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Rangitoto re-visited: new insights to an old friend

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THE UNIVERSITY OF AUCKLAND
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School of Environment

Rangitoto re-visited: new insights to an old friend

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Overview

Rangitoto is one of Auckland's more iconic landscape features. Standing like a bastion in the Waitemata harbour, Rangitoto last erupted some ~550 years ago after Auckland was settled by Maori, and is therefore the youngest volcano in the Auckland Volcanic Field (Lindsay 2010). Recent research has revealed more about Rangitoto's history, which will be discussed ascending its summit and exploring its various volcanic features.

The ferry departs from the downtown ferry terminal at 9.15am and Devonport at 9.25am, and will leave Rangitoto at 3.45pm. The walk is a moderate one on rough tracks and requires sturdy footwear and a moderate level of fitness.

Key Facts

Maori name: Rangitoto, derived from the phrase 'Nga Rangi-i-totongia-a Tama-te-kapua' - the days of the bleeding of Tama-te-kapua - captain of the Arawa waka, referring to a battle between Tamatekapua and the Tainui at Islington Bay (e.g. Murdoch 1991).
Location: Auckland City. Part of the Auckland Volcanic Field
Height: 260 m
Age: Formed during two eruptions, 600 and 550 years ago (ca 1400 AD and 1450 AD)
Composition: Basalt lava, scoria and ash
Volume volcanic material: About 2 cubic km

Introduction

Rangitoto Island is a graceful, almost symmetrical, volcanic cone which dominates the skyline to the north-east of Auckland City (Fig. 1). It is the youngest and by far the largest of the ca. 50 volcanoes in the basaltic Auckland volcanic field. The estimated volume of basalt in the volcano (2 cubic kilometres) is about half the volume of all of the basalt in the field. The volcano has a complex structure created during two distinct periods of eruption. The lower lava-covered slopes are relatively gentle although they steepen towards the summit of the island. The upper part of the volcano is made up of steep slopes of scoria. At the summit there is a central crater 60 m deep and 150 m in diameter. A second smaller crater to the east and a complex series of mounds, ridges and depressions to the north of the main crater show that activity was not confined to a single vent. Some of these features are remnants of older craters which were destroyed as the eruption progressed.

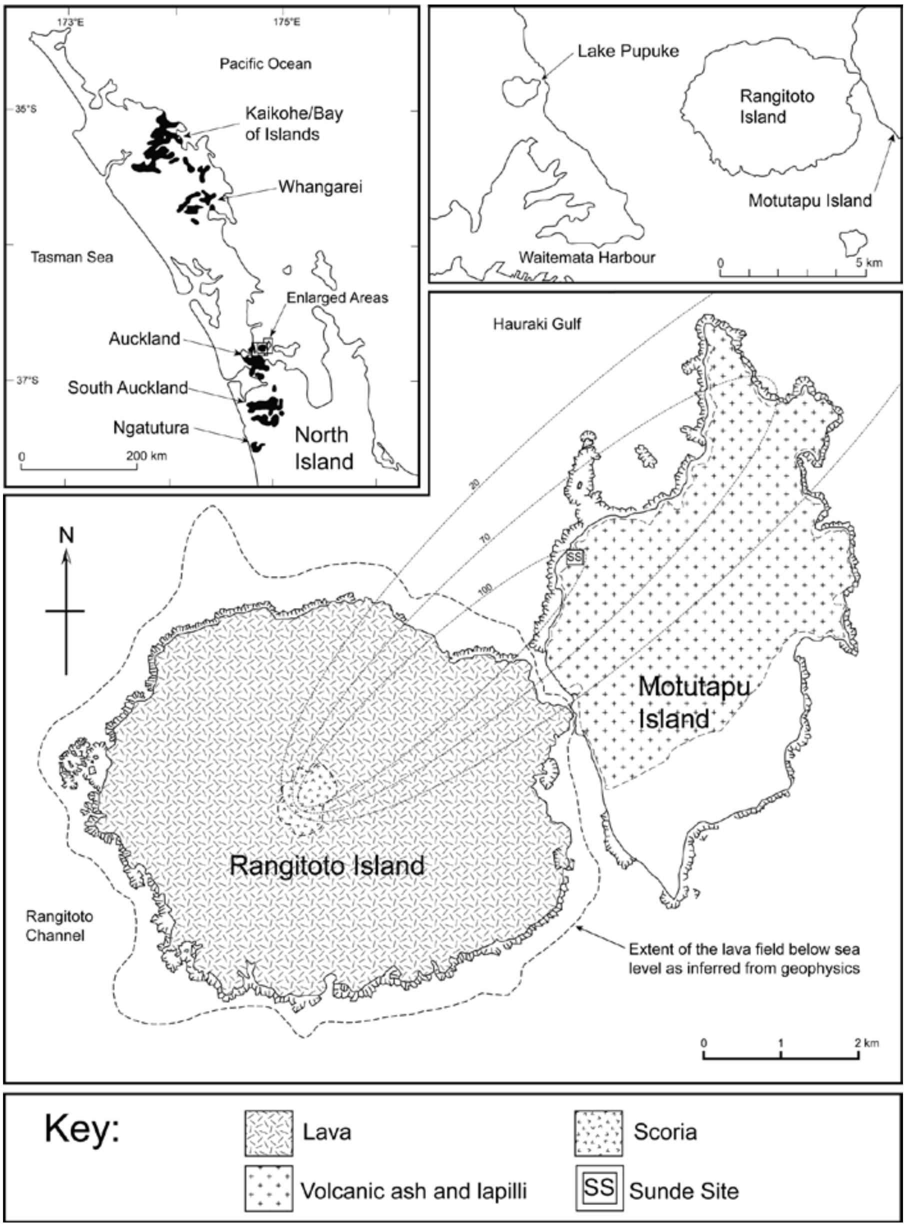

***Figure 1**. Geological sketch map of Rangitoto volcano and adjacent Motutapu Island, showing the main Rangitoto eruptive products. Ellipses show generalised areas of equal ash thickness (in cm) for the first Rangitoto eruption. Insets show the location of the Auckland Volcanic Field and other basaltic intraplate volcanic fields in the upper North Island, and the position of Lake Pupuke relative to Rangitoto. Adapted from Needham et al. (2010).*

Formation of the island

Rangitoto began as a series of explosive phreatomagmatic eruptions caused when magma, originating from the mantle at depths of about 80 km, broke through the sea bottom at the entrance to the Waitemata Harbour (Fig. 2). A series of ash explosions built up a low cone which eventually acted as a rampart denying the sea water further access to the hot magma. A period of mildly explosive magmatic activity followed, during which lava fountaining and intermittent explosive activity built up an overlapping series of steep sided scoria cones (e.g. North Cone), and covered much of nearby Motutapu Island in ash (Fig. 1). The alkaline basalt chemistry of these older deposits is similar to other Auckland volcanoes and is probably from an initial smallish eruption perhaps equivalent to Mt Wellington in size. Following a time break of maybe a few decades, a new fire fountaining eruption occurred, producing the current summit scoria cone (i.e. Central Cone; Fig. 2). Towards the end of this eruption, lava flows broke out from fractures around the flanks of the cone to create a smooth apron of lava. The basalt rocks produced during this younger (and larger) eruption have a different geochemical composition (sub-alkaline), suggesting the magma was formed from extensive melting of rock at a shallower depth in the mantle (about 60 km). It is possible that the passage of the first batch of magma through the mantle somehow triggered melting in another (higher) zone in the mantle on its way to the surface (Needham et al. 2010).

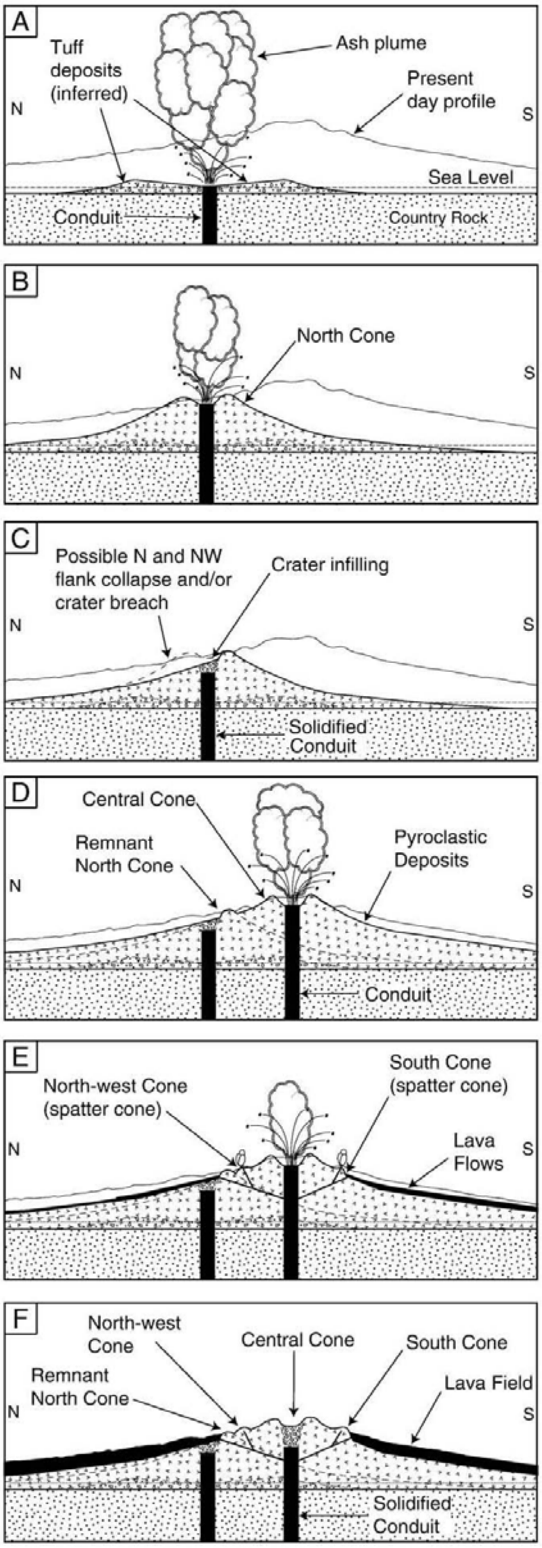

Figure 2. *Schematic diagram illustrating the eruptive history of Rangitoto Volcano. A) The first eruption from Rangitoto commenced about 600 years ago, probably erupting through shallow seawater and generating a phreatomagmatic tuff ring; B) strombolian style activity resulted in the formation of a scoria cone ~200m asl, depositing ash on nearby Motutapu Island; C) a period of quiescence of several decades followed the first eruption, during which the original conduit partially solidified; D) the early stages of the second eruption, possibly about 550 years ago, were dominated by Strombolian style activity, which built a steep-sided scoria cone forming the present-day summit and deposited a thin layer of ash on Motutapu; E) a period of lava effusion lead to the development of the extensive lava field and associated near-vent spatter cones; F) the main features of Rangitoto Volcano today. (From Needham et al. 2010)*

Maori Presence

Although no oral tradition has survived that describes the actual eruption and creation of Rangitoto, we know that Maori were living on the adjacent Motutapu Island at the time. Ash from the early eruption buried wood and shell of a habitation site in Administration Bay, and excavations at the Sunde Site have revealed casts of dog and human footprints in the ash. Carbon-14 dates of ca. 600 years old measured on charred wood beneath the ash on Motutapu Island give a maximum age for the volcano. It is possible that the name Rangitoto, which some say means “bloody sky”, may have originally referred to the spectacle of the volcanic event.

Flora of Rangitoto

The flora on Rangitoto is unique among the islands situated in the Hauraki Gulf. The island is home to some 200+ species of plants, ferns and mosses that have established themselves over the past 200 years on a relatively soil-less, water-less, barren landscape. The establishment and development of flora on Rangitoto is thought to have been a slow process, with the development of an appropriate soil on the basalt requiring the longest period of time; although this process gradually became faster as the island became more inhabitable.

In the beginning, the first plants (lichens and mosses) established themselves by growing in crevices in-filled with fine ash from the final stages of the eruption. As the fine, spongy, highly humic, brown detritus accumulated in the crevices, this soil-like surface allowed larger plants (ferns and shrubs) to establish themselves on the lava field. Today Rangitoto is dominated by Pohutukawa (*Metrosideros excelsa*) ‘New Zealand Christmas’ trees, a primary rock coloniser, which forms ‘vegetation islands’ that gradually fuse together to form large forested area (Millener 1979). Rangitoto is home to the largest Pohutukawa forest in the world.

Various pest eradication schemes have been conducted over the years to remove introduced pests and restore vegetation on Rangitoto and Motutapu.

Geological Features

A walk on Rangitoto reveals many interesting volcanic features. The gentle lower slopes are composed of many overlapping lava flows whose surfaces commonly show good **pahoehoe** textures near to their source, and **aa** textures at their distal (coastal) ends. Toward their distal ends the margins of many flows are defined by prominent **levees** formed by accumulation of chilled lava at the margins of moving flows.

A small but well-developed system of **lava tunnels** linked by **lava trenches** occurs on the south-eastern flanks of Rangitoto Island close to the boundary between the summit **scoria cones** and the surrounding **lava field**. The tunnels formed after still-molten lava withdrew from a channel roofed by chilled lava; the trenches formed in places where the roof was too thin and collapsed as the lava withdrew, or where a roof did not form.

The summit **scoria cone** rises from the “**moat**” at the top of the lava slopes. As seen from Auckland the cone is a multiple structure with two outer hills flanking the younger summit cone and crater that represent the remnants of earlier cones destroyed by later eruptions. Good exposures of **scoria** forming the summit area are seen on tracks on the north-eastern side; these formed by episodic **fire fountaining**.

When fresh, the scoria is normally dark grey but reaction with water percolating through the hot porous scoria soon after the eruption has caused some of the rock to turn a deep red. The red colouration is due to oxidation of the iron in the basaltic scoria.

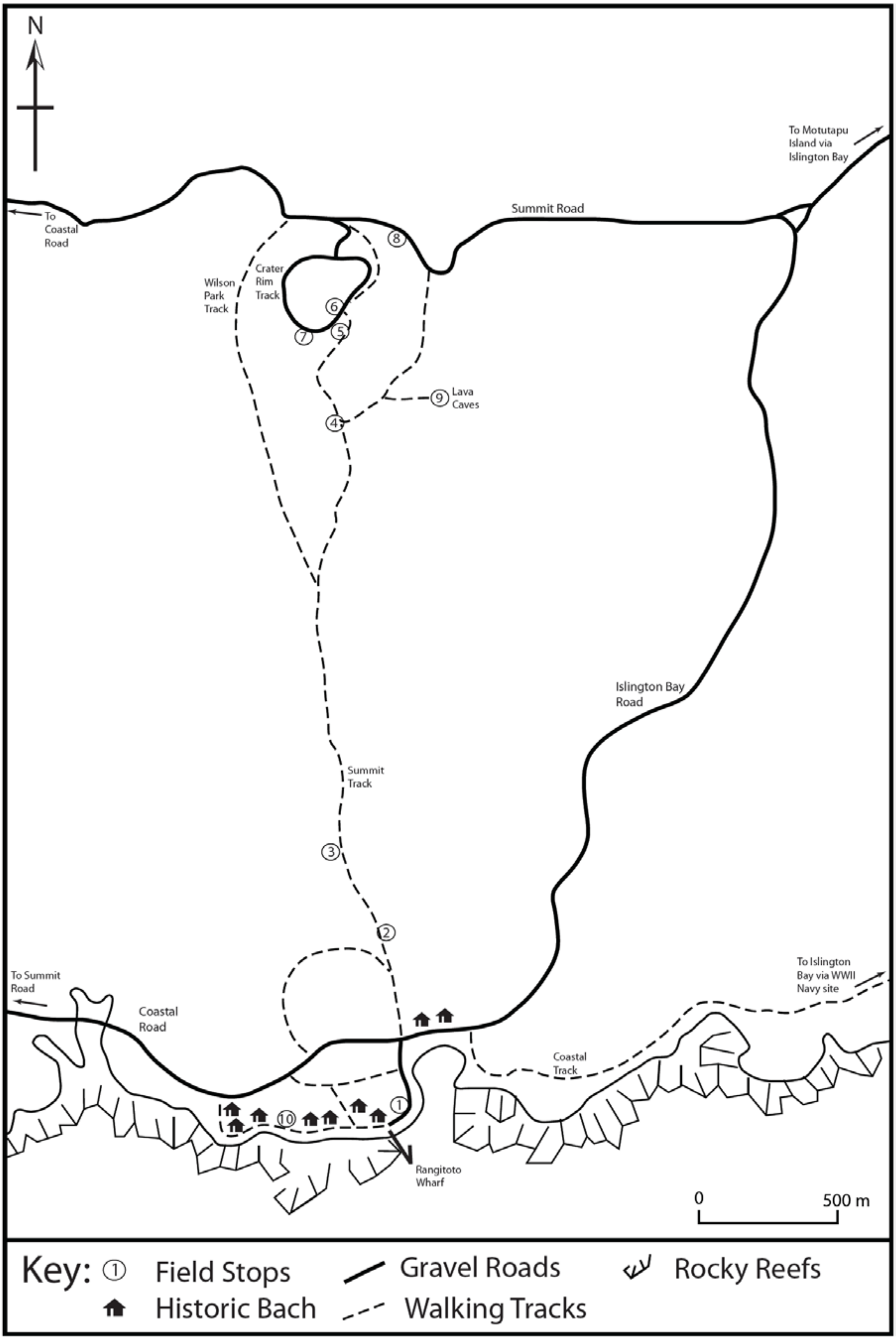

Figure 3*. Map showing the localities of the various field stops and general geographical features of the southern part of Rangitoto Island.*

Description of Field Stops (see also Fig. 3)

Ferry arrives approximately 9.45 am

1. **Information shelter at Rangitoto Wharf**. *Introduction and briefing*.

   After a short 15-20 minute ferry ride we will arrive at Rangitoto Wharf, situated on the southern coast of Rangitoto Island and at the periphery of the Rangitoto lava field. Sea level has remained virtually the same since the eruptions of Rangitoto, so the features seen on the coast will shed some light on how the lava interacted with the sea water towards the latter stages of the second eruption. Be sure to look at the smooth, wrinkly, curved lava features that snake their way into the water parallel to the wharf.

2. **Raised margin of lava flow.** *Brief discussion of the Rangitoto lava field and of lava flow textures.*

   As we make our way towards the summit we will see the features and textures of the Rangitoto lava field. Near the source of lava effusion (at the base of the scoria cone) the lava field is quite thick, up to 50 m, whilst at the coast is considerably thinner, less than 20 m; although individual flows themselves are no more than 5 m thick. The majority of the lava field is comprised of blocky, clinker a’a lava flows, with rarer occurrences of smooth, ropey pahoehoe lava flows along the main track to the summit and along coastal areas, e.g. near Islington Bay and the Rangitoto Wharf.

   During eruption, the a’a flow tops transported brecciated, broken lava blocks downslope, which sit atop a more massive flow core. The blocks form at the leading edge of a flow due to instantaneous cooling with the air or water. Blocks generally tumble down the steep flow fronts and are either ‘bulldozed’ or buried by the advancing flow. Rocks on the outside of the flow tend to be highly vesicular and glassy, whilst those from the flow interior tend to be more massive and crystalline.

3. **DOC information point.** *This is on the boardwalk, on the left side of the main track as we ascend. It provides a good opportunity to discuss the structure of the lava field and view to summit.*

4. **Moat between lava field and summit cone.** *Pause to regroup and discuss the two eruptive styles of Rangitoto. Leave this stop at 11 am.*

   At an elevation of 150 m the southern and eastern flanks of the volcano are dominated by an unusual moat-like structure, which defines the boundary between the lower lava-covered slopes and the scoria crown. It is understood to have formed as a result of a subsidence event following the release of significant volumes of lava from fissures on the upper flanks.

5. **On track immediately before summit crater.** *Deposits of lapilli from the scoria cone*.

   Exposed in cuttings next to the summit track not far from the main crater are layers of the pyroclastic material (scoria, lapilli and bombs) that make up the central scoria cone of Rangitoto. These glassy, highly vesicular rock fragments originate from gas-rich molten or semi-molten lava that has been ejected into the air, quickly cooled and deposited close to the vent, frequently still partially molten. Pyroclastics are typically cylindrical, spherical, teardrop, dumbbell or button-like in shape, and generally take their shape when they are airborne. Also common in the pyroclastic deposits of Rangitoto is ‘welded’ scoria, which forms when semi-molten scoria fragments ‘stick’ to other fragments when they land. The accumulation of the pyroclastic fragments described above formed the Rangitoto scoria cone.

6. **Summit crater.** *Not far from Stop 5 is the observation deck located on the rim of the main crater of Rangitoto.*

The near circular bowl-shaped crater of Rangitoto is approximately 150 m in diameter and 60 m in depth, and reaches a height of ~260 m above sea level. This is the position of the vent for the second Rangitoto eruption, which started off as a moderately explosive (Strombolian style) eruption, forming the scoria cone, and then becoming more effusive (Hawaiian style) towards the latter stages of the eruption.

7. **Summit.** *Discussion of the Auckland Volcanic Field and of the two eruptive phases of Rangitoto. Lunch. Leave this stop at 12.30 pm.*

   At the summit we are presented with a 360° view of Rangitoto volcano and the surrounding natural and man-made features. To the south-west we can see the Auckland CBD, situated next to the Waitemata Harbour, and some of the other larger volcanic cones (Mt Wellington, Mt Eden, One Tree Hill, The Domain, Mt Mangere) in the AVF. To the west we see the residential suburbs of North Shore City and smaller volcanic cones (North Head, Mt Victoria) and slightly larger explosion craters (Lake Pupuke, Tank Farm, Onepoto Basin). To the north-east we see Motutapu Island, which was covered in significant volumes of volcanic ash from the Rangitoto eruptions. Ash from both Rangitoto eruptions has also been found in drill core from Lake Pupuke (Fig. 1). To the south and south-east we see the other islands of the Hauraki Gulf, the islands of Waiheke and Motuihe, and volcanic cone of Motukorea (Brown's Island).

8. **Small quarry on northern side of main cone.** *Discussion of the structure of the cone, and varying alteration of deposits*.

   Exposed in this quarry are alternating pyroclastic layers of black to dark brown and red, and less frequent patches of yellow-tinted scoria. Each colour indicates different processes acting on the pyroclastic material prior to, during and after eruption. Dark coloured scoria (black and dark brown) reflects relatively unaltered rock fragments. In comparison, red scoria generally indicates oxidizing conditions (higher temperature and/or presence of permeating magmatic gases) acting on the iron content of the scoria at the time of eruption. Red scoria may also result from post-depositional chemical weathering. The yellow coloured scoria seen in some areas in the quarry has probably been altered by hydrothermal activity at some stage.

9. **Lava Caves/Tubes (time permitting)** *Leave this stop at 2.15 pm*

   South-east of the Central Scoria Cone, and in close proximity to the "moat" are some of Rangitoto's most popular geological features – the lava caves. These formed when the exterior of a low-viscosity pahoehoe lava flow "chilled" (in contact with ground and air) and crusted over, creating an insulated tube that allowed the molten lava interior to continue flowing. Towards the latter stage of the eruption, lava supply down the lava tube system waned, and subsequently drained, leaving behind the cave-like structures we are about to walk through. Be sure to have a torch and watch out for the Wetas!!

10. **Baches adjacent to wharf.**

    Here we will look at some of the remaining bach communities on Rangitoto. These were built in the 20s and 30s, and consist of private holiday dwellings and boatsheds as well as communal facilities such as the swimming pool and a community hall. Built by families during the depression era, they demonstrate the kiwi do-it-yourself attitudes of the times. Since 1937 it has been prohibited to build further buildings on the island.

Ferry departs 3.45 pm

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Volcanoes in the big smoke: A review of hazard and risk in the Auckland Volcanic Field

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ABSTRACT: The potentially active Auckland Volcanic Field (AVF) comprises ca. 50 basaltic 'monogenetic' volcanic centres and is coincident with New Zealand's largest city, Auckland. The most recent eruption occurred 550 years ago and was witnessed by early indigenous Maori. Although the volcanoes in Auckland are small and their eruptions have been infrequent, the risk associated with future activity is very high given the high physical and economic vulnerability of Auckland (population 1.3 million; 2006 census). Assessing long term volcanic hazard and associated risk in Auckland is challenging, however a boost in research in this area over the past 10 years has lead to an improved understanding of both the inner workings of the field and also what we might expect in the event of a future eruption.

1 INTRODUCTION

1.1 *Auckland Volcanic Field*

The AVF is a young monogenetic intraplate volcanic field made up of about 50 small basaltic volcanoes within an area of approximately 30 × 20 km centered on Auckland City in northern New Zealand (Fig. 1). Early work by Searle (1964) and more recently Kermode (1992) and Smith and Allen (1993) showed that past eruptions have ranged in style from phreatomagmatic (forming maars and tuff rings) to magmatic (producing scoria cones and lava flows). It is thought that the earliest eruptions might date back to 250,000 kya, and the youngest eruption, forming Rangitoto Island (Fig. 2), occurred about 550 years ago and was witnessed by early indigenous Maori living on nearby islands (Brothers and Golson 1959). The geologically relatively recent eruption of Rangitoto, comparison with life spans of analogue volcanic fields and the presence of a mantle anomaly at depths of about 70–90 km beneath Auckland that has been interpreted as a zone of partial melting (Horspool et al. 2006) all suggest the field will erupt again.

1.2 *Assessing hazard and risk*

A volcanic hazard is a potentially damaging volcanic event or phenomenon that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation. A volcanic hazard is typically characterised by its location (e.g. aerial extent), intensity (e.g. style, size, duration), frequency (e.g. of past activity) and probability (likelihood of a future event). Risk is the probability of harmful consequences, or expected losses (deaths, injuries, property, financial etc) resulting from interactions between hazards and vulnerable conditions (LWR 2004). In its simplest form, risk can be expressed as a function of a Hazard(s) and Vulnerability:

$$\text{Risk} = f\,(\text{hazard, vulnerability})$$

Volcanic hazards are natural phenomena which usually cannot be altered or influenced by people, although this has been attempted with success on rare occasions (e.g. lahar diversion,

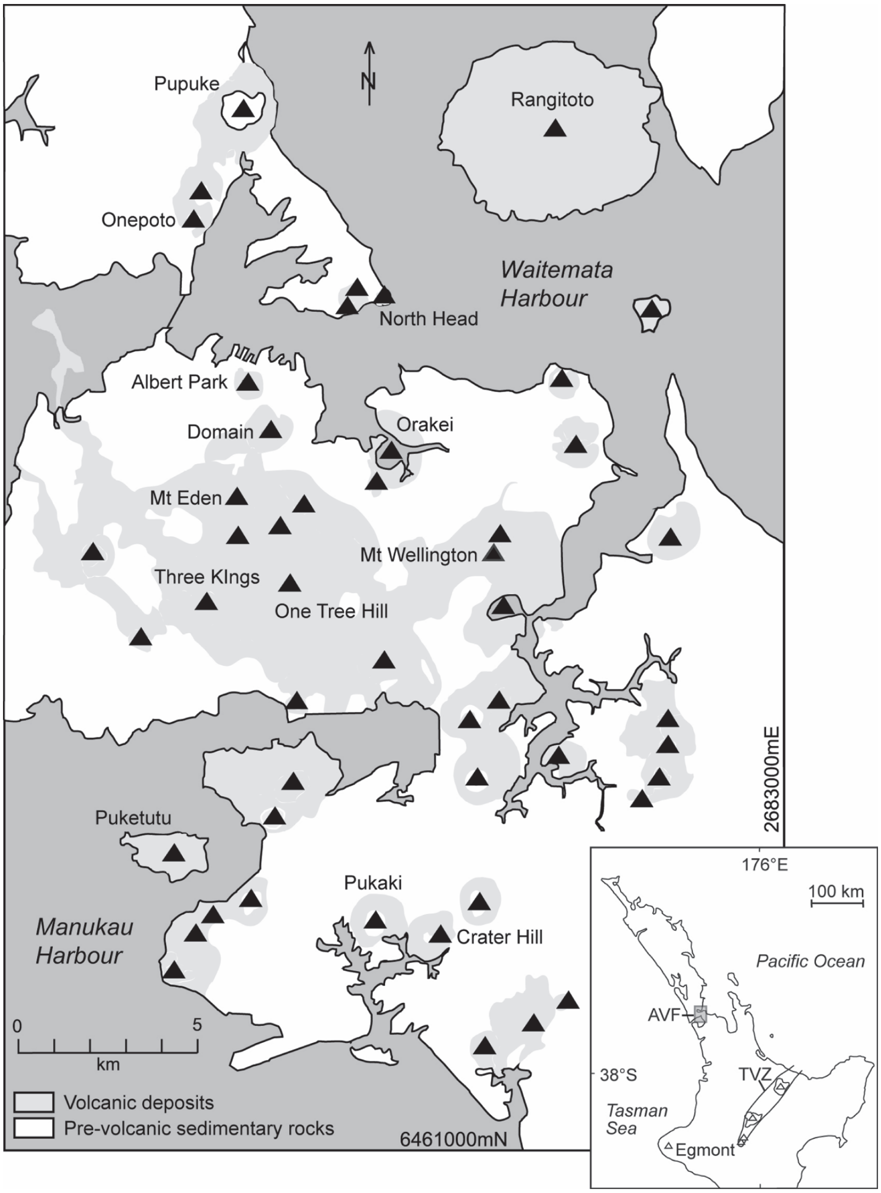

Figure 1. Map of the Auckland region showing the Auckland Volcanic Field centers (black triangles) and deposits (after Kermode 1992). Inset shows the position of the AVF relative to other major volcanic centers, Egmont and the Taupo Volcanic Zone (TVZ), in the North Island of New Zealand.

Ruapehu, New Zealand; cooling and diverting of lava flows, Heimaey, Iceland). Thus in order to reduce risk, the exposed vulnerability of life and property in potentially hazardous areas needs to be reduced.

Assessing volcanic hazard in the AVF involves detailed investigation of past activity in the AVF, comparison with similar volcanoes and volcanic fields elsewhere in the world, and probabilistic modeling of future activity. Evaluating volcanic risk is more complicated, and involves assessing all the relevant vulnerabilities (social, physical, environmental, economic), how these might be affected by the particular hazard, identifying the capacities and resources available to address or manage the hazards, and determining acceptable levels of risk.

Figure 2. Rangitoto Island from Takapuna Beach. In the foreground is a fossil forest, preserved in basaltic lava from Pupuke volcano.

2 STYLE, INTENSITY AND DURATION

2.1 *Style and intensity*

Past eruptions in the AVF have typically initiated with phreatomagmatic explosions and base surges, with explosive activity continuing until the water supply is exhausted, or blocked off through the sealing of the magma conduit at shallow depths or the formation of an ejecta rampart. Some past eruptions have stopped after this phase, producing maars and tuff rings (e.g. Orakei, Onepoto, Pukaki). In cases where magma supply has continued, mildly to moderately explosive strombolian to sub-plinian activity has built up scoria (cinder) cones (e.g. North Head, Mt. Wellington). This style of activity typically continues until volatiles are depleted, in which case the last phase of an eruption results in lava flows (e.g. Rangitoto, Pupuke, Mt. Eden, Three Kings; Figs. 2 & 3). In some cases these lava flows have rafted away parts of the previously-formed tuff ring and scoria cone (e.g. Motukorea/Browns Island). Centres where all eruption stages have occurred reflect the largest magma batches (e.g. Rangitoto, Three Kings, One Tree Hill). AVF volcanoes are, however, typically small (<150 m in height; <0.1 km^3 in volume, Allen and Smith 1994), although the last two eruptions (Rangitoto [2 km^3], and Mt. Wellington) are two of the biggest.

2.2 *Duration*

Eruptions in so-called 'monogenetic' fields may range in duration from a few hours (e.g. Teishi Knoll, Higashi-Izu volcanic Field, Japan) to as long as a decade (e.g. Jorullo and Paricutin volcanoes, Michoacán Guanajuato volcanic field, Mexico) and may result in the formation of one or more features such as cinder cones, tuff rings, satellite cones, fissure vents and lava fields (e.g. Jorullo volcano) (Sherburn et al. 2007). Evidence from past eruptions suggests that the AVF follows this pattern, although volumes of eruptive products from most centres are much smaller than those of the long-lived Paricutin and Jorullo centres. Most of the volcanoes in Auckland are thus thought to have grown during eruptions lasting a few months or possibly a few years, although Blake et al. (2006) suggest the entire volume of Crater Hill may have been erupted between 14 hours to 12 days. Several volcanoes in the field (e.g. Rangitoto, One Tree Hill, Mt. Eden, Pupuke, Mt Wellington) comprise numerous volcanic features and/or satellite cones, also indicating that several eruptive episodes may have occurred during their formation, perhaps with time breaks between eruptions.

Figure 3. Mt Eden scoria cone and lava flow; Auckland Boys Grammar playing fields in the foreground.

2.3 *The Rangitoto problem*

Recent investigations of the stratigraphy of Rangitoto pyroclastic deposits that have been preserved in swamps on nearby Motutapu Island and in Lake Pupuke on the mainland (Fig. 1) reveal that Auckland's youngest volcano erupted twice; radiocarbon dating of 10 samples from the two tephra units in the swamps indicates eruption ages of 553 ± 7 and 504 ± 5 Cal yr BP, for the lower and upper tephra layers, respectively (Needham 2009; Needham et al. in revision).

Geochemistry of the lava field and various scoria cones on Rangitoto Island itself reveals two distinct compositional groups: an alkali olivine basalt group (that correlates geochemically with the lower tephra layer) and a group that is sub-alkali and transitional to tholeiite (that correlates geochemically with the lower tephra layer) (Needham et al. in revision). All other volcanoes in the AVF have erupted alkali basalts; thus the most recent eruption in the AVF represents an anomalous shift in composition. Not only were the magmas derived from different parental melts, they also appear to have been sourced from different mantle depths: trace element modelling indicates the alkali and sub-alkali parental melts could have been derived by ~1 and 6 wt. % partial melting of an anhydrous garnet peridotite source at ~80 and 65 km depth, respectively (Needham et al. in revision).

Taking into account the error in the radiocarbon ages, the time gap between eruptions cannot have been more than about 60 years. This raises questions about the possibility of eruption triggering and a time window for a particular conduit being reactivated in a basaltic field. Had the time gap been longer, giving the conduit time to fully anneal, it is likely that the second eruption would have produced a spatially separate volcano, thus following the more "expected" behavior of a monogenetic field. This has implications for hazard assessment—such that a future eruption scenario in the AVF needs to consider a recently-active conduit as "potentially active", and thus a possible pathway for another eruption, for at least a period of several decades while the conduit may be still considered thermally weakened.

3 FREQUENCY OF PAST ACTIVITY

3.1 *Insights from tephrochronology*

Over the past 10 years or so 5 AVF craters have been drilled to extract cores containing tephra layers interbedded with laminated lake sediments. Detailed investigation of these layers by Sandiford et al. (2001), Shane and Hoverd (2002), Horrocks et al. (2005), and more recently by Molloy et al. (2009) have provided great insight into the frequency with which Auckland has been impacted by eruptions in the past. At least 30 local eruptions in the last 80,000 yrs have so far been recognized, at an average frequency over this time period of 1 per 2,600 yrs (Zawalna-Geer, written communication). This is similar to long-lived basaltic volcanic fields elsewhere (Molloy et al. 2009).

The tephra record also reveals that activity has been episodic, with a major 'flare-up' in volcanism at 32 ± 2 ka (Fig. 4). A combination of sedimentation rates and the presence of known-age ash layers from elsewhere in the North Island in the cores means the ages for the tephra layers in the cores can be estimated with a certain degree of accuracy.

3.2 *Age of individual volcanoes*

Many attempts have been made to determine the age of individual centres in the AVF, but with only limited success: excess Ar inhibited early attempts using the K-Ar technique, and radiocarbon dating is limited to centres younger than ca. 40,000 years. As mentioned above, the tephra record obtained from drilling Auckland's paleo-lakes is providing excellent interpolated ages for basaltic AVF ash layers; as yet, however, only very few ash layers retrieved from cores can be correlated to individual centres (e.g. Rangitoto ash in Pupuke core; Crater Hill ash in Pukaki core, Mt Wellington ash in Panmure core). Recent Ar-Ar dating of AVF basalts has yielded exciting results, and future dating using this technique promises to fill many of the gaps in the chronology of the field.

A recent review of the seemingly large number (>170) of age determinations available for centres in the AVF by Lindsay and Leonard (2009) concluded that we still have a very poor understanding of the ages of most centres. Strongly reliable age estimates can only be given for three centres: Rangitoto (0.6 ka), Mt Wellington (10 ka) and Three Kings (28.5 ka). A further 6 seem to have reliable single ages, or several reliable ages spanning a small age range: Purchas Hill (11 ka) Ash Hill (32 ka), Puketutu (30–34 ka), Wiri Mountain (27–33 ka), Crater Hill (32–34 ka) and Panmure Basin (31.5–32.5 ka) (Fig. 4). Minimum ages based on tephrochronology and sedimentation rates of core are available for 5 centres: St Heliers (>45 ka), Kohuora (>27 ka), Hopua (>29 ka), Pukaki (>52.4 ka) and Orakei (>83.1 ka). A further 15 centres have yielded conflicting ages. Twenty centres are undated, although in some cases relative ages can be determined based on stratigraphic relationships. The oldest ages have

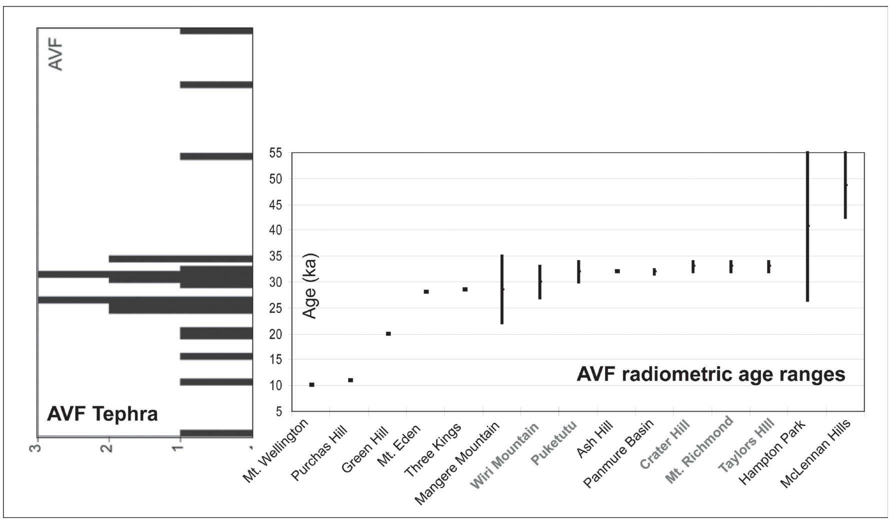

Figure 4. Comparison of the temporal distributions of basaltic tephra layers found in AVF sediment cores from Molloy et al. (2009) (left) with the best estimate ages and age ranges for the centres in the AVF presented in Lindsay and Leonard (2009), excluding the youngest (Rangitoto), oldest (Pupuke), and minimum ages. Centres with anomalous paleomagnetic signatures are: Wiri, Puketutu, Crater Hill, Mt. Richmond and Taylors Hill (Cassidy 2006; Cassata et al. 2008).

been obtained by Ar-Ar from Onepoto (249 ka) and Pupuke (200–260 ka) (Lindsay and Leonard, 2009).

Best-estimate radiometric ages available for the AVF display a marked clustering of possible ages between 28 and 33 ka, which corresponds well with the clustering of basaltic tephra in the same age range observed in the maar sediment cores as well as a clustering of activity during this timeframe indicated by several centres in the field that display anomalous paleomagnetic signatures (Cassidy 2006, Cassata et al. 2008; Fig. 4).

4 SPATIO-TEMPORAL RELATIONSHIPS

To date there have been no spatio-temporal trends identified in the AVF. If any trends are present, they appear to be obscured by a general lack of reliable numeric ages, the fact that past eruptions have been small with restricted deposits that seldom overlap those of neighbouring centres, and little evidence for structural control of vent locations (e.g. von Veh and Nemeth 2009). The fact that the most recent eruption (Rangitoto) is anomalous in size, composition and duration also makes modelling difficult. The limited age data do indicate that eruption frequency and magnitude have been variable during the life of the field, and that overall eruption magnitude may have increased with time (although this is based largely on the anomalously large Rangitoto) (Allen and Smith 1994; Cassidy et al. 2007).

Using an eruption age order presented in Allen and Smith (1994), Magill et al. (2005) showed that the distance between consecutive vents was significantly smaller than that between all pairs of vents, and concluded that eruptions do not occur randomly, but rather preferentially closer to the previous eruption.

They then ran a probabilistic model that suggested a future vent is most likely to occur in the north of the field near Rangitoto.

Recently, Bebbington and Cronin (in revison) have re-examined the age constraints within the AVF and performed a correlation exercise matching the well-dated record of tephras from cores distributed throughout the field to the most likely source volcanoes. Combining this age information with known stratigraphic constraints, they have produced a new age-order algorithm for the AVF, which they then used to update the earlier work of Magill et al. (2005). Analysis of the new age model discounts earlier appreciations of spatio-temporal clustering in the AVF. Instead, the spatial and temporal aspects appear independent; hence the location of the last eruption provides no information about the next location.

5 MONITORING NETWORK

Volcano monitoring can be difficult in small distributed volcanic fields such as the AVF as the next vent location is not known, and traditional techniques such as geochemical and ground deformation monitoring are therefore not feasible as there is no obvious target for measurements. In such cases, seismic monitoring may be the only technique suitable. High levels of background (cultural) seismic noise and extremely low levels of historical seismicity make volcano monitoring particularly challenging in the AVF. Another complication is that basaltic fields are known to have fast magma ascent rates; in the AVF, estimated ascent rates suggest transit times of a few days to weeks from source to surface (Blake et al. 2006; Sherburn et al. 2007). Early detection of precursory activity is therefore an essential component of risk mitigation strategies.

The Auckland Volcanic Field is monitored by GNS Science through the GeoNet project (www.geonet.org.nz). The monitoring network currently consists of 9 seismographs: a mix of short-period and broadband stations, and surface (5) and downhole (4) stations. This permits earthquakes down to about $ML = 1.5$ to be reliably detected, and events with $ML >$ ca. 2.5 to be reliably located (uncertainty in location of 5–10 km).

Historically, there has been a low level of seismicity in the AVF. Between 1995 and 2005, just 24 earthquakes were located in the Auckland region (Sherburn et al. 2007); all were

<5 km deep, but only one occurred within the AVF. Magnitudes ranged from ML 1.6 to 3.3, and five earthquakes of $ML \geq 2.4$ were felt. In early 2007, a swarm of earthquakes, some felt, occurred several kilometres north of the AVF. Although precursory earthquake swarms may occur away from the eventual vent (e.g. Aspinall et al. 1998), in this particular case, the earthquakes are thought to be related to faulting on the adjacent Hauraki rift (not related to the AVF). All the above earthquakes were of high-frequency, tectonic type; no low-frequency volcanic earthquakes have been recorded (Sherburn et al. 2007). All historical Auckland earthquakes represent normal background seismicity rather than eruption precursors (Sherburn et al. 2007).

6 EXERCISE RUAUMOKO

6.1 *Background*

Although the volcanoes in Auckland are small and their eruptions have been infrequent, the risk associated with future activity is very high given the high physical and economic vulnerability of Auckland (population 1.3 million; 2006 census). In recognition of this, in 2008 the New Zealand government ran Exercise Ruaumoko, a test of New Zealand's nationwide arrangements for responding to a major disaster resulting from a volcanic eruption in Auckland. The exercise took approximately 18 months to plan, and included the participation of over 120 organisations at local, regional and national levels. The exercise scenario was developed in secret and covered the two week period of precursory activity up until the eruption. Exercise Ruaumoko provided an excellent and rare opportunity to test a large number of mitigation, scientific and technical procedures in this uncertain geological environment. Some of the main lessons learned during Exercise Ruaumoko are outlined below.

6.2 *Impacts, consequences and lessons learned*

Although a future eruption in Auckland would be relatively small, its effects would be devastating to the economy of New Zealand. Through the recent Eyjafjallajökull eruption in Iceland (March-April 2010), the world is now familiar with the ability of a relatively small eruption to have a devastating economic impact purely because of its location with respect to vulnerable infrastructure and services (in this case European air transport hubs). In Auckland, the evacuation of hundreds of thousands of people and likely closure of the international airport would have a huge impact, modeling of a worst-case near-CBD eruption by Auckland consultants Market Economics anticipates that the Auckland region would suffer a 47% reduction in gross domestic product (GDP), but this could be reduced to 40% if businesses had effective mitigation and preparedness measures in place. The rest of the North Island, together with the South Island, would benefit somewhat from the relocation of some displaced businesses to their regions, with an estimated 3% increase in GDP. Overall, this would result in a 14% decline in GDP for New Zealand, which could be reduced to 12% with effective industry preparedness (Exercise Ruaumoko, Final Report 2008). In comparison, the drop in GDP during the Great Depression in the 1930s was only 7%.

The exercise highlighted the difficulties in calling a mass evacuation in a situation where the source of the hazard (the eruption vent) is not known until shortly before the outbreak. Auckland emergency managers now have a better appreciation of the trade-off between certainty in eruption location and time available (i.e. the longer you wait the more certain the vent location but the shorter the time available to complete the evacuation). The authorities and scientists are now working together to investigate the possibility of using probabilistic methods of eruption forecasting to aid decision making (e.g. Lindsay et al. 2010; Lindsay et al. this volume).

A mass evacuation itself in Auckland would be a huge challenge; a recent GIS study showed that any mass evacuation out of Auckland from an AVF eruption would almost certainly cause gridlock (Tomsen 2010), and went on to recommend that an effort be made to plan for evacuation within the Auckland region.

Good communication proved vital during Ruaumoko: communication between scientists and the authorities, and between the authorities and the media. Scientists need to know in advance how the authorities would like information about the volcano delivered (especially uncertainties and likelihoods) in order to avoid misunderstandings. Messages through the media should be given at the first sign of volcanic unrest, and should be simple and short and always contain clear instructions on what to do.

7 ONGOING AND FUTURE RESEARCH

Since 2008 there has been a boost in research into the hazard and risk associated with the Auckland Volcanic Field through the multi-disciplinary, multi-agency **DE**termining **VO**lcanic **R**isk in **A**uckland (DEVORA) research programme. This effort has core funding from the New Zealand Earthquake Commission (EQC), Auckland Regional Council (ARC), The University of Auckland and GNS Science.

The Geological theme of DEVORA aims to integrate structural, petrological and geophysical data into a geological model of the AVF to explain source-to-surface magma migration and dynamics. The Probabilistic Volcanic Hazard theme focuses on creating a realistic volcanic hazard outlook for Auckland, using dating and tephrochronology to assess magnitude-frequency patterns and possible spatio-temporal trends. In the Risk and Social theme, the economic and social effects of an AVF eruption on Auckland and the rest of New Zealand are being investigated, and a quantitative risk assessment and emergency management risk reduction framework for Auckland's vulnerable groups and structures prepared.

Some of the key questions currently being addressed are:

How will groundwater, seawater and the soft substrate affect the initial stages of an eruption? Is the 5 km evacuation radius realistic?
Can we produce a useful spatio-temporal model to predict areas of likely vent opening?
How will magma behave as it rises, and what signals will it give?
How intensive should the monitoring be to provide adequate warning of an AVF eruption?
Can we develop hazard maps for monogenetic fields where precursory seismicity is likely to at best provide a wide zone of possible outbreak sites rather than a point source?
How can probabilities and uncertainties best be communicated to emergency managers?
What are the flow-on effects nation-wide from an eruption affecting Auckland?

Despite the uncertainties associated with a future AVF eruption, scientists, authorities, lifeline organisations and funding agencies are all working together to ensure that New Zealand is well prepared should the volcanic field become restless again.

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