with them. Of note is the number of centres which, based on errors, could have erupted at a given time, for example at 50 ka: there are 18 potential centres (Mt Cambria, McLaughlins Hill, Hopua, One Tree Hill, Mt Victoria, Mt Hobson, Waitomokia, Onepoto, St Heliers, Tank Farm, Domain, Grafton, Otuataua, Puhinui Craters, Mt Robertson, Cemetery Hill, Boggust Park, and Pigeon Mt) whose age ranges include 50 ka.

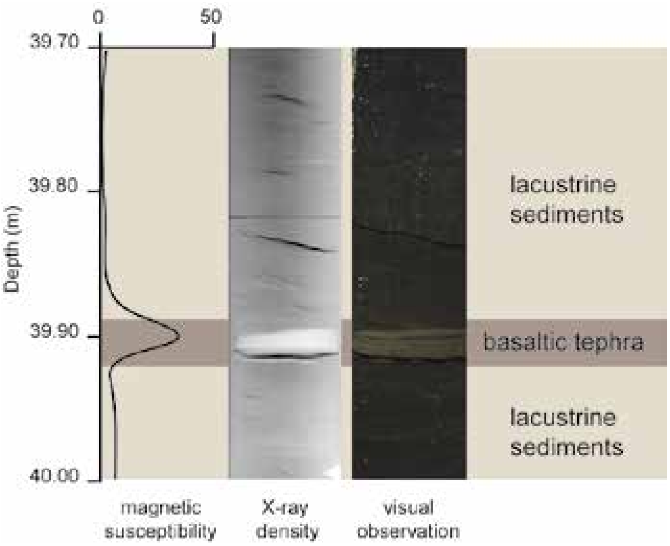

Figure 4. An example of a typical basaltic horizon exhibiting a sharp peak in magnetic susceptibility (SI units) and the bright contrast of the horizons on the X-ray density scan, in comparison to the 'background' lacustrine sediments (adapted from Hopkins *et al.* 2015).

between 50,000 years ago and the present, with an average repose period of 1400 years. The average repose periods are helpful in highlighting an increase in eruption rate from 50,000 years ago to the present, but they also mask some of the finer detail relating the eruption timings. For example, within both these time windows (200,000 to 50,000 years ago, and 50,000 years ago to present) there are repose periods of less than 500 years. From these results we have highlighted evidence for increasing activity to the present, an interesting and important outcome in relation to hazard and risk mitigation.

In addition to eruption timings, the evolution of the dispersal pattern for the AVF eruptions has also now been addressed. The results from this study indicate a large variation in distances between successive eruptions, in general varying from < 0.5 km to 14 km in distance. As detailed by previous studies, some vents do show alignments linked to near-surface faults (e.g. Kenny *et al*. 2011; Kereszturi *et al*. 2014), but in general there is no spatial progression or pattern to vent location through time, and therefore a definitive future vent site remains an unknown.

Correlation of tephra deposits both between core sites across the Auckland region and to their source centre allows estimations of tephra dispersal patterns to be characterised. Of the 29 tephra horizons found within the cores, 17 were only found in a single site location, indicating that for a large number of eruptions the tephra dispersal was limited. This suggests that in the event of a future eruption the entire city may not be affected. However, for some of the larger eruptions, for example One Tree Hill, Mt Eden, or Three Kings, the tephra was dispersed across the entire field, from Pukaki in the south to Pupuke in the north (Fig. 5). For some of these larger eruptions, deposits > 10 cm thick were identified at < 6 km from the vent. These results support previous research indicating that dangerous pyroclastic density currents will affect the proximal vent area in the case of phreatomagmatic eruptions (Brand *et al*. 2014). The results also indicate that tephra shard size decreases away from the vent, an important additional health implication when considering evacuation planning and risk management for areas not directly affected. For example research shows that smaller size fractions of ash can be more hazardous than larger size fractions as they can enter the respiratory system, causing acute and chronic respiratory diseases (e.g. Horwell 2007).

Tephra fall is considered to be one of the most likely and potentially most costly of the volcanic hazards to impact Auckland, causing disruption to transport systems, contaminating water supplies, damaging buildings, and being hazardous to

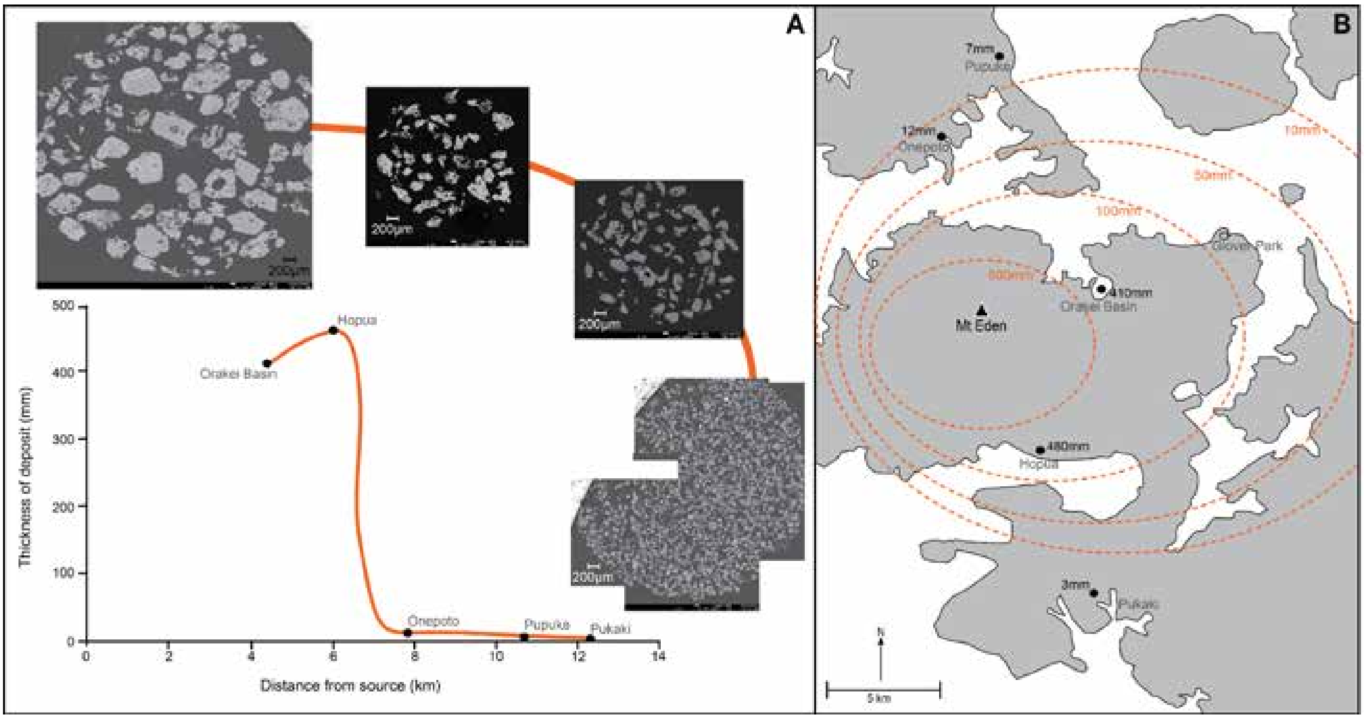

Figure 5. Example of the correlation of Mt Eden eruption to tephra deposits across the AVF: (A) Change in deposit thickness away from source. Note the extreme decline in thickness after c. 6 km distance. Also shown are backscatter electron images of the shards from each core site taken on electron microprobe (EMPA). All pictures are at the same scale with the bar at the base of the images representing 200 μm. (B) Inferred isopach map of the tephra dispersal from Mt Eden, based on the deposit thicknesses found in the cores. Dispersal is skewed to the east to reflect the westerly winds likely to have been present at the time of eruption (Hayward *et al.* 2011).

human health (Hayes *et al*. 2015). This scientific research is a highly important input into modelling eruption scenarios in order to define potential outcomes, and thus inform hazard and risk management plans. Teams at both GNS Science and Massey University are currently developing hazard and risk models as part of the DEVORA project. RiskScape, a multi-hazard risk assessment tool has been developed and expanded to evaluate the proximal volcanic hazards likely to affect Auckland (Deligne *et al*. 2015). Multiple hypothetical eruption scenarios have been modelled in order to account for a variety of eruption characteristics. For example, the outcomes of eruptions occurring through differing substrates, in differing locations (e.g. city, airport, residential) and at differing volumes can be evaluated. The impacts to infrastructure can be identified before, during, and after an eruption, and the long-term impacts of an eruption can be modelled (Deligne *et al*. 2015).

Predicting when and where the next volcanic eruption from Auckland will occur is certainly not an easy task. Over the course of the DEVORA project to date, the scientific gains made by many multidisciplinary scientists are an invaluable input into the planning and prediction for future eruption scenarios. We now have a much better grasp on many of the characteristics and are able to use this knowledge to model the potential outcomes from an eruption, and the impacts on the people of Auckland, the infrastructure, and the economy.

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Glossary

andesite/andesitic – volcanic rock (or lava) containing 54% to 62% silica and moderate amounts of iron and magnesium. High silica content characterises siliceous andesite.

^{40}Ar/^{39}Ar (argon-40/argon-39) dating – a variation of potassium–argon dating, in which the concentration of stable ^{40}Ar, created from radioactive 40K in a reactor, is compared with the concentration of stable ^{39}Ar.

ash – fine particles smaller than 2 mm in diameter of pulverised rock (tephra) erupted from the vent of a volcano.

basalt/basaltic – volcanic rock (or lava) containing less than 54% silica, commonly producing more effusive, runny and less explosive lava.

diatreme – a long vertical pipe or plug formed when gas-filled magma forced its way up through overlying strata.

intraplate volcanism – volcanic activity that occurs within tectonic plates and is generally not related to plate boundaries and plate movements.

isopach – a line on a map connecting points below which a particular rock stratum has the same thickness.

ka – thousands of years ago.

Ma – millions of years ago.

maar – a volcanic crater formed by a phreatomagmatic eruption. Typically the eruption occurs in a wet or low-lying area. These craters are often wide, but shallow.

morphostratigraphic – organisation of rock or sediment strata into units based on their surface morphology (landforms).

monogenetic volcanic field – a field of individual volcanoes each of which generally only erupts once.

phreatomagmatic – an explosive volcanic eruption that results from the sudden interaction of surface or subsurface water and magma.

polygenetic volcanic field – a group of polygenetic volcanoes, each of which erupts repeatedly.

pyroclastic surge, or base surge – an extremely fast turbulent horizontal flow of a hot fluid mixture of rocks, tephra, gas and steam from the base of an eruption column.

radiometric dating – a method for determining the age of geological materials using radioactive isotopes.

rhyolite/rhyolitic – volcanic rock or highly viscous magma, with a high silica content (typically more than 69%), found as pumice, ignimbrite, or obsidian.

scoria cone – a small volcanic hill formed mainly of scoria (a frothy basaltic rock) erupted from a central vent.

siliceous – pertaining to silica content; basalt is poor in silica and is very hot and flows freely, while rhyolite is rich in silica, is cooler and more viscous.

subduction zone – where two tectonic plates meet, with one moving down into the mantle.

tephra – solid material of all types and sizes erupted from a volcanic vent and that travel through the air.

tephrochronology – a stratigraphic method that uses tephra deposits to date and link geological events.

tuff – a light, porous rock formed by consolidation of volcanic ash.