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Coupled eruptions in the Auckland volcanic field: are we underestimating the threat to our city? (#17/U745)

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1. Summary

Of the 53 volcanic centres identified in the Auckland volcanic field, twenty are defined as "coupled". This term is here defined are eruptions that have occurred close in space (≤ 1 km apart) and time (≤ 1 kyrs apart, but generally ≤ 100 yrs apart). The geochemical relationship between these twenty couplets was investigated using major, trace and isotope chemistry to determine if their coupled natures is linked to the mantle source processes. Using the geochemical characteristics of the two centres in a couplet, the couplets are initially split into four groups, which is then reduced to two groups during investigations. Group 1 shows a geochemical evolution from a less evolved source in the first eruption, to a more evolved source for the second eruption. Group 2 shows no geochemical variation between the first and second eruptions. Hypotheses for mantle mechanisms that could form both of these types of eruption scenarios are proposed and tested. Our results suggest that neither fractional crystallisation or crystal assimilation on ascent are responsible for the geochemical signatures identified. However, partial melting of a heterogeneous mantle source could be used to explain the signatures seen for both the Group 1 and Group 2 geochemical signatures.

Additionally, we identify two overprinted structural controls on the ascent dynamics of the rising melt. These include 1) the interaction of the Dun Mount Ophiolite Belt (DMOB), with perpendicular E-W trending faults controlling the location of the volcanic field, and 2) the shallow crustal NNE-SSW trending faults that dictate the locations of the coupled volcanic centres themselves.

2. Introduction
Monogenetic basaltic volcanic fields are common across the globe. The term monogenetic implies these centres are active only once, from one batch of magma, and the eruptions are discrete in both space and time. However, previous studies have highlighted this understanding is far too simplistic. In Wudalianchi (China)

evidence exists for both monogenetic and polygenetic centres erupting coevally in a single field (Hwang et al., 2005). In Michoacan-Guanatuato (Mexico), Connor (1990) showed that the volcanic field evolved from polygenetic to monogenetic as vents moved from north to south. In Springerville volcanic field (Arizona), the location of the eruptive centres is strongly influenced by pre-existing faulting (Condit and Connor, 1996), and in San Francisco volcanic field (Arizona), the centres are observed to migrate relative to plate motion (Tanaka et al., 1986). Additionally, in Ojika Jima (Japan), Auckland volcanic field (AVF: New Zealand), Sand Mountain volcanic field (Oregon), and Michoacán-Guanajuato volcanic field (Mexico), clustering of multiple monogenetic eruptions in both space and time has shown evidence for "flare-ups" in activity (e.g. Molloy et al., 2009; Guilbaud et al., 2012; Le Corvec et al., 2013; Deligne et al., 2016; Mahgoub et al., 2017; Leonard et al., 2017; Reyes-Guzmán et al., 2018). This clustering of eruptions has been attributed by Smith and Németh (2017) to the shallow surface expression of a spatially diverse magmatic plumbing system with episodic eruptive events. In comparison, however, Condit and Connor (1996) discuss clustering of events as a result of localised deep mantle melting events. In addition, and more controversially, "flare-ups" in activity have also been linked to external forcing events, for example, changes in sea level (e.g. Sporli et al., 2015).

As well as the structural complexities and physical relationships of the vents, the geochemical signatures of these monogenetic vents can also be complex. The small volume of the magma batches allows remarkably small-scale changes in the geochemical variations to be observed, which in larger systems are often homogenised and lost (McGee and Smith, 2016). The primitive nature of the magmas coupled with the absence of shallow crystallising phases (e.g. Smith et al., 2008), presence of mantle xenoliths (e.g. Sporli et al., 2015), and limited crustal contamination (e.g. Hopkins et al., 2016) suggests there is a lack of crustal stalling of the melt that reaches the surface. This lack of melt modification on ascent has allowed detailed analysis of source characteristics to be undertaken. For example, many monogenetic vents are commonly characterised by changes in geochemical composition throughout an eruption sequence (e.g. Smith et al., 2008; McGee et al., 2012; Larrea et al., 2019) often associated with the volcanic stratigraphy (e.g. Houghton et al., 1999; Brenna et al., 2010; Németh et al., 2003; Rasoazanamparany et al., 2016).

The eruptive products at intraplate monogenetic volcanic fields can range through the full spectrum of magma types, but are most commonly associated with relatively primitive basalts. Within the basaltic spectrum the geochemical compositions can range from Si-undersaturated nephelinite to Si-saturated tholeiite within a field as a whole, or even within a single eruption. (e.g. Smith and Németh, 2017). Systematic evolution of the magma during the course of an eruption has been identified by some studies, whereby magma that erupts early in the sequence is typically relatively evolved (with lower MgO, higher total alkalis and higher incompatible elements) in comparison to the magma that erupts later in the sequence (e.g. Reiner, 1998, 2002, McGee et al., 2012). Previous studies have also identified a significant correlation between the erupted volume of magma and the geochemical composition, where smaller volumes are generally alkaline and Si-undersaturated whilst larger volumes have higher Si contents and are generally less alkalic (e.g. McGee et al., 2015; McGee and Smith, 2016; Smith and Németh, 2017).

Present research has focused on what the geochemistry or the eruptive products of the volcanoes can tell us about the mantle source mechanics and the processes that generate the magma itself. It is now widely accepted that very few monogenetic volcanoes have their source in a simple homogeneous mantle volume (McGee and Smith, 2016), instead they are sourced from multiple heterogeneous sources including the involvement of discrete, enriched domains (e.g. McGee et al., 2013, 2015; McGee and Smith, 2016). The mixing of multiple mantle sources is identified by the range in trace element and isotopic ratios seen in the products of the volcanic fields (e.g. Cook et al., 2004; Smith et al., 2008; Brenna et al., 2010, 2012; Needham et al., 2011; McGee et al., 2012, 2013; Deligne et al., 2016). Typical findings from these studies show evidence for interaction between asthenospheric (garnet bearing) and lithospheric (spinel bearing) sources (defined by their geochemical compositions), and commonly propose an ascent model in which the melt batch starts deep and ascends rapidly, with variable degrees of interaction with the rocks through which it ascends (e.g. Hopkins et al., 2016). This process is however, suggested to vary depending on the tectonic setting (e.g. intraplate vs. extension vs. arc).

Upwelling rates of melt batches at intraplate monogenetic volcanic fields have been studied through U-Th isotopes and show a range between 0.1 – 1.6 cm/yr (Zou et al., 2003; Demidjuk et al., 2007; McGee et al., 2011). McGee et al. (2011) took this study further using Ra isotopes to show that the two eruption events from Rangitoto volcano (Auckland volcanic field, New Zealand) could be modelled via two differing ascent pathways, the first through a slow, diffuse porous-like flow and the second through a high-speed, deep channelised conduit flow. Ascent rates have also been studied through diffusion profiling, with Brenna et al. (2015) suggesting ascent from source could occupy on the order of weeks to months, and ascent through the upper crust on the order of a few hours.

Such complex behaviour in the physical and geochemical properties of global volcanic fields therefore suggests the future eruption characteristics could be very difficult to predict, and in areas where the fields are located close to large urban centres (e.g. Chichinautzen and Michoacán-Guanajuato volcanic fields close to Mexico City), these uncertainties can lead to difficulties in formulating accurate hazard and risk management plans. In addition to their complex structural and tectonic controls, and variable mantle source dynamics, commonly there is a lack of well-constrained and accurate age data for active volcanic fields (e.g. Lindsay et al., 2011). This lack of age constraints leads to an inability to determine the repose periods for eruptive activity, and thus determine the temporal and spatial relationship between the eruptions. These factors can lead to a number of ambiguities when attempting to physically characterise when, where and what a future eruption will be like.

Recent research in the Auckland volcanic field has produced age estimates for 48 of the 53 volcanic eruptions in the AVF (Hopkins et al., 2017, Leonard et al., 2017) allowing the repose periods and temporal relationships of the eruptions to be quantified. In this research we investigate “coupled eruptions” identified through these new findings. The coupled eruptions are defined as a pair of centres that show a strong relationship in their timing (≤1 ka, but commonly ≤100 yrs repose) and location (≤1 km apart) within the field as a whole. Using major element, trace element and isotopic geochemistry, we investigate the geochemical relationship between these eruptions in order to determine if they are indeed linked in their mantle source(s) and/or their ascent dynamics as well. We investigate the impacts of fractional crystallisation, crustal contamination, and partial melting on the relationship between the couplets, and use these relationships to investigate the source mechanisms and ascent pathways. We also discuss the impact that structural constraints have on the vent location of the second eruption in the couplets.

3. Objectives

At the conception of this project, Hopkins (2015) had identified 20 centres as being coupled (in addition to the already known Rangitoto 1&2, Purchas Hill and Mt Wellington, and Motukorea 1&2). Of the twenty identified, five were highlighted as not having enough major and trace element data, and twelve did not have enough isotopic data to be useful to this investigation. Therefore, the first objective of this research was to sample material from the centres lacking data and run analyses for major and trace element concentrations and isotopic ratios. Following this, the data gathered were assessed in order to answer the key overarching objectives for this project. These were outlined in the project proposal and are detailed below. These objectives are then used to structure the section below on "Conclusions and key findings".

1. Do the remaining coupled centres show the same geochemical relationship as those already investigated? *(e.g. Increasing SiO_2 and Mg#, decreasing LREE/HREE element ratios, and decreasing $^{206}Pb/^{204}Pb$ isotope signatures between eruption 1 and eruption 2?)*
2. If so, can they officially be classes as "coupled" in space, time *and* geochemistry? *(e.g. How common is this phenomenon in the AVF?)*
3. What can the geochemical signatures tell us about the mantle source processes responsible for these eruptions? *(e.g. Are the geochemical signatures consistent with previous research, and if not, why?)*
4. Are these mantle mechanics predictable based on the geochemical signature of the erupted products? *(e.g. If there is another eruption in the AVF and we can sample the products, can the geochemistry tell us about the source of the magma, and the likelihood of a coupled eruption occurring?)*
5. Do crustal weaknesses influence the surface expression of the eruptions? *(e.g. if there is sub-surface faulting does this allow the magma to ascend more easily and cause couplets rather than dual eruptions from a single centre?)*

4. Conclusions and key findings

4.1 Sampling and field work

As outlined above, the centres Rangitoto 1&2, Motukorea 1&2 and Purchas Hill plus Mt Wellington were already proposed to fall into the category of "coupled". The new centres identified at the onset of this study included Green Mt and Styaks Swamp, Otara and Hampton Park, Mt Eden and Te Pou Hawaiki, Wiri Mt and Ash Hill, Mangere Mt and Mangere Lagoon, Domain and Grafton Park, Tank Farm and Onepoto (**Table 1, Fig. 1**). In addition to these seven couplets, during field work and initial assessment of existing age data the centres Pukeiti and Otuataua were added to the list of couplets.

Samples for this study were obtained either from the University of Auckland (UoA) collection or, where samples did not exist, through new field sampling. Centres sampled in the field included Ash Hill, Mangere Lagoon, Tank Farm and Onepoto. For those centres without exposed lava or scoria outcrops juvenile material was collected from within the tuff rings (e.g. for Ash Hill, Tank Farm and Onepoto).

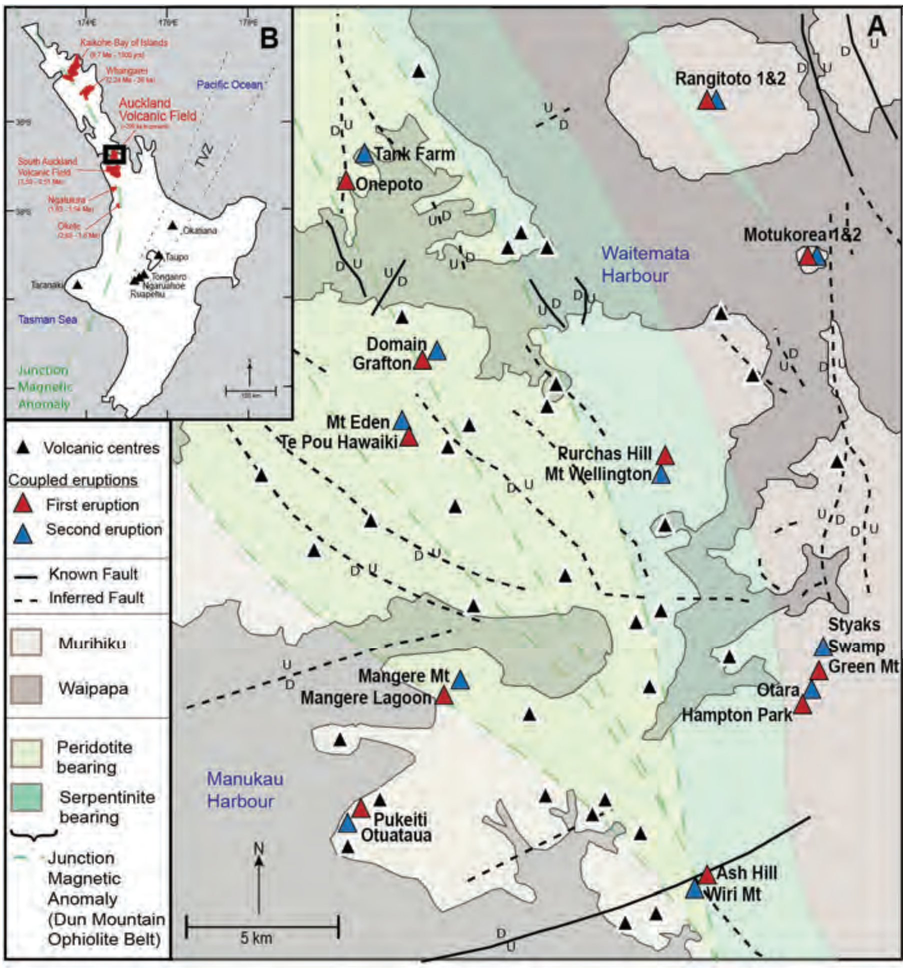

Figure 1. A) *Location map of the Auckland volcanic field (AVF), including the sites of the coupled eruptions (first eruption in red, second eruption in blue). Known and inferred surface faults are shown (from Kenny et al., 2012), and geological basement rocks are highlighted along with the trace of the Dun Mountain Ophiolite Belt and its dominant compositions (from Eccles et al., 2005).* ***B)*** *North Island, New Zealand, including the location of the AVF and the other monogenetic volcanic fields. Also highlighted in green is the location of the Junction Magnetic Anomaly (JMA) or Dun Mountain Ophiolite Belt (DMOB), and the location of the Taupo Volcanic Zone (TVZ) and other currently active or dormant volcanoes found on the North Island, including Taranaki (Egmont), Ruapehu, Ngauruhoe, Tongariro, Taupo and Okataina.*

4.1.1. Pukeiti and Otuataua

At present, the absolute and relative ages of Pukeiti and Otuataua remain poorly defined. Pukeiti has an unreliable K-Ar age of 32 ± 6 ka (McDougall et al., 1969), an Ar-Ar age of 11.4 ± 3.6 ka (1 sd) (Leonard et al., 2017), and a low-confidence tephra correlation age of 15.3 ± 0.65 ka (Hopkins et al., 2017). Otuataua has two unreliable K-Ar ages of 29 ± 10 ka and 36 ± 6 ka (1sd), which are now believe to be overestimates due to contamination from excess Ar (Lindsay et al., 2011), and a low confidence tephra correlation age of 24.2 ± 0.88 ka (Hopkins et al., 2017). Therefore, to distinguish the age relationship between these two centres the geomorphology was assessed. Searle (1959) identified a number of lava flows in this region, and suggested that flows from Pukeiti appeared to flow under those of Otuataua, and no soil horizons were identified between these flows. In addition, flows from Pukeiti were apparently "thinly coated in ash" (Searle 1959), however those from Otuataua were not. From this we suggest that Pukeiti represents a small initial eruption, followed by the first phreatomagmatic phase of the eruption of Otuataua which produced ash that fell on Pukeiti and the surrounding area, and was then covered over in the Otuataua area by subsequent flows from the volcano (**Fig. 2**). They therefore qualify as coupled eruptions as they have erupted both close in space (≤ 1 km) and time (here estimated as ~50 years due to no soil formation between the respective deposits).

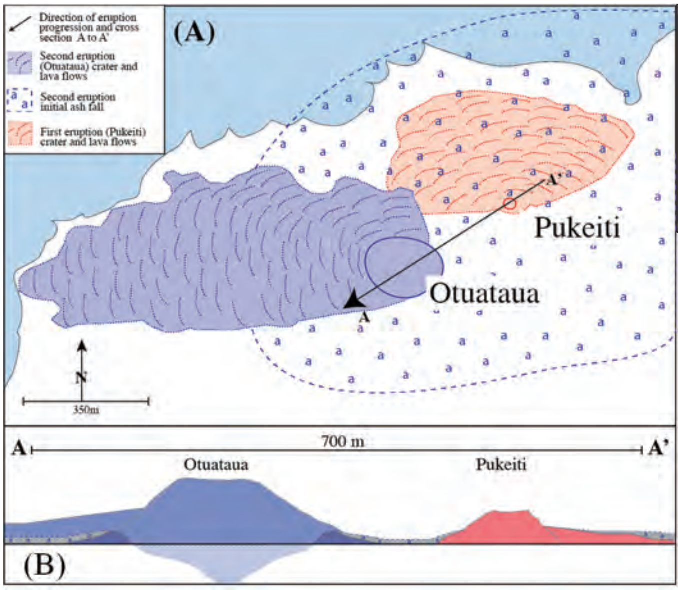

Figure 2. A) *To scale sketch of the proposed morphological relationship between the Otuataua and Pukeiti centres,* ***B)*** *cross section view, highlighted on image (A) as a arrowed line between A and A'. The arrow indicates the general movement of the eruptions from Pukeiti to Otuataua.*

4.1.2. Ash Hill

This centre was sampled at a site located at 284 Wiri Station Road, on the corner of Ash Road and Wiri Station road. The in-situ tuff section within the carpark represents the remainder of a ca. 4 m high tuff ring section that has been removed at this point through urbanisation (**Fig. 3**). The deposit is very sparse in juvenile basaltic material, which is mixed in with larger amounts of wood, peat, charcoal and country rock. This is indicative of the paleo-forest which was destroyed by the eruptions of Ash Hill and Wiri Mt. A collection of small juvenile fragments was taken from within the tuff ring deposits.

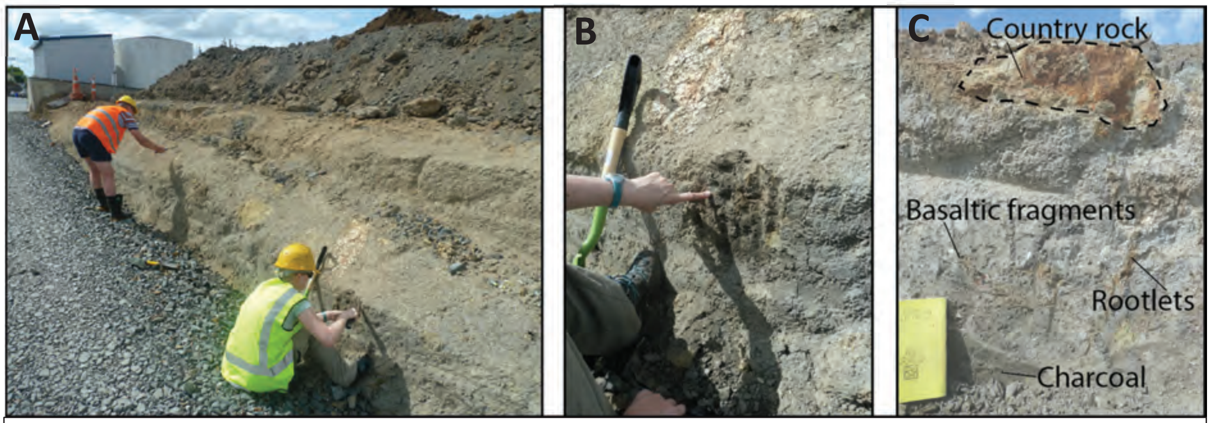

Figure 3. *Images to show the location and sampling of Ash Hill tuff section.* ***A)*** *Field assistants Bruce Hayward and Elaine Smid pull out juvenile basaltic material from within the tuff.* ***B)*** *Large bomb of juvenile basaltic material presumed from the Ash Hill eruption with sag structures into the tuff beneath. This was sampled as a juvenile clast.* ***C)*** *Representative cross section through the tuff to show the componentry including large intact blocks of country rock, juvenile basaltic fragments, preserved rootlets and charcoal.*

4.1.3. Mangere Lagoon

Three sites were visited and sampled from the Mangere Lagoon centre (**Fig. 4A**). Site 1 is a small exposed section of tuff ring at the south eastern edge of the crater. Site 2 is the central cone, where original outcrop from a small scoria cone that was built during the eruption was sampled from below the high tide mark. Site 3 is an exposed section of tuff ring, overlain by lava flows from Mangere Mt (**Fig. 4C**). This field relationship had not been identified before, and therefore added extra support to the temporally-coupled nature of these two eruptions.

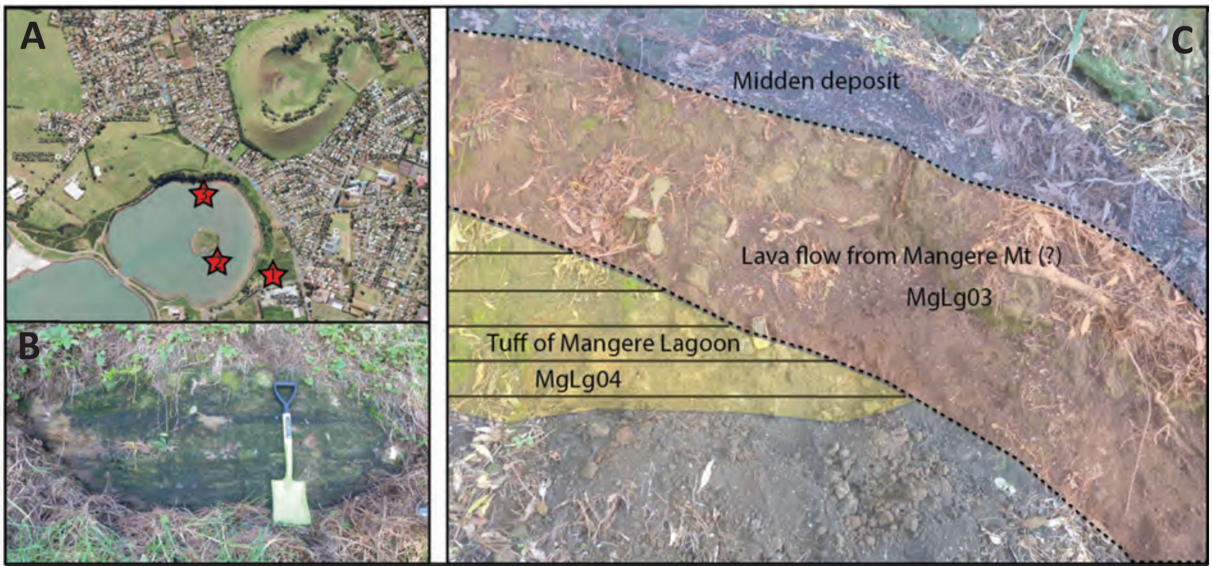

Figure 4. *Images from the Mangere Lagoon site.* ***A)*** *map view of sample locations with Mangere Lagoon crater and central scoria cone at the bottom of the image and Mangere Mt's large scoria cone and triple crater seen in the top of the image. The site locations discussed in the text are highlighted by the red stars.* ***B)*** *Overgrown outcrop of the tuff ring found at location 1, from which juvenile basaltic material was taken for analysis.* ***C)*** *Cross cutting relationships identified between the Mangere Lagoon tuff (yellow) and a lava flow from Mangere Mt (red), above which was a Maori midden deposit (purple).*

4.1.4. Tank Farm

Fortuitously, a new section of slumped tuff ring deposits was recently exposed in the north eastern rim of the crater. A 2-3 m vertical exposure of layered sandy, tuff deposit was identified with a moderate concentration of juvenile basaltic clasts (**Fig. 5A**). Clasts were highly weathered and potentially altered therefore their usefulness for analysis was questionable (**Fig. 5B**).

4.1.5. Onepoto

An exposure of tuff ring was identified on the south eastern rim of the crater, close to the on-ramp at junction 421 of State Highway 1. The exposure is heavily overgrown, 5-6 m above the road and, at the time of writing, is impossible to access. As a result, no samples were obtained for Onepoto.

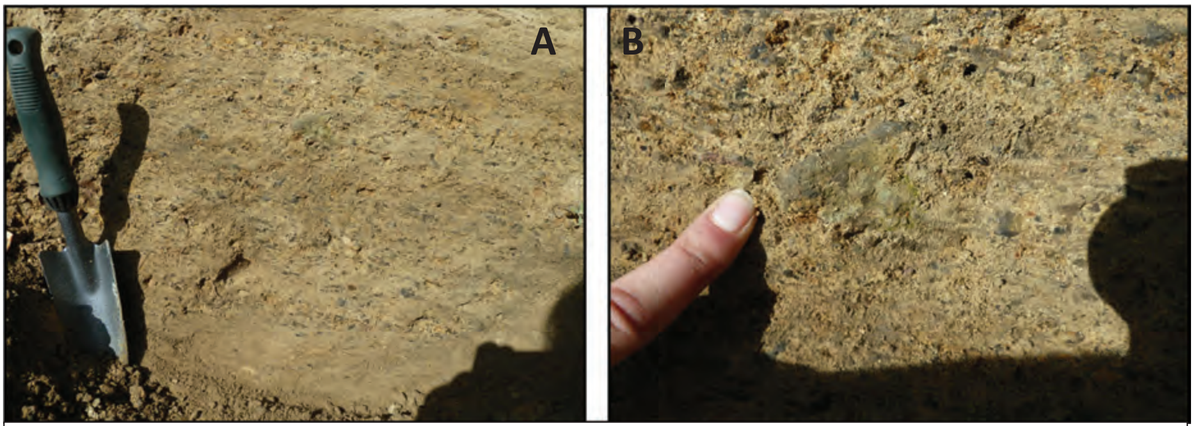

__Figure 5.__ Photographs of site location at Tank Farm crater. ***A)*** *general view of the tuff outcrop with a large country rock component (sandy coloured material) with a number of darker clasts representing the juvenile basaltic material.* ***B)*** *weathered juvenile basaltic material.*

4.2. Methods

Fresh bulk rock samples were crushed using a Rocklabs Boyd crusher to chips of <15 mm in size, then powdered using a TEMA tungsten-carbide swing mill at UoA. Powdered samples were then split into aliquots for major element, trace element and isotopic analysis. For major element analysis, powders were made into fused lithium metaborate glass discs (1g sample to 10g (12:22) flux) and were analysed by X-Ray Fluorescence (XRF) at Macquarie University (Australia) using a PANalytical Axios 1kW Spectrometer. Rock standards BRC-2, BIR-1 and BHVO2 were run between every 10 samples. Trace elements were analysed by solution ICP-MS at Victoria University of Wellington (VUW). Samples were prepared using conventional HF-HNO_3 digestion techniques, then analysed on an Agilent 7500CS ICP-MS. Bracketing standard BHVO-2 and internal standard BCR-2 were run between every 5 samples. Individual analyses were run for 120s durations preceded by a 30s water wash, 180s 1% HNO_3 wash out, and a 60s 1% HNO_3 background analysis. Trace element abundances were calculated using the reduction program Iolite (Paton et al., 2011) using ^{43}Ca as an internal standard, calculated from CaO contents measured by XRF. For the XRF analysis analytical precision for all elements on both standards is 0.25 (2sd) or better, and accurate to within ≤ 3% of the standard value. Trace element analyses were accurate to within ≤10% of the standard value with the exception of Hf ±12 %, Cr ±12 %, Zr ±14 %, Th ±16 %, Cs ±22 %, Rb ±38 % and Pb ±39 %. The analytical precision is ≤ 2.5 (2sd) with the exception of V ±14.0, Sr ±14, Zr ±23 and Ba ±31. Isotopic analyses (Pb, Sr, Nd) were undertaken at Geomar Helmholtz Centre for Ocean Research (Kiel, Germany) on a TIMS.

4.3. Key Findings

4.3.1. Do the remaining coupled centres show the same geochemical relationship as those already investigated? *(e.g. Increasing SiO_2 and Mg#, decreasing LREE/HREE element ratios, and decreasing $^{206}Pb/^{204}Pb$ isotope signatures between eruption 1 and eruption 2?)*

Based on the major and trace element geochemical signatures of the centres identified as coupled we initially place them into 4 groups (which is later reduced to two on further investigation, detailed below; **Table 1**). The geochemical characteristics of each group are discussed in detail below. However, in general Group 1 couplets show evolution from eruption 1 to 2, from primitive to more evolved geochemical types, for example; low SiO_2 (~40 wt.%) to high SiO_2 values (~46 wt.%); and from high incompatible element ratios (e.g. $(La/Yb)_N$ ~40) to low incompatible element ratios (e.g. $(La/Yb)_N$ ~20). Group 2 couplets exhibit indistinguishable geochemical signatures regardless of eruption order or edifice size. Group 3 couplets show the inverse of the relationship of Group 1, and Group 4 couplets do not have enough data to be investigated and are therefore not discussed further.

4.3.1.1. Group 1

Bivariate plots of selected major, trace and trace element ratios are presented in **Figure 6**. Between the first and second eruptions the samples produce similar trends in these diagrams, for example, major elements TiO_2, FeO, MnO, CaO, Na_2O, K_2O and P_2O_5 decrease with increasing SiO_2, whereas, Al_2O_3 increases with increasing SiO_2. The relationship between MgO and SiO_2 is variable between the different centres. For Motukorea 1&2 and Purchas Hill plus Mt Wellington, MgO contents increase within increasing SiO_2, and for Rangitoto 1&2 and Pukeiti plus Otuataua, MgO contents decrease with increasing SiO_2. Incompatible trace elements such as La and Ba decrease with increasing SiO_2, whereas compatible trace elements such as Ni and Cr show a similar relationship with SiO_2 as MgO.

Between the first and second eruptions there is also a decreasing trend between CaO and MnO (wt%) showing a transition to decreasing clinopyroxene and pyroxenite in the second eruption. A decreasing trend is also observed between the first and second eruptions for mantle normalised ratios of HREE/LREE (e.g. Gd/Yb_N vs. La/Yb_N) suggesting an increasing lithospheric input with increasing spinel content over garnet content and increasing fluid input between the first and second eruptions. This is also supported by the strontium anomaly Sr^*_N vs. Th/Yb, and Sr^*_N vs. K/La ($Sr^*_N = Sr_N/\sqrt{(Pr_N \times Nd_N)}$). The Pb isotope ratios ($^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$) plot in general in a triangular pattern previously attributed by McGee et al. (2013) to the influence of three mantle sources: HIMU, ambient asthenospheric mantle and lithosphere. For the Group 1 couplets the Pb isotopes progress towards more lithospheric-like signatures from the first to second eruptions (cf. **Figure 6**).

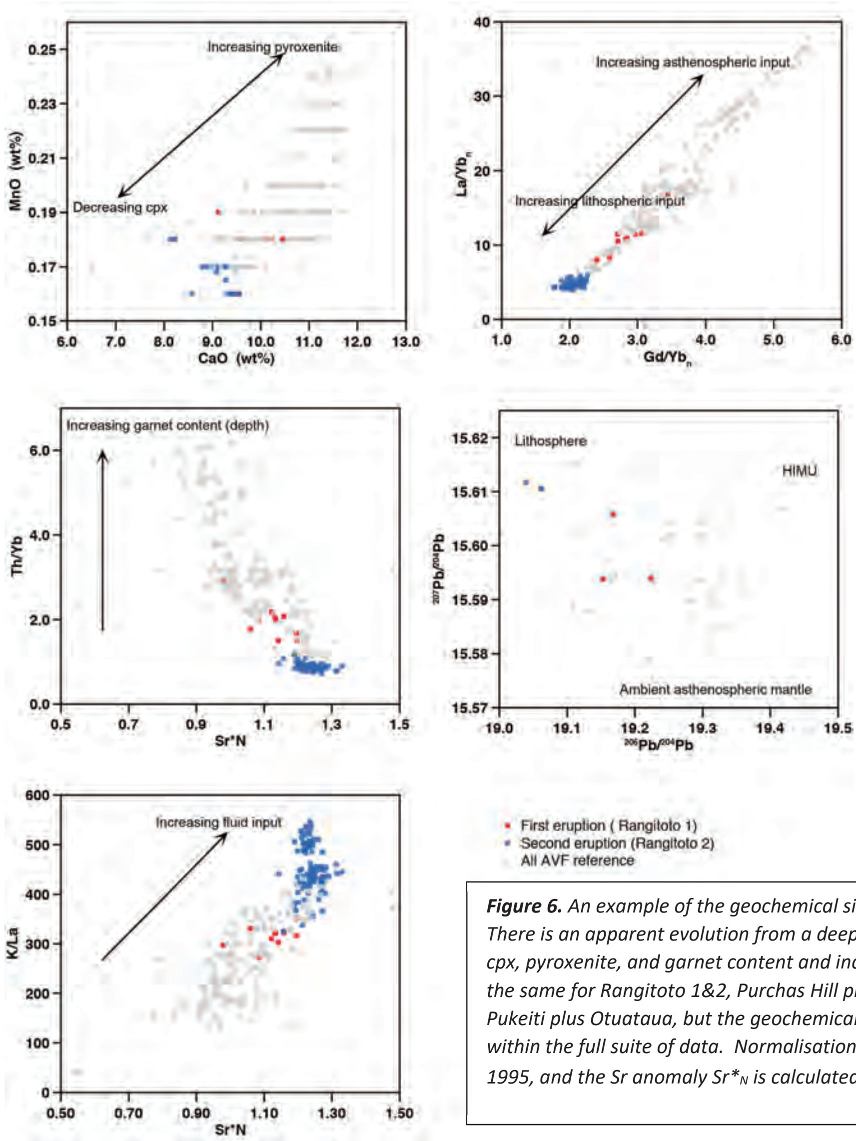

Figure 6. *An example of the geochemical signatures seen in the Group 1 relationships. There is an apparent evolution from a deeper to shallower source, with decreasing cpx, pyroxenite, and garnet content and increasing fluid input. These signatures are the same for Rangitoto 1&2, Purchas Hill plus Mt Wellington, Motukorea 1&2, and Pukeiti plus Otuataua, but the geochemical concentrations vary in their position within the full suite of data. Normalisation values (N) are from McDonough and Sun 1995, and the Sr anomaly Sr*$_N$ is calculated by $Sr_N/\sqrt{(Pr_N \times Nd_N)}$.*

4.3.1.2. Group 2

Group 2 samples are characterized by no change in the geochemical signatures between the first and second eruptions. **Figure 7** shows the geochemical compositions of these three couplets (Mangere Mt plus Lagoon, Otara plus Hampton Park, and Domain plus Grafton Park) all sit within the mid-range of the Auckland volcanic field's overall extent. The Pb isotopic ratios plot closest to the ambient mantle signatures with no obvious digressions towards either of the extreme end members of HIMU or lithospheric mantle values.

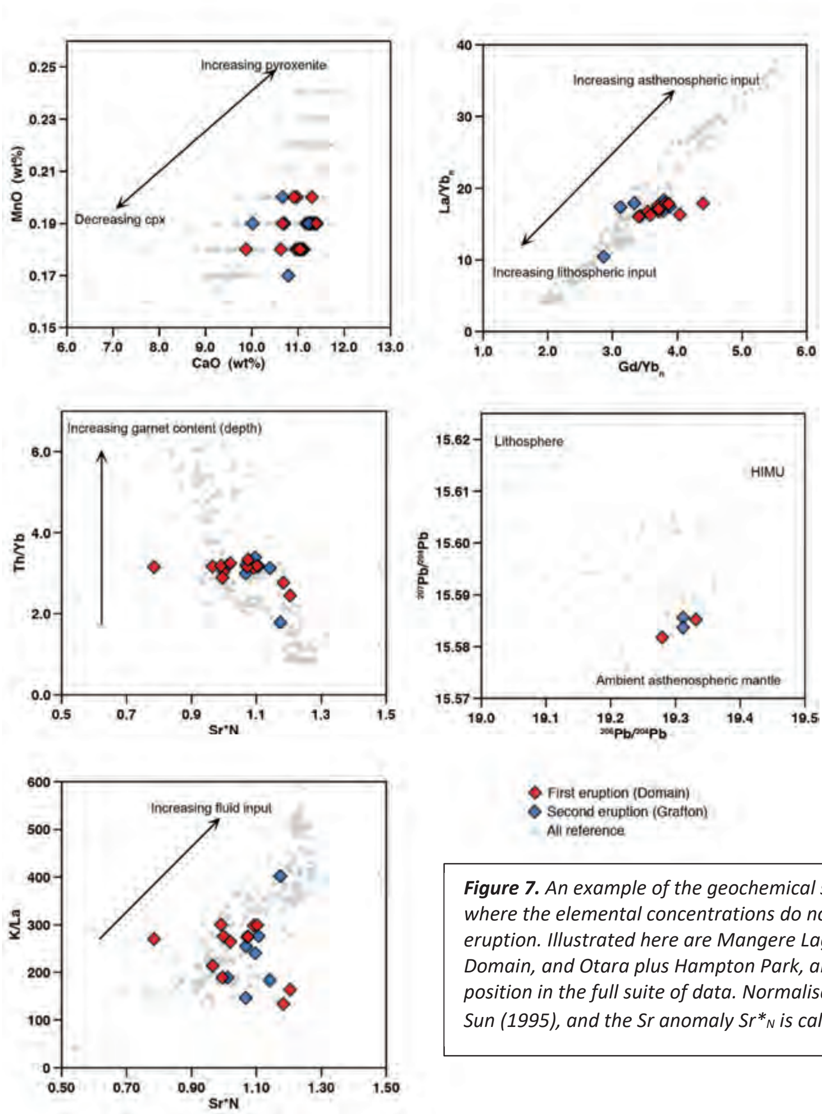

Figure 7. An example of the geochemical signatures seen in the Group 2 relationships, where the elemental concentrations do not vary between the first and second eruption. Illustrated here are Mangere Lagoon plus Mangere Mt, Grafton Park plus Domain, and Otara plus Hampton Park, and generally all sit in a similar, centralised position in the full suite of data. Normalisation values (N) are from McDonough and Sun (1995), and the Sr anomaly Sr^*_N is calculated by $Sr_N/\sqrt{(Pr_N \times Nd_N)}$.

4.3.1.3. Group 3

The relationships between the first and second eruptions of Group 3 produce more complex trends than within the Group 1 samples (**Fig. 8**). For Ash Hill plus Wiri Mt the concentrations of FeO, MnO, MgO, and Na_2O increase with decreasing SiO_2 from the first to the second eruption, whereas the concentrations of TiO_2, K_2O, and P_2O_5 are similar between the first and second eruption, and for Al_2O_3 the concentration decreases from the first to the second eruption with decreasing SiO_2. For Te Pou Hawaiki plus Mt Eden the concentrations of elements do not sit on a linear trend, instead sit on parallel trends with Te Pou Hawaiki having slightly high SiO_2 values overall in comparison to Mt Eden. The have similar TiO_2, MgO, MnO, Na_2O and K_2O values, but Mt Eden has slightly higher FeO, P_2O_5 concentrations and slightly lower Al_2O_3 concentrations to those of Te Pou Hawaiki. For the trace elements and isotope relationships between the first and second eruptions, the Group 3 samples show in general the inverse of the Group 1 samples with evidence for increasing trends in HREE/LREE (e.g. Gd/Yb_N vs. La/Yb_N) and Sr^*_N vs. Th/Yb, coupled with decreasing trends in Sr^*_N vs. K/La and $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$.

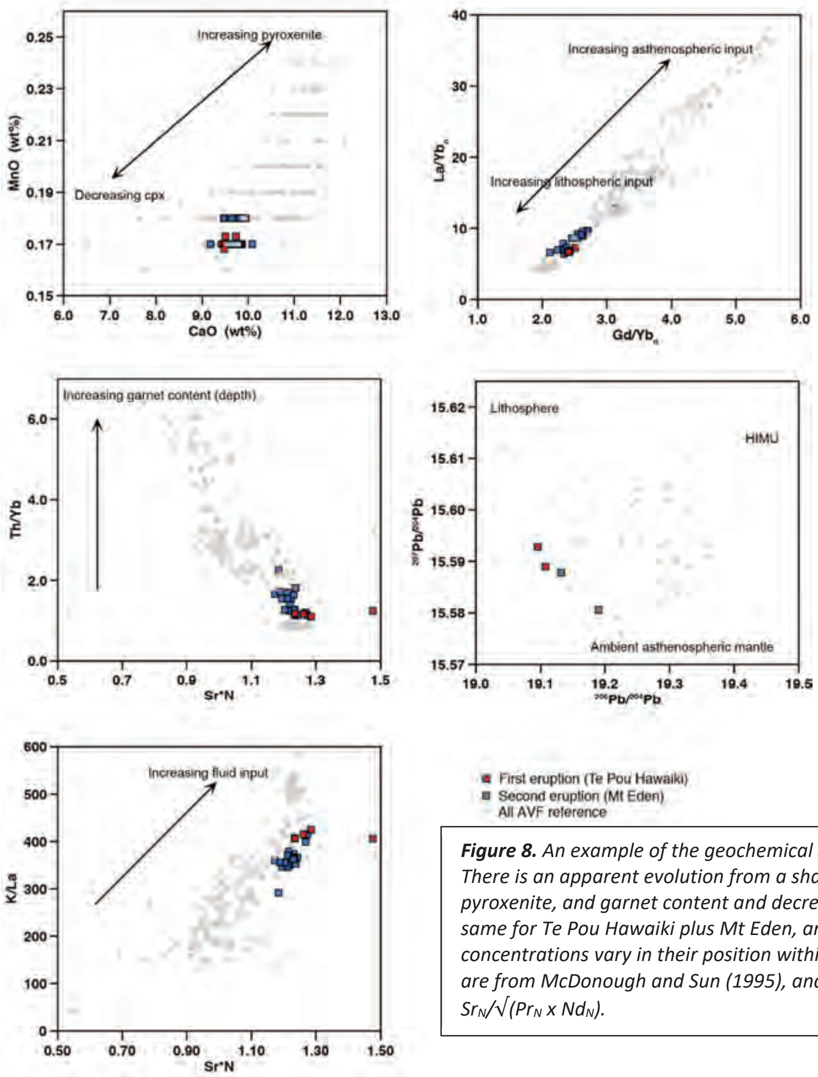

Figure 8. *An example of the geochemical signatures seen in the Group 3 relationships. There is an apparent evolution from a shallow to deep source, with increasing cpx, pyroxenite, and garnet content and decreasing fluid input. These signatures are the same for Te Pou Hawaiki plus Mt Eden, and Ash Hill plus Wiri Mt but the geochemical concentrations vary in their position within the suite of data. Normalisation values (N) are from McDonough and Sun (1995), and the Sr anomaly* Sr^*_N *is calculated by* $Sr_N/\sqrt{(Pr_N \times Nd_N)}$.

More in-depth age discussions can resolve the issues with the Group 3 signatures. For couplet Wiri Mt plus Ash Hill (Group 3), Wiri Mt has two Ar-Ar ages of 30.1 ± 2.2 ka and 31.0 ± 1.4 ka (Cassata et al., 2008), and has been placed in the Mono Lake excursion through palaeomagnetic analysis. Ash Hill has one ^{14}C date of 31.8 ± 0.2 ka (Hayward, 2008) and has a “residual magnetic anomaly” (Cassidy and Locke, 2010) but no paleomagnetic excursion data are reported. The relationship of these two centres is initially discussed in Searle (1961), where Ash Hill is described as a “minor phreatic eruption that built a tuff cone”. Searle (1961) hypothesized that as no ash from the Ash Hill eruption was found mantling the Wiri Mt lava flows, and no tuffaceous material from Ash Hill was found emplaced on top of the Wiri Mt lava flows Ash Hill must have been emplaced first. Hayward (2008) suggests that Ash Hill could have been produced by an offshoot of Wiri Mt, potentially coeval to the Wiri Mt eruptions. No studies show any evidence for Ash Hill being older than Wiri Mt, however, any morphostratigraphic evidence that could be used to resolve these uncertainties now no longer exists. The geochemical data (discussed below) suggests that these two eruptions are most likely to have occurred coevally (due to the similarity in the geochemical signatures), and that Ash Hill is therefore likely a small satellite crater of Wiri Mt.

For couplet Mt Eden plus Te Pou Hawaiki (Group 3 couplet), Mt Eden has a $^{40}Ar/^{39}Ar$ age of 21.2 ± 3.3 ka (Leonard et al., 2017), one ^{14}C age of 28.4 ± 0.3 cal yr BP (East and George, 2003), and a tephra correlation age of 28.03 ± 0.26 ka (Hopkins et al., 2017). Te Pou Hawaiki has not been directly dated, however, stratigraphic relationships suggest Te Pou Hawaiki predated Mt Eden (Bartrum, 1928; Affleck et al., 2001) but postdates Three Kings volcano (Allen and Smith, 1994). Evidence from gravity anomalies and borehole mapping suggest that Te Pou Hawaiki is in fact quite a large eruptive centre buried by subsequent Mt Eden lava flows (Affleck et al., 2001), this is supported by its geochemical signatures, discussed below (c.f. McGee et al., 2013; Hopkins, 2015). It is likely that these centres do not have a coupled relationship, but that Mt Eden flows have swamped a pre-existing cone.

Based on these stratigraphic and temporal observations, it is possible that the “Group 3” inverse geochemical relationships are only apparent, not actual genetic relationships. We therefore propose that Mt Eden and Te Pou Hawaiki are not a couplet, but are in fact an independent older centre (Te Pou Hawaiki) buried by a younger voluminous eruption (Mt Eden). We propose that Wiri Mt plus Ash Hill still remain defined as “coupled”. However, we suggest that, based on their (limited) geochemical relationship it is most likely that Ash Hill represents a satellite cone, coeval with the eruption of Wiri Mt, and therefore maybe is more suited to Group 2.

4.3.1.4. Group 4

Centres with not enough data to make geochemical comparisons or interpretations. These centres include Onepoto plus Tank Farm, and Styaks Swamp plus Green Mt.

Geochemical Group	Centre	Age (ka) (1sd error)	Method	Age Reference	Approx. age difference between the centres (yrs)	Distance between centres (m)	Volume (DRE)	Eruption Order
1	Rangitoto 2	0.504 ± 0.05	^{14}C	Needham et al., 2011	~ 50	450	691	2
	Rangitoto 1	0.553 ± 0.07	^{14}C	Needham et al., 2011			7.4?[a]	1
	Mt Wellington	10.3 ± 1.0	^{14}C	Lindsay et al., 2011	~ 60	650	82.3	2
	Purchas Hill	10.9 ± 0.2	^{14}C	Lindsay et al., 2011			1.68	1
	Motukorea 2	14.3 ± 12.0 24.41 ± 0.29	Ar-Ar, tephrostratigraphy	Leonard et al., 2017, Hopkins et al., 2017	0	0	3.6	2
	Motukorea 1						0.97	1
	Otuataua	just younger than Pukeiti	morphostratigraphy	Searle 1959	~50	350	6.3	2
	Pukeiti	11.4 ± 7.2	$^{40}Ar/^{39}Ar$	Leonard et al., 2017			3.7	1
2	Mangere Mt	70.3 ± 3.6	$^{40}Ar/^{39}Ar$	Leonard et al., 2017	~50	875	46.2	2
	Mangere Lagoon	younger than Mangere Mt	morphostratigraphy	Hayward et al., 2016			2.04	1
	Domain	younger than Grafton	morphostratigraphy	Hayward et al., 2011	Minimum ~50	300	11.4	2
	Grafton Park	older than Domain	morphostratigraphy	Hayward et al., 2011			11.4	1
	Hampton Park	55.0 ± 18.0	$^{40}Ar/^{39}Ar$	Cassata et al., 2008	~50	750	2.41	2
	Otara	just older than Hampton Park	morphostratigraphy	Hayward et al., 2011			2.3	1
3*	Wiri Mt	30.2 ± 4.6	$^{40}Ar/^{39}Ar$	Cassata et al., 2008	0 - 1600	780	16.4	2
	Ash Hill	31.8 ± 0.2	^{14}C	Hayward 2008			0.076	1
	Mt Eden	21.2 ± 3.3 24.8 ± 0.3 28.03 ± 0.26	$^{40}Ar/^{39}Ar$, ^{14}C, tephra correlation	Leonard et al., 2017	unknown	500	89.8	2
	Te Pou Hawaiki	older than Mt Eden	morphostratigraphy	Affleck et al., 2001			28.1	1
4ª	Tank Farm	181.0 ± 1.0	tephrostratigraphy	Hopkins et al., 2017	0 - 6600	720	5.87	2
	Onepoto	187.6	tephrostratigraphy	Molloy et al., 2009			2.62	1
	Styaks Swamp	just younger than Green Mt	morphostratigraphy	Hayward et al., 2011	~50	550	0.37	2
	Green Mt	19.6 ± 6.6	$^{40}Ar/^{39}Ar$	Leonard et al., 2017			12.2	1

Table 1. *Overview details of coupled eruptions in the Auckland volcanic field. Their geochemical groupings are discussed in the text and locations can be found on* ***Figure 1****. *Group 3 are removed after further chronological investigation, with Wiri Mt and Ash Hill assigned Group 2, and Mt Eden and Te Pou Hawaiki removed from the "coupled" list. ªGroup 4 are samples which do not have enough geochemical data to be useful for the geochemical assessment, but still qualify as coupled based on their age and proximity. Morphostratigraphic constraints of the ages are assigned based on field observations of the interaction between deposits from the two eruptions. Where no soil horizon has formed between the two units (usually a lava flow from the second eruption over topping a tuff ring from the first eruption) an arbitrary age of ~50 years is assumed (based on the rate of soil horizon formations in maritime conditions). For some centres the absolute ages overlap within error (e.g. Wiri Mt plus Ash Hill, and Tank Farm plus Onepoto), and therefore their absolute ages are less certain than field observation which indicate a very short repose between the two eruptions (discussed in the text). This is why some ages differences are larger than the 1000 yr cut off for the coupled relationships. The distance between the centres is calculated as a straight line between the assumed centre of the crater/tuff ring/scoria cone, and is rounded to the nearest 5 m. Volume estimates are from Kereszturi et al (2012) with the value for Rangitoto 1 (?ª) assumed from the calculated volume of the phreatomagmatic component of the Rangitoto eruptions (Kereszturi pers. comm., 2016)*

4.3.2. Using the geochemical findings can the couplets be officially be classed as "coupled" in space, time, *and* geochemistry? *(e.g. How common is this phenomenon in the AVF?).*

The geochemical results from our study suggest this originally proposed question is potentially too simplistic in light of the research outcomes. We originally considered eruptions that showed the relationship of the centres in Group 1 to be geochemically coupled, showing an evolution between two(/three) mantle sources (discussed further below). However, we also consider the geochemical relationship of the centres in Group 2 to show a linked relationship as well (again discussed further below). We therefore proposed that of the centres with geochemical data, all of them show rational geochemical relationships between the first and second eruption. Therefore, of the 53 centres in the AVF, we can propose that sixteen show a coupled relationship in space, time, *and* geochemistry, which equates to 30% of the eruptions in the field as a whole. The coupled phenomenon is spread across the life-time of the field, from inception through to the most recent eruption(s) of Rangitoto. There is an increase in the number of coupled events through time, but this could be attributed to an increased number of eruptions in general (as discussed in Leonard et al., 2017.). The duration between coupled eruptions is mostly on the order of tens of years apart (minimum eruption times), they are spaced 0-875 m apart (**Table 1**), and for all but two of the couplets the second eruption is larger in volume than the first eruption.

4.3.3. What can the geochemical signatures tell us about the mantle source mechanics responsible for these eruptions? *(e.g. Are the geochemical signatures consistent with previous research, and if not, why?)*

In order to explain the geochemical relationships seen between the Group 1 and Group 2 couplets, we propose two hypotheses for mantle source and ascent dynamics.

Hypothesis 1: the geochemical signatures represent variable amounts of stalling of the magma between eruptions 1 and 2. Eruption 2 shows evidence of a more evolved signature than eruption 1 due to fractional crystallization and crustal contamination, with the degree of evolution proportional to the duration of stalling. Stalling may allow (or may be caused by?) closure of the conduit, forcing translocation of the conduit for eruption 2. Under this hypothesis, Group 2-type eruptions are linked to the homogenisation of the source whilst stalled, and repeated tapping of this same stalled, homogenised, magma body (**Fig. 9A**).

Hypothesis 2: the geochemical signatures are formed through variable melt contributions from different mantle sources. There is limited stalling and therefore little to no evolution of the magma from assimilation, fractional crystallization, or partial melting processes. Translocation of the vent between eruptions 1 and 2 suggests some minor stalling must occur to allow the initial conduit to close and the magma to find an alternative ascent pathway. Under this hypothesis, the Group-2 type eruptions are explained by tapping of the same mantle source, leading to a similar geochemical signature between the first and second eruptions (**Fig. 9B**).

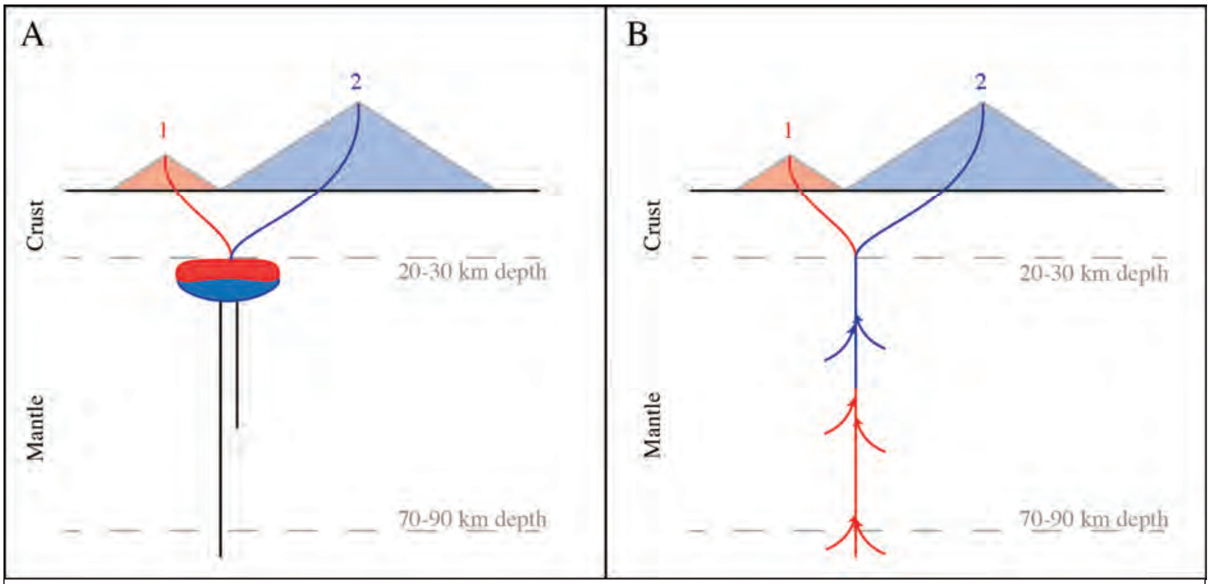

Figure 9. *Schematic images of proposed hypotheses for magma ascent.* ***A)*** *Ponding or stalling of the magma at the crust-mantle boundary prior to the second eruption, leading to a more evolved geochemical signature.* ***B)*** *Ascent of magma without any stalling where the difference in the geochemical signatures observed in the couplets is as a result of differing mantle sources, depths are proposed by McGee et al. (2013), linked to the appearance of spinel and garnet in the source signatures.*

In order to determine which of the proposed hypotheses is most likely to cause the geochemical signatures observed in the coupled eruptions for both Group 1 and Group 2, I evaluate each hypothesis with regards to crustal contamination, fractional crystallisation, partial melting, and mantle source mechanics.

4.3.3.1. The effects of crustal contamination and fractional crystallisation on the ascending melt

A number of studies from the AVF have highlighted evidence for interaction of the melt with the crust (Sporli et al., 2015; Hopkins et al., 2016) or potentially some stalling within the crust during ascent (Brenna et al., 2018). This crustal interaction or stalling, leading to fractional crystallization of and/or crustal assimilation by the ascending melt, could potentially lead to a change in the geochemical composition of the magma. For Hypothesis 1 (discussed above) the source of the magma would be the same, and the second eruption represents a more evolved version of the magma from the first eruption that has just stayed in the mantle or crust for longer. This process may thereby explain the change in the geochemistry between the first and second eruptions. If correct, we would expect to see a positive correlation between the length of time spent stalled in the mantle or crust and the degree of crustal contamination or fractional crystallisation (e.g. eruption two will show a more contaminated signature than eruption one).

Figure 10 shows that for all the isotopes (Sr-Nd-Pb) the signatures of couplets can be explained through ≤ 10 % input from the Waipapa terrane (basement metasediments, cf. **Figure 1**). However, there is a range of relationships for the coupled centres, and no systematic or consistent evolution from the first to the second eruption (e.g. **Figure 10**). For Rangitoto 1&2 the second eruption does exhibit an apparently more contaminated signature than the first eruption, but for Wiri Mt plus Ash Hill, and Motukorea 1&2, the inverse is seen, where the second eruption appears to show a more contaminated signature. For the remaining majority of couplets, they show no consistent pattern in their isotopic signatures between eruptions 1 and 2 that can be attributed to crustal contamination. This suggests that crustal contamination is not the sole cause of the geochemical relationships observed between eruption 1s and 2 of the couplets, and thus the geochemical data supports Hypothesis 2 more than Hypothesis 1 (**Fig. 9**).

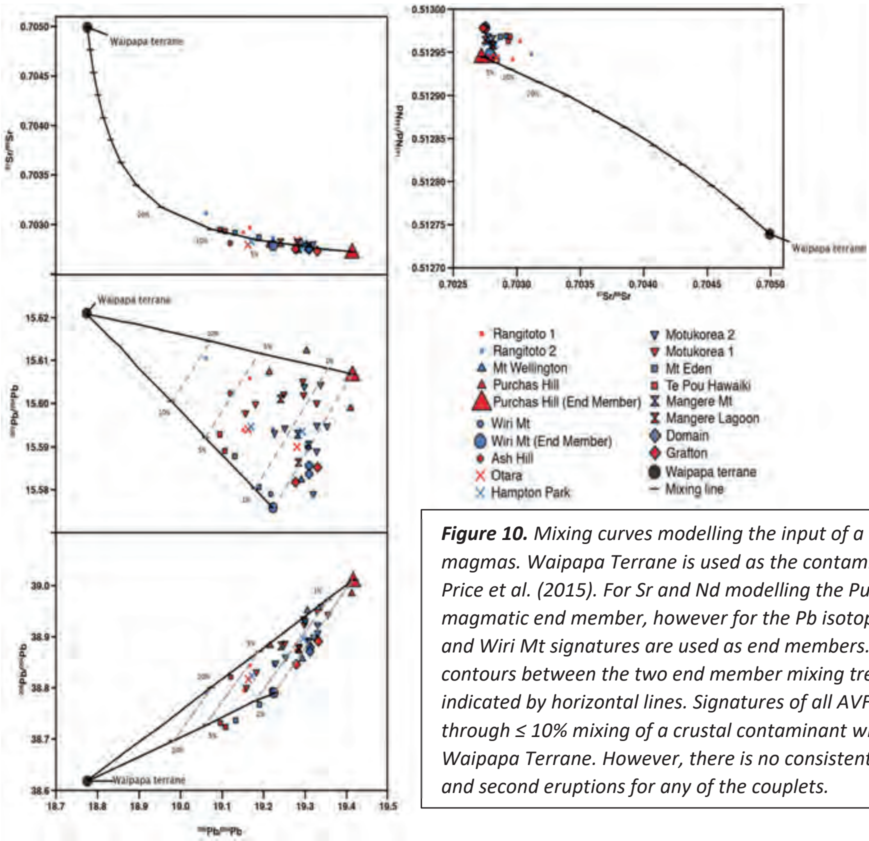

__Figure 10.__ Mixing curves modelling the input of a crustal contaminant into the AVF magmas. Waipapa Terrane is used as the contaminant signature with data from Price et al. (2015). For Sr and Nd modelling the Purchas Hill signature is used as a magmatic end member, however for the Pb isotope signatures, both Purchas Hill and Wiri Mt signatures are used as end members. Dashed lines indicate mixing contours between the two end member mixing trends, and percentage mixing is indicated by horizontal lines. Signatures of all AVF couplets can be explained through ≤ 10% mixing of a crustal contaminant with an isotopic signature like the Waipapa Terrane. However, there is no consistent relationship between the first and second eruptions for any of the couplets.

All the Group 1 centres, that show differing geochemical signatures between the first and second eruptions, were compared to the vectors of fractional crystallisation (olivine, clinopyroxene, and high pressure clinopyroxene), which have been shown previously to be responsible for some of the changes in geochemistry seen within individual eruptions (e.g. Crater Hill: Smith et al., 2008). Fractional crystallisation can occur at any stage of ascent; however, it would be more prevalent if stalling occurred, thus causing slight cooling and therefore crystallisation of the melt. **Figure 11** shows a representative example from one of the Group 1 couplets plotted with the vectors of fractional crystalllisation. Although trends are seen in some elements between the first and second eruptions, there is no consistent trend in all elements, suggesting that fractionating phases are not responsible for the change in the geochemical signatures between the first and second eruption. This lends further support to Hypothesis 2, rather than Hypothesis 1.

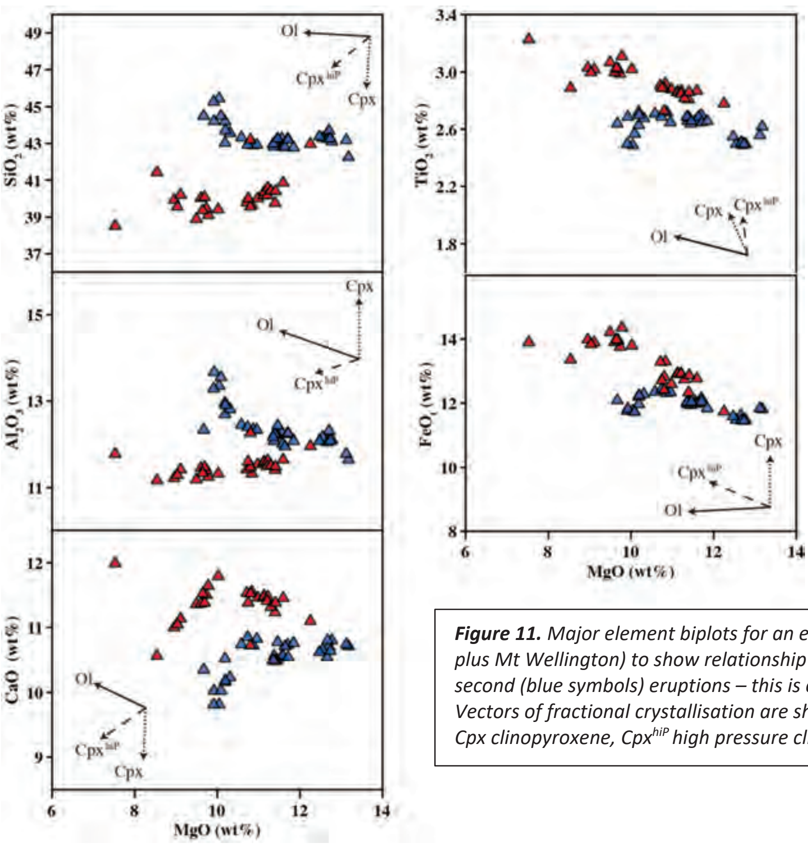

Figure 11. Major element biplots for an example couplet from Group 1 (Purchas Hill plus Mt Wellington) to show relationship between the first (red symbols) and second (blue symbols) eruptions – this is consistent for all couplets seen in Group 1. Vectors of fractional crystallisation are shown (after McGee et al., 2013); Ol olivine, Cpx clinopyroxene, Cpx^{hiP} high pressure clinopyroxene (after Smith et al., 2008).

In reality, assimilation of a crustal contaminant and fractional crystallization of a parent magma occur at the same time as "assimilation fractional crystallisation" (AFC; DePaolo, 1981). Therefore, it may be more appropriate to assess a scenario where these processes are occurring simultaneously and therefore, the combination of the two could be responsible for the change in geochemistry observed by the coupled eruptions. To model the AFC processes we use the Purchas Hill composition as the "original starting signature" as this starts at the most extreme end of the $(La/Yb)_N$ vs. $(Gd/Yb)_N$ diagram. As with the isotopic models shown in **Figure 10** we use the Waipapa terrane as the crustal contaminant (values from Price et al., 2015). We use an arbitrary rate of crystallisation and assimilation of (r=) 0.8 (similar to those suggested in Putirka et al., 2009), and model the mixing of these two end members through varying degrees of input from the contaminant (**Fig. 12**). The results show that AFC processes of ≤ 20% could be responsible for the differences seen between the signatures of the first and second eruptions for the Group 1 couplets. However, the Rangitoto 2 signatures are very similar to the signatures of the contaminant, suggesting that a much higher input (upwards of 80%) would be responsible for creating the Rangitoto-like signatures if the Purchas Hill-like signature was the sole mantle end member. In addition, this modelling is not consistent with the isotopic models produced by this study (which suggest ≤ 10 % input from the contaminant) or by previous studies (e.g. Hopkins et al., 2016) that show limited crustal contamination (≤ 1%). If it were realistic we would also expect to see isotopic signatures that were more influenced by the crustal contaminant, which we do not. These results suggest that the relationship in the geochemistry between the first and second eruptions cannot simply be explained by the evolution of a single batch of magma through stalling, fractional crystallisation and/or crustal assimilation. If stalling did however occur in the mantle we would see more limited evidence for fractional crystallisation and no crustal contamination. This evidence therefore does not rule out Hypothesis 1, but does suggest that if stalling does occur for an extended period of time to the magma that finally makes it to the surface, it is not occurring in the crustal domain.

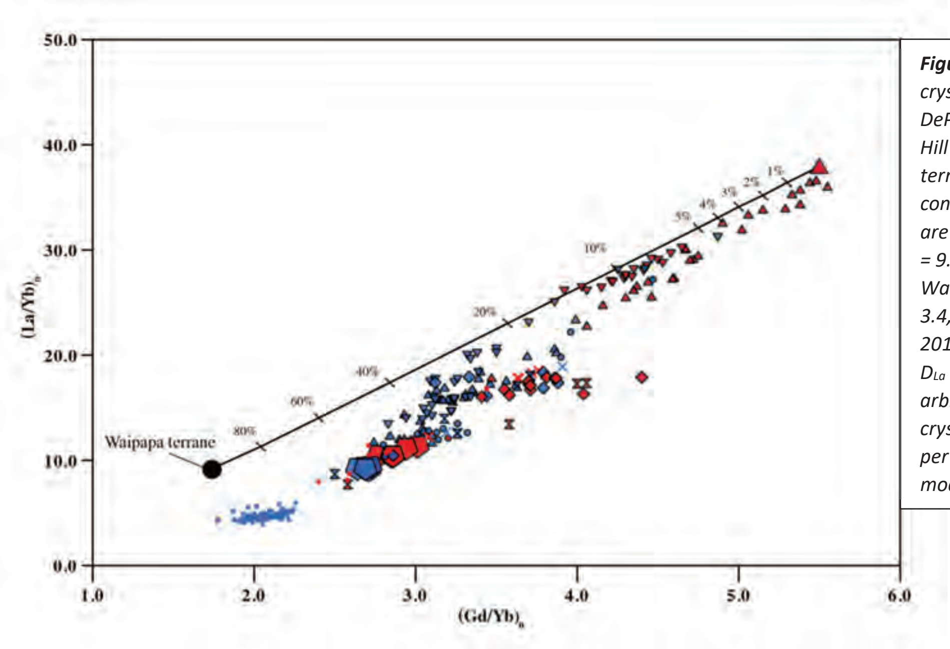

*Figure 12. Assimilation fractional crystallisation model (AFC, after DePaolo, 1981) for mixing Purchas Hill end member into the Waipapa terrane. Initial trace element concentrations used for modelling are from Purchas Hill (La = 65.6, Gd = 9.52, Yb = 1.74; from this study); Waipapa terrane (La = 17.86, Gd = 3.4, Yb = 1.59; from Price et al., 2015); Bulk distribution coefficients D_{La} = 0.09, D_{Gd} = 0.08, D_{Yb} = 0.049, arbitrary rate of fractional crystallisation r = 0.8. Symbols as per **Figure 10,** percentage AFC modelling is shown in black text.*

4.3.3.2. The effects of partial melting on the ascending melt

As show above, fractional crystallization and crustal assimilation cannot be used to fully explain the relationship between the geochemical signatures of the first and second eruptions. We therefore further investigated to see if variable partial melting of the mantle source can be used to explain this relationship. We model partial melting using batch melting equations with inputs from three mantle sources (after McGee et al., 2013, 2015), including a carbonated peridotite, a fertile garnet-bearing peridotite and a depleted spinel-bearing peridotite (cf. **Figure 13**). Our modelling indicates that the full suite of coupled eruptions data can be explained through mixing of these three sources in varying amounts, with a 2-3% partial melt of the carbonated peridotite signature, a 1-4% melting of the fertile garnet bearing peridotite, and a 0.25-4% melting of the depleted spinel bearing peridotite signature, in accordance with McGee et al (2013), (data from Hofmann, 1988; Ionov, 1998; Takazawa et al., 2003).

For the Group 1 couplets (**Figure 13A**), all the first eruptions from the couplets plot with an increased amount of $(Gd/Yb)_N$ and $(La/Yb)_N$ in comparison to the second eruptions, although they plot in varying proportions across the full spread of data. Purchas Hill and Motukorea 1 plot with the most carbonated peridotite-like signatures, mixed in with some proportions (0-50% for Purchas Hill and 50-90% for Motukorea 1) of the fertile garnet-bearing signature. The second eruptions in these couplets then plot with either a higher percentage of fertile garnet-bearing signature (for Mt Wellington (with Purchas Hill)) or with an increasing proportion of the depleted spinel bearing signature mixed into the fertile garnet-bearing signature (e.g. 0-40%

for Motukorea 2). For the Rangitoto couplets, Otuataua plus Pukeiti, and Ash Hill plus Wiri Mt, the signatures of the first and second eruptions are related through an increased input of the depleted spinel bearing source, into the fertile garnet bearing source, but with similar amounts of initial partial melting of each of these sources.

The geochemical signatures of the Group 2 couplets (**Figure 13B**) by definition do not change between the first and the second eruption, however, they do all sit very close to a 2% partial melting signature of the fertile garnet-bearing source. This observation suggests that these centres are showing minimal addition of the two other sources (carbonated peridotite; depleted spinel-bearing peridotite), but instead all exhibit the signature of what could be suggested as an “ambient mantle source”.

It could be argued that if the eruptions systematically progress from the carbonated peridotite source, through the garnet bearing peridotite source and on to the spinel bearing peridotite source, that we have simply sampled the “middle” of the eruptions and we are therefore not seeing the spread in geochemical signatures as would be seen if a full eruption sequence could be sampled. However, the Mangere Mountain (Mt) plus Mangere Lagoon (Lg) couplet help to dispel this argument. We know that Mangere Lg very shortly predates Mangere Mt due to morphostratigraphic relationships (Hayward et al., 2016), where lava from Mangere Mt is seen spilling over the tuff ring of Mangere Lg with no evidence of soil horizon formation between the two. By sampling these two centres, we have effectively sampled both early and late phases of this coupled eruption. The geochemical signatures of these couplets show no difference in signature between the first (Mangere Lg) and second (Mangere Mt) eruption suggesting therefore that there is minimal evidence for a systematically evolving mantle source for these eruptions.

The partial melt modelling suggests that for the Group 1 coupled eruptions, the relationship between the first and second eruption can be explained through the mixing of melts from three mantle sources. The carbonated peridotite source is only seen in the first eruptions of the couplets, suggesting that this is the source of the initial phases of these eruptions. Additionally, as all the couplets evolve toward the depleted spinel bearing source, it is most likely that this represents the final source input into these systems. The most common signature seen in these couplets is the fertile garnet bearing source: we therefore propose that this is the key component of these systems with the two other sources acting as minor component end-members. These results agree with the original work by McGee et al (2013, 2015) produced for just single eruptive centres. McGee et al (2013) showed that this evolution in source can be seen within single centres. If this evolution is also seen spread across two centres, it adds further support to the discussed geochemical coupling for the eruptions focussed on by this research.

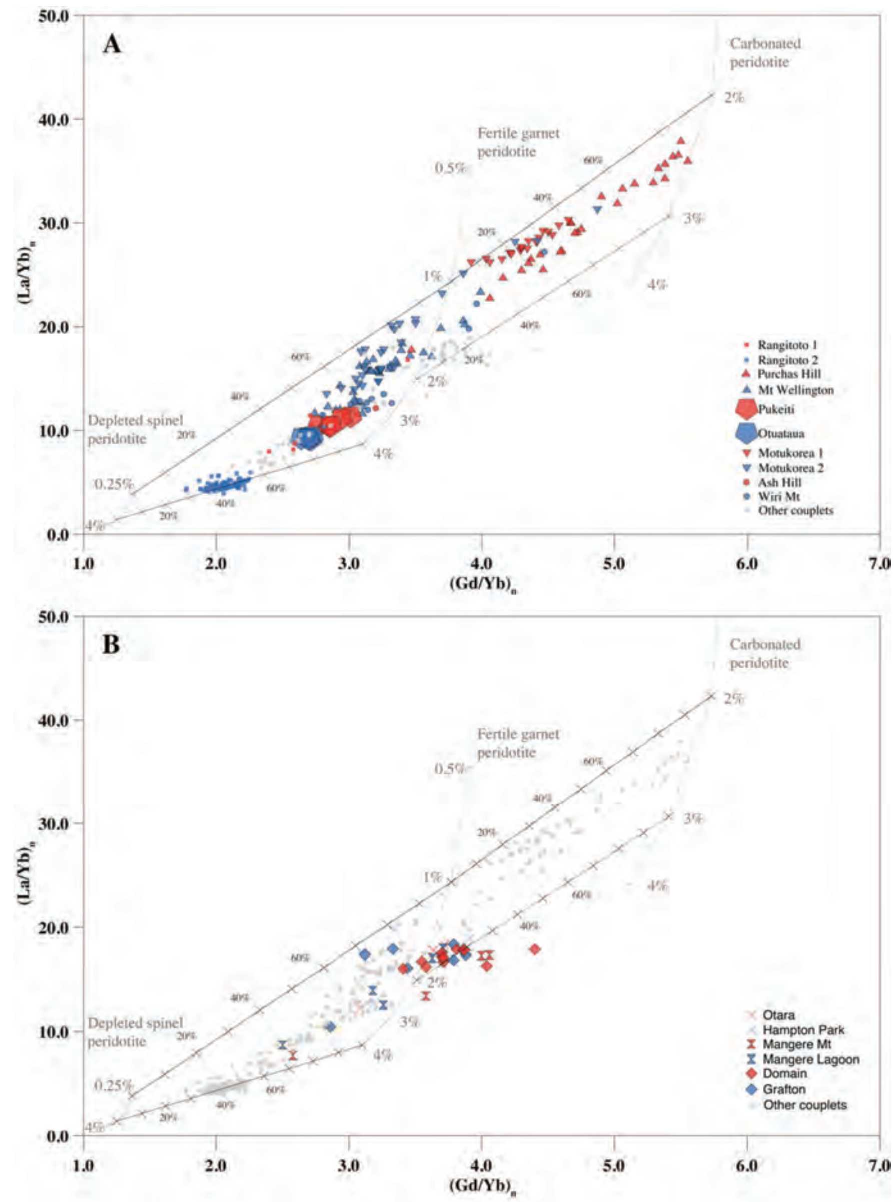

Figure 13. *Partial melting modelling for the coupled eruptions from the AVF (after McGee et al., 2013).* ***A)*** *Group 1 couplets,* ***B)*** *Group 2 couplets. Input data includes; Fertile garnet peridotite data from Hofmann (1988) (La = 0.6139, Gd = 0.5128, Yb = 0.4144, source mode Ol 54%, Cpx 17%, Opx 23%, Gt 6%); Carbonated peridotite data from Ionov (1998) (La = 1, Gd = 0.6, Yb = 0.4, source mode Ol 61%, Cpx 18%, Opx 9%, Gt 12%); Depleted spinel peridotite data from Takazawa et al. (2003) (La = 0.25, Gd = 0.55, Yb= 0.5, source mode Ol 55%, Cpx 15%, Opx 26%, Sp 4%). Partial melting curves are modelled by batch melting with percentage melting listed on the figure in grey text, and partition coefficients from McKenzie and O'Nions (1991), Green et al. (2000), and Adam and Green (2006). Mixing of these partial melts is modelled through simple binary mixing into the fertile garnet peridotite, with percentage mixing shown on the figure in black text.*

4.3.4. Are these mantle processes predictable based on the geochemical signature of the erupted products? *(e.g. If there is another eruption in the AVF and we can sample the products, can the geochemistry tell us about the source of the magma, and the likelihood of a coupled eruption occurring?)*

Our findings suggest that there is a predictable geochemical relationship between the first and second eruptions to some extent. Based on the findings discussed above, it is possible to suggest that the geochemical signature of a future eruption in the AVF could be used to show a number of characteristics pertaining to the eruption, these include:

1. *The depth of the mantle source from which the melt is ascending, and thus the scale of the eruption*

For example if the products of an eruption have high $(La/Yb)_N$ vs. $(Gd/Yb)_N$ geochemical signature, we know the source is likely deeper, representative of a small body of partial melt, and the eruption could either remain small (e.g. like Purchas Hill) or could become much larger over time (e.g. Motukorea 1&2). Conversely, if the products of the eruption have a low $(La/Yb)_N$ vs. $(Gd/Yb)_N$ geochemical signature, we know the source is likely shallower, linked to a larger amount of partial melt in the mantle (e.g. Rangitoto), and therefore could be a large volume eruption.

2. *The likelihood of a coupled eruption occurring*

Although a key aspect of this (crustal structure) is discussed further below, from our results we show that a coupled eruption is more likely to form when the initial eruptive products come from a deep source, with the geochemistry of the magma evolving and entraining the shallower source as the eruption progresses. During this progression, if there is a pause in the eruption, then it is possible the upwelling magma could stall and block the first vent, and therefore find an alternative route to the surface, thereby producing a secondary (coupled) vent.

4.3.5. Do crustal weaknesses impact the surface expression of the eruptions? *(e.g. if there is sub-surface faulting does this allow the magma to ascend more easily and cause couplets rather than dual eruptions from a single centre?)*

Our results indicated that there are two structural controls that are encompassed by the AVF that are responsible for the location of the field itself, followed by the location of the coupled centres within the field. These aspects are discussed below with regards to the regional structure and the local structure.

4.3.5.1. Regional structure

The relationships of the older volcanic fields on the North Island, New Zealand with the Dun Mountain Ophiolite Belt (DMOB) has been noted by a number of previous publications (e.g. Hopkins et al., 2016; cf. **Figure 1**). The DMOB (or Junction Magnetic Anomaly, JMA) is a major boundary that separates terranes that were sutured onto the Gondwana margin (e.g. Eccles et al., 2005). In the Auckland region it consists of steeply, eastward dipping slices that extend deeply to the base of the crust (e.g. Eccles et al., 2005). It has been postulated that this rheological suture line through the crust is a line of weakness exploited by the ascending magma (e.g. Hopkins et al., 2016). The volcanic fields coincide with regions where the DMOB is intersected by

NE to E-striking, perpendicular, cross-cutting fault systems, for example the South Whangaparoa Offset (Hatherton and Sibson, 1970). The location of the AVF is consistent with these observations, overlying the complex, potentially weak, and cross-cut suture line of the DMOB.

4.3.5.2. Local structure

In Auckland on either side of the DMOB suture line are the Mesozoic Murihiku (to the SW) and Waipapa (to the NE) terranes (**Fig. 1**). The Murihiku terrane is made up of diagenetically altered volcaniclastic sediments that are folded into a regional-scale syncline, whereas in comparison the Waipapa terrane is made up of non-foliated metasediments (Black et al., 1993). Overprinting these original structures is an overarching N to NE trending fault systems (Kermode, 1992). The eruptions from the AVF do not preferentially favour either of these terranes for ascent with an equal number of vents spread across the suture line and into each of the bounding terranes (**Figure 1**). This suggests that the terrane types are not a controlling factor on the location of the vents. However, for the coupled eruptions, all the first and second eruptions sit on a structural alignment with NNE-SSW striking trajectories (**Figure 1**). There is no consistency in the location of the first vs. second eruption (e.g. 70% of couplets have their first eruption in the SSW, 30% in the NNE), therefore the location of a secondary vent could not be predicted specifically. However, in the case of a future eruption sequence, the bearing of the secondary vent could be identified with some certainty, and thus two regions can be proposed for a secondary vent location (i.e. ≤ 1km NNE or SSW of the first eruption).

The orientation of the vents for the coupled eruptions suggests that the magma migration patterns through the crust are highly sensitive to the local tectonics (Martí et al., 2016, Jaimes-Viera et al., 2018). The transport of magma through the crust occurs most commonly through sheeted intrusions of dikes or sills, and as such, the conditions of flow through magma filled cracks will be controlled by rock and fluid mechanic interaction. Previous studies have shown that changes in stress fields produced by regional or local tectonics control the magma migration (e.g. Le Corvec et al., 2013, Martí et al., 2016) and that magma will migrate along pre-existing faults if the pressure of the ascending magma can overcome the compressive normal stresses acting to keep the fault walls closed (Gaffney et al., 2007, Martí et al., 2016).

Pre-existing faults have also been shown to capture ascending magma, aiding the reactivation of the faults when lubricated by the intruding magma, although this process is thought to be restricted to high angle faults at shallow depths (Gaffney et al., 2007). Le Corvec et al. (2013) showed that for ~78% of the volcanic fields in their global study, the orientation of the vents aligned with the pre-existing tectonic features. Where these vents are aligned in a single preferred orientation, as seen in the AVF couplets, it is indicative of a high differential stress system, with low upwelling magma pressure. Similar behaviour was also outlined by Pinel and Jaupart (2004), who showed that magma rising under a conical edifice (for example, the footprint of the first eruptions in the couplet), would likely be diverted through radially propagating cracks, to emerge at some distance from the earlier vent site.

It has been proposed by a number of authors prior to this study that, due to the small quantity of magma produced at these types of volcanoes, the conduit systems may not stay active for long periods of time. Here we hypothesis that if the conduit becomes blocked or inactive, the ascending magma will find an alternative path within the shallow crust to the surface. We suggest that this pausing of the magma in the shallow crust could be caused by a number of factors including, the cooling and or the degassing of the ascending magma leading to increased viscosity and therefore a retardation of ascent, or the reduction in the rate of upwelling effectively reducing the rate of recharge of the first erupting vent. Our findings suggest that as a result of this, the second eruption in the couplet will find an alternate path to exploit, likely along the same fault system, causing it to ascend a short distance to the NNE or SSW of the existing (blocked or stalled) first vent.

We cannot however overlook the complexity of the crust beneath the AVF, with the possibility that numerous intrusions may present, representing failed magma ascent. At present the resolution of the imagery gained through geophysical methods is not good enough to identify dykes or sills in the lithosphere or crust, therefore we cannot know for certain how complex the system is below the AVF. The interaction of ascending magma with these intrusions will likely also play a role on the location of the vent on the surface, however, we currently do not know what this interaction is. We also do not know what causes the difference in formation between a single monogenetic eruption, and a coupled monogenetic eruption. It could be the interaction with the surface faults leading to multiple viable ascent pathways, or it could be linked to stalling in the ascent through a decrease in supply, or the cooling and degassing of the erupting material, or the first eruption passing through, and triggering instability of the melt fraction in the shallower mantle. The geochemical relationships between the couplets reveals that the source of the magma and/or the amount of partial melting at the source can change during the eruption, and this may also play a role in the shifting of vent locations. However, this variability is also seen in single vent eruptions (e.g., Three Kings), and additionally as the geochemical Group 2 show, the shifting vent can also be linked to no obvious change in geochemistry, and thus the geochemical variations is certainly not a controlling factor in the vent location variability. The geochemical relationships also show us that there is limited evidence for stalling in the crust with no obvious crustal assimilation or fractional crystallisation taking place, at least between the couplets. The structural evidence does however suggest that shallow level structural weaknesses are most likely the key controlling factor in the production of coupled eruption systems.

*5. **Impact** (i.e., how this research reduces the impact of natural disaster on people and property)*

Prior to this research our general understanding of the AVF eruptions was that of a single, independent event, that occurred over a short time period, with an impact zone set as a ≤ 6 km radius around the source vent (e.g. Brand et al., 2011; Hayes et al., 2018). Our hazard and risk mitigation protocols (e.g. Hayes et al., 2018) have been designed based on this understanding. However, with the discovery of coupled eruptions we now realise that this previous understanding potentially underestimates the threat posed by a future eruption scenario. The characteristics of the identified coupled centres imply that any second vent would appear within the currently imposed impact zone (≤ 6km), however, the migration of vents is not taken into account in current models.

We can also predict the orientation of the second eruption on the NNE-SSW bearing from the first eruption, thereby constraining the potential location for the second vent. Based on the geochemical composition of the volcanic products we can now make estimates of the likely scale of the eruption, and or if the second eruption is likely to be bigger in volume. These results can be fed into the future modelling scenarios for the eruptions of the AVF. Our results will increase the characteristic details of a future eruption, allowing more detailed plans to be put in place for evacuation and hazard mitigation. These results will therefore allow the impact to people and property in a future AVF eruption scenario to be better protected.

6. Future work

At present there a three key aspects of the AVF that we feel could benefit from future work, including (but not limited to) the following.

1. Sampling and geochemical analysis of Onepoto, Tank Farm and Styaks Swamp centres.

These are listed as coupled based on their temporal and spatial relationships, however, either during field campaigns or in sample analysis, we could not obtain suitable material for analysis. As a result these centres, and for Styaks Swamp its couplet Green Mt, were not included in the geochemical relationship assessment between the identified coupled centres. It would be a really great addition to this study in the future if some juvenile material could be sourced relating to these eruptions.

2. Improving the dating of some of the “undated” centres.

For many of the centres their age relationships are based on the morphological evidence found in the field (e.g. Hayward 2008; Hayward et al., 2016). Whilst this is a valid way of assessing the relative ages of the centres, this does not allow the absolute ages to be established. Having said this, most of the dating techniques that could be used for these eruptions are likely to have uncertainties that are too great to allow the ordering of eruptions to be confirmed. Therefore potentially investigating new dating techniques could be a good option to gain valuable information about the absolute ages of these centres.

3. Mineralogical work to distinguish depth of formation of minerals (e.g. potential stalling depths).

Our results suggest that there is limited evidence for stalling of the ascending magma batches that feed the AVF eruptions. However, there are mineral inclusions (dominantly olivine and pyroxene) that have been identified in some of the centre’s eruptive products. A fruitful avenue to investigate the depth at which these minerals have formed could include some mineral thermobarometry techniques (e.g. Putirka, 2008) in order to ascertain the temperatures and pressures under which these minerals have formed, and thus identifying the depths of stalling.

4. Structural investigations of the shallow crustal regions beneath the AVF

One of the exciting key outcomes of this work is the identification of a common orientation for the location of the coupled eruptions. Proposed reasons for this are identified in the text above, but there remain many unknowns relating to the structure of the shallow crust beneath the AVF, especially those linked to failed eruptions building complex sill and dike systems beneath the AVF. More detailed subsurface mapping at higher resolutions would be exceptionally helpful for this, however, at present the technology is not available to permit this approach.

7. Acknowledgements

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8. References

Affleck, D.K., Cassidy, J., Locke, C.A., 2001. Te Pou Hawaiki volcano and pre-volcanic topography in central Auckland: volcanology and hydrogeological implications. New Zealand Journal of Geology and Geophysics 44, 313-321.

Bartrum. J.A., 1928. Lava slickensides at Auckland. New Zealand Journal of Science and Technology 10, 23-25.

Bebbington, M.S., 2013. Assessing probabilistic forecasts of volcanic eruption onsets. Journal of Volcanology and Geothermal Research 252, 14-28.

Bebbington, M.S., 2015. Spatio-volumetric hazard estimation in the Auckland volcanic field. Bulletin of Volcanology 77, 39-54.

Black, P.M., Clark, A.S.B., Hawke, A.A., 1993. Diagenesis and very low-grade metamorphism of volcaniclastic sandstones from contrasting geodynamic environments, North Island, New Zealand: the Murihiku and Waipapa terranes. Journal of Metamorphic Geology 11, 429-435.

Brand, B.D., Gravley, D.M., Clarke, A.B., Lindsay, J.M., Bloomberg, S.H., Agustín-Flores, J., Németh, K., 2014. A combined field and numerical approach to understanding dilute pyroclastic density current dynamics and hazard potential: Auckland Volcanic Field, New Zealand. Journal of Volcanology and Geothermal Research 276, 215-232.

Brenna, M., Cronin, S.J., Smith, I., Sohn, Y., Németh, K., 2010. Mechanisms driving polymagmatic activity at a monogenetic volcano, Udo, Jeju Island, Korea. Contributions to Mineralogy and Petrology 160, 931-950.

Brenna, M., Cronin, S.J., Smith, I.E., Maas, R., Sohn, Y.K., 2012. How small-volume basaltic magmatic systems develop: a case study from the Jeju Island Volcanic Field, Korea. Journal of Petrology 53, 985-1018.

Brenna, M., Cronin, S.J., Kereszturi, G., Sohn, Y.K., Smith, I.E., Wijbrans, J., 2015. Intraplate volcanism influenced by distal subduction tectonics at Jeju Island, Republic of Korea. Bulletin of Volcanology 77, 7.

Brenna, M., Cronin, S.J., Smith, I.E., Tollan, P.M., Scott, J.M., Prior, D.J., Bambery, K., Ukstins, I.A., 2018. Olivine xenocryst diffusion reveals rapid monogenetic basaltic magma ascent following complex storage at Pupuke Maar, Auckland Volcanic Field, New Zealand. Earth and Planetary Science Letters 499, 13-22.

Briggs, R.M., Okada, T., Itaya, T., Shibuya, H., Smith, I.E.M., 1994. K-Ar ages, paleomagnetism, and geochemistry of the South Auckland volcanic field, North Island, New Zealand. New Zealand Journal of Geology and Geophysics 37, 143-153.

Cassata, W.S., Singer, B.S., Cassidy, J., 2008. Laschamp and Mono Lake geomagnetic excursions recorded in New Zealand. Earth and Planetary Science Letters 268, 76-88.

Cassidy, J., Locke, C.A., 2010. The Auckland volcanic field, New Zealand: geophysical evidence for structural and spatio-temporal relationships. Journal of Volcanology and Geothermal Research 195, 127-137.

Connor, C.B., 1990. Cinder cone clustering in the Trans-Mexican Volcanic Belt: implications for structural and petrologic models. Journal of Geophysical Research 95, 19395-19405.

Condit, C.D., Connor, C.B., 1996. Recurrence rates of volcanism in basaltic volcanic fields: An example from the Springerville volcanic field, Arizona. Geological Society of America Bulletin 108, 1225-1241.

Cook, C., Briggs, R.M., Smith, I.E.M., Maas, R., 2004. Petrology and geochemistry of the intraplate basalts in the South Auckland Volcanic Field, New Zealand: evidence for two coeval magma suites from distinct sources. Journal of Petrology 46, 473-503.

Deligne, N.I., Conrey, R.M., Cashman, K.V., Champion, D.E., Amidon, W.H., 2016. Holocene volcanism of the upper McKenzie River catchment, central Oregon Cascades, USA. Geological Society of America Bulletin 128, 1618-1635.

Demidjuk, Z., Turner, S., Sandiford, M., George, R., Foden, J., Etheridge, M., 2007. U-series isotope and geodynamic constraints on mantle melting processes beneath the Newer Volcanic Province in South Australia. Earth and Planetary Science Letters 261, 517-533.

DePaolo, D.J., 1981. Trace element and isotopic effects of combined wallrock assimilation and fractional crystallisation. Earth and Planetary Science Letters 53, 189-202.

East, G.R.W., George, A.K., 2003. The construction of the Auckland Central Remand Prison on the Mt Eden basalt flow. In: Geotechnics on the Volcanic Edge: Tauranga, March 2003, New Zealand Geotechnical Society Symposium (p. 387). Institution of Professional Engineers, New Zealand.

Eccles, J.D., Cassidy, J., Locke, C.A., Spörli, K.B., 2005. Aeromagnetic imaging of the Dun Mountain Ophiolite Belt in northern New Zealand: insight into the fine structure of major SW Pacific terrane suture. Journal of the Geological Society, London 162, 723-735.

Gaffney, E.S., Damjanac, B., Valentine, G.A., 2007. Localization of volcanic activity: 2. Effects of pre-existing structure. Earth and Planetary Science Letters 263, 323-338.

Guilbaud, M.N., Siebe, C., Layer, P., Salinas, S., 2012. Reconstruction of the volcanic history of the Tacámbaro-Puruarán area (Michoacán, México) reveals high frequency of Holocene monogenetic eruptions. Bulletin of Volcanology 74, 1187-1211.

Hatherton, T., Sibson, R.H., 1970. Junction magnetic anomaly north of the Waikato River. New Zealand Journal of Geology and Geophysics 13, 655-662.

Hayes, J.L.; Tsang, S.W.; Fitzgerald, R.H.; Blake, D.M.; Deligne, N.I.; Doherty, A.; Hopkins, J.L.; Hurst, A.W.; Le Corvec N.; Leonard, G.S.; Lindsay, J.M.; Miller, C.A.; Németh, K.; Smid, E.; White, J.D.L.; Wilson, T.M., 2018. The DEVORA scenarios: multi-hazard eruption scenarios for the Auckland Volcanic Field. Lower Hutt, N.Z.: GNS Science. GNS Science report 2018/29. 138 p.

Hayward, B.W., 2008. Ash Hill Volcano, Wiri. Geocene (Auckland Branch, Geoscience Society of New Zealand Newsletter) 3, 8-9.

Hayward, B.W., Morley, M.S., Sabaa, A.T., Grenfell, H.R., Daymond-King, R., Molloy, C., Shane, P.A., Augustinus, P.A., 2008. Fossil record of the post-glacial marine breaching of Auckland's volcanic maar craters. Records of the Auckland Museum 45, 73-99.

Hayward, B.W., Murdoch, G., Maitland, G., 2011. Volcanoes of Auckland, The Essential Guide. Auckland University Press, Auckland, New Zealand.

Hayward, B.W., Hopkins, J.L., Smid, E.R., 2016. Mangere Lagoon predated Mangere Mt. Geocene (Auckland Branch, Geoscience Society of New Zealand Newsletter) 14, 4-5.

Herzberg, C., Asimow, P.D., 2008. Petrology of some oceanic island basalts: PRIMELT2. XLS software for primary magma calculation. Geochemistry, Geophysics, Geosystems, 9, Q09001.

Hofmann, A.W., 1988. Chemical differentiation of the Earth: the relationship between mantle, continental crust, and oceanic crust. Earth and Planetary Science Letters 90, 297-314.

Hopkins J.L., 2015. New perspectives on the magmatic evolution of the Auckland Volcanic Field, New Zealand. Doctoral dissertation, Victoria University of Wellington, Wellington, New Zealand.

Hopkins, J.L., Millet, M.-A., Timm, C., Wilson, C.J.N., Leonard, G.S., Palin, J.M., Neil, H., 2015. Tools and techniques for developing tephra stratigraphies in lake cores; a case study from the Auckland Volcanic Field, New Zealand. Quaternary Science Reviews 123, 58-75.

Hopkins, J.L., Timm, C., Millet, M.-A., Poirier, A.P., Wilson, C.J.N., Leonard, G.S., 2016. Os isotopic constraints on crustal contamination in Auckland Volcanic Field basalts, New Zealand. Chemical Geology 439, 83-97

Hopkins, J.L., Wilson, C.J.N., Millet, M.-A., Leonard, G.S., Timm, C., McGee, L.E., Smith, I.E.M., Smith, E.G.C., 2017. Multi-criteria correlation of tephra deposits to source centres applied in the Auckland Volcanic Field, New Zealand. Bulletin of Volcanology 79, 55.

Horspool, N.A., Savage, M.K., Bannister, S., 2006. Implications for intraplate volcanism and back-arc deformation in northwestern New Zealand, from joint inversion of receiver functions and surface waves. Geophysical Journal International 166, 1466-1483.

Houghton, B.F., Wilson, C.J.N., Smith, I.E.M., 1999. Shallow-seated controls on styles of explosive basaltic volcanism: a case study from New Zealand. Journal of Volcanology and Geothermal Research 91, 97-120.

Huang, Y., Hawkesworth, C., van Calsteren, P., Smith, I., Black, P., 1997. Melt generation models for the Auckland volcanic field, New Zealand: constraints from U-Th isotopes. Earth and Planetary Science Letters 149, 67-84.

Hwang, S.K., Jin, X., Ahn, U.S., 2005. Volcanic forms and eruption processes of Laiheishan and Huoshaoshan in the Wudalianchi volcanics, NE China. Journal of the Petrological Society, Korea 14, 251-263.

Ionov, D., 1998. Trace element composition of mantle-derived carbonates and coexisting phases in peridotite xenoliths from alkali basalts. Journal of Petrology 39, 1931-1941.

Jaimes-Viera, M.C., Del Pozzo, A.M., Layer, P.W., Benowitz, J.A., Nieto-Torres, A., 2018. Timing the evolution of a monogenetic volcanic field: Sierra Chichinautzin, Central Mexico. Journal of Volcanology and Geothermal Research 356, 225-242.

Kenny, J.A., Lindsay, J.M., Howe, T.M., 2012. Post-Miocene faults in Auckland: insights from borehole and topographic analysis. New Zealand Journal of Geology and Geophysics 55, 323-343.

Kereszturi, G., Németh, K., Cronin, S.J., Agustin-Flores, J., Smith, I.E.M., Lindsay, J., 2013. A model for calculating eruptive volumes for monogenetic volcanoes – implications for the Quaternary Auckland Volcanic Field, New Zealand. Journal of Volcanology and Geothermal Research 266, 16-33.

Kereszturi, G., Németh, K., Cronin, S.J., Procter, J., Augustin-Flores, J., 2014. Influences on the variability of eruption sequences and style transitions in the Auckland Volcanic Field, New Zealand. Journal of Volcanology and Geothermal Research 286, 101-115.

Kermode, L.O., 1992. Geology of the Auckland Urban Area. Institute of Geological and Nuclear Sciences Ltd. .

Larrea, P., Widom, E., Siebe, C., Salinas, S., Kuentz, D., 2019. A re-interpretation of the petrogenesis of Paricutin volcano: Distinguishing crustal contamination from mantle heterogeneity. Chemical Geology, 504, 66-82.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B., 1986. A chemical classification of volcanic rocks based on the Total Alkali-Silica diagram. Journal of Petrology 27, 745-750.

Le Corvec, N., Spörli, K.B., Rowland, J., Lindsay, J., 2013. Spatial distribution and alignments of volcanic centres: Clues to the formation of monogenetic volcanic fields. Earth-Science Reviews 124, 96-114.

Leonard, G.S., Calvert, A.T., Hopkins, J.L., Wilson, C.J.N., Smid, E.R., Lindsay, J.M., Champion, D.E., 2017. High-precision $^{40}Ar/^{39}Ar$ dating of Quaternary basalts from Auckland Volcanic Field, New Zealand, with implications for eruption rates and paleomagnetic correlations. Journal of Volcanology and Geothermal Research 343, 60-74.

Lindsay, J.M., Leonard, G.S., Smid, E.R., Hayward, B.W., 2011. Ages of Auckland Volcanic Field: a review of existing data. New Zealand Journal of Geology and Geophysics 54, 379-401.

Linnell, T., Shane, P., Smith, I.E.M., Augustinus, P., Cronin, S., Lindsay, J., Maas, R., 2016. Long-lived shield volcanism within a monogenetic basaltic field: the conundrum of Rangitoto volcano, New Zealand. Geological Society of America Bulletin 128, 1160-1172.

Mahgoub, A.N., Böhnel, H., Siebe, C., Salinas, S., Guilbaud, M.N., 2017. Paleomagnetically inferred ages of a cluster of Holocene monogenetic eruptions in the Tacámbaro-Puruarán area (Michoacán, México): implications for volcanic hazards. Journal of Volcanology and Geothermal Research 347, 360-370.

Martí, J., López, C., Bartolini, S., Becerril, L., Geyer, A., 2016. Stress controls of monogenetic volcanism: A review. Frontiers in Earth Science, 4, 106.

McDougall, I., Polach, H.A., Stipp, J.J., 1969. Excess radiogenic argon in young subaerial basalts from the Auckland volcanic field, New Zealand. Geochimica et Cosmochimica Acta 33, 1485-1520.

McGee, L.E., Smith, I.E.M., 2016. Interpreting chemical compositions of small scale basaltic systems: A review. Journal of Volcanology and Geothermal Research 325, 45-60.

McGee, L.E., Beier, C., Smith, I.E.M., Turner, S., 2011. Dynamics of melting beneath a small-scale basaltic system: a U-Th-Ra study for Rangitoto volcano, Auckland Volcanic Field, New Zealand. Contributions to Mineralogy and Petrology 162, 547-563.

McGee, L.E., Millet, M.-A., Smith, I.E.M., Németh, K., Lindsay, J.M., 2012. The inception and progression of melting in a monogenetic eruption: Motukorea Volcano, the Auckland Volcanic Field, New Zealand. Lithos 156, 360-374.

McGee, L.E, Smith, I.E.M., Millet, M.-A., Handley, H., Lindsay, J., 2013. Asthenospheric control of melting processes in a monogenetic basaltic system: a case study of the Auckland Volcanic Field, New Zealand. Journal of Petrology 54, 2125-2153.

McGee, L.E., Millet, M.-A., Beier, C., Smith, I.E.M., Lindsay, J.M., 2015. Mantle heterogeneity controls small-volume basaltic eruption characteristics. Geology 43, 551-554.

Molloy, C., Shane, P., Augustinus, P., 2009. Eruption recurrence rates in a basaltic volcanic field based on tephra layers in maar sediments: implications for hazards in the Auckland volcanic field. Geological Society of America Bulletin 121, 1666-1677.

Needham, A.J., Lindsay, J.M., Smith, I.E.M., Augustinus, P., Shane, P.A., 2011. Sequential eruption of alkaline and sub-alkaline magmas from a small monogenetic volcano in the Auckland Volcanic Field, New Zealand. Journal of Volcanology and Geothermal Research 201, 126-142.

Németh, K., White, J.D.L., Reay, A., Martin, U., 2003. Compositional variation during monogenetic volcano growth and its implications for magma supply to continental volcanic fields. Journal of the Geological Society, London, 160, 523-530.

Paton, C., Hellstrom, J., Paul, B., Woodhead, J., Hergt, J., 2011. Iolite: Freeware for the visualisation and processing of mass spectrometric data. Journal of Analytical Atomic Spectrometry 26, 2508-2518.

Pinel, V. and Jaupart, C., 2004. Magma storage and horizontal dyke injection beneath a volcanic edifice. Earth and Planetary Science Letters 221, 245-262.

Putirka, K.D., 2008. Thermometers and barometers for volcanic systems. Reviews in mineralogy and geochemistry 69, 61-120.

Putirka, K.D., Kuntz, M.A., Unruh, D.M., Vaid, N., 2009. Magma evolution and ascent at the Craters of the Moon and neighboring volcanic fields, Southern Idaho, USA: implications for the evolution of polygenetic and monogenetic volcanic fields. Journal of Petrology 50, 1639-1665.

Reyes-Guzmán, N., Siebe, C., Chevrel, M.O., Guilbaud, M.N., Salinas, S., Layer, P., 2018. Geology and radiometric dating of Quaternary monogenetic volcanism in the western Zacapu lacustrine basin (Michoacán, México): implications for archeology and future hazard evaluations. Bulletin of Volcanology 80, 18.

Rasoazanamparany, C., Widom, E., Siebe, C., Guilbaud, M.N., Spicuzza, M.J., Valley, J.W., Valdez, G., Salinas, S., 2016. Temporal and compositional evolution of Jorullo volcano, Mexico: implications for magmatic processes associated with a monogenetic eruption. Chemical Geology 434, 62-80.

Reyes-Guzmán, N., Siebe, C., Chevrel, M.O., Guilbaud, M.N., Salinas, S. and Layer, P., 2018. Geology and radiometric dating of Quaternary monogenetic volcanism in the western Zacapu lacustrine basin (Michoacán, México): implications for archeology and future hazard evaluations. Bulletin of Volcanology 80, 18.

Sandri, L., Jolly, G., Lindsay, L., Howe, T., Marzocchi, W., 2012. Combining long- and short-term probabilistic volcanic hazard assessment with cost-benefit analysis to support decision making in a volcanic crisis from the Auckland Volcanic Field, New Zealand. Bulletin of Volcanology 74, 705-723.

Searle, E.J., 1959. The volcanoes of Ihumatao and Mangere, Auckland. New Zealand Journal of Geology and Geophysics 2, 870-888.

Searle, E.J., 1961. The age of the Auckland volcanoes. New Zealand Geographer 17, 52-63.

Seebeck, H., Nicol, A., Giba, M., Pettinga, J., Walsh, J., 2014. Geometry of the subducting Pacific plate since 20 Ma, Hikurangi margin, New Zealand. Journal of the Geological Society, London 171, 131-143.

Shane, P., Gehrels, M., Zawalna-Geer, A., Augustinus, P., Lindsay, J., Chaillou, I., 2013. Longevity of a small shield volcano revealed by crypto-tephra studies (Rangitoto volcano, New Zealand): Change in eruptive behaviour of a basaltic field. Journal of Volcanology and Geothermal Research 257, 174-183.

Smith, I.E.M. and Németh, K., 2017. Source to surface model of monogenetic volcanism: a critical review. Geological Society, London, Special Publications 446, 1-28.

Smith, I.E.M., Blake, S., Wilson, C.J.N., Houghton, B.F., 2008. Deep-seated fractionation during the rise of a small-volume basalt magma batch: Crater Hill, Auckland, New Zealand. Contributions to Mineralogy and Petrology 155, 511-527.

Smith, I.E.M., McGee, L.E., Lindsay, J.M., 2009. Review of the petrology of the Auckland Volcanic Field. Institute of Earth Science and Engineering technical report 2009.03, University of Auckland, Auckland.

Spörli, K.B., Black, P.M. and Lindsay, J.M., 2015. Excavation of buried Dun Mountain–Maitai terrane ophiolite by volcanoes of the Auckland Volcanic field, New Zealand. New Zealand Journal of Geology and Geophysics 58, 229-243.

Takazawa, E., Okayasu, T., Satoh, K., 2003. Geochemistry and origin of the basal lherzolites from the northern Oman ophiolite (northern Fizh block). Geochemistry, Geophysics, Geosystems 4, 1021.

Tanaka, K.L., Shoemaker, E.M., Ulrich, G.E., Wolfe, E.W., 1986. Migration of volcanism in the San Francisco volcanic field, Arizona. Geological Society of America Bulletin 97, 129-141.

Wilson, G., Wilson, T.M., Deligne, N.I., Cole, J.W., 2014. Volcanic hazard impacts to critical infrastructure: A review. Journal of Volcanology and Geothermal Research 286, 148-182.

Zou, H., Reid, M.R., Liu, Y., Yao, Y., Xu, X., Fan, Q., 2003. Constraints on the origin of historic potassic basalts from northeast China by U–Th disequilibrium data. Chemical Geology 200, 189-201.

9. Outputs and Dissemination

9.1. Conference/ Meeting presentations:

Presentation title: Coupled eruptions in a monogenetic basaltic volcanic field: physical, geochemical, and temporal relationships, and what these tell us about mantle source.
Authors: J.L. Hopkins, C. Timm, C.J.N. Wilson, G.S. Leonard, F. Hauff.
Conference: Cities on Volcanoes 10, Naples Italy, September 2018
Date of presentation: 7th September 2018

Presentation title: Coupled eruptions in the Auckland volcanic field
Authors: J.L. Hopkins
Conference: Annual DEVORA Research Forum
Date of presentation: 25th October 2018

Presentation title: Coupled eruptions in the Auckland volcanic field, are we underestimating the risk?
Authors: J.L. Hopkins
Meeting: Victoria University Geochemistry, Geophysics, Petrology and Volcanology Group (invited talk)
Date of presentation: 11th June 2019

9.2. Papers in progress:

Manuscript title: Coupled eruptions in a monogenetic volcanic field, their spatial, temporal and geochemical relationships with respect to mantle mechanics: a case study from the Auckland volcanic field.
Authors: J.L. Hopkins, C. Timm, L.M. McGee, M.-A. Millet, F. Hauff., C.J.N. Wilson, G.S. Leonard, Rowland, J.R.
Journal: TBD
Second draft stage, edited by key collaborators, predicted submission August 2019

Manuscript title: Auckland volcanic field magmatism and volcanic hazard research – a review.
Authors: J.L. Hopkins, E. Smid, J. Eccles, J.L Hayes, B. Hayward, G.S. Leonard, J.M. Lindsay, T.M. Wilson
Journal: IAVCEI Special Issue, publication date Dec 2020
First draft stage

10. Links to publications/theses

N/A

11. List of key end users

DEVORA (Determining Volcanic Risk in Auckland) Group including participants from Auckland Council, Auckland Emergency Management, Auckland Police, GNS, EQC, Auckland University, University of Canterbury, University of Otago, Victoria University of Wellington, University of Waikato, CDEM.

Coupled eruptions in the Auckland volcanic field: are we underestimating the volcanic threat to our city?

Snapshot

The Auckland volcanic field (AVF) is made up of 53 volcanic centres that have formed from individual eruptive events. Our current hazard and risk models assume a single eruption occurring in one location, and thus base hazard mitigation plans and evacuation procedures on this understanding. Our research investigates the classification, identification and geochemical investigation of coupled eruptions in the AVF, in order to assess if our current hazard and risk models are underestimating the threat to our city.

Coupled eruptions are defined by this study as eruptive events that occur close in space (≤ 1000 m apart) and time (generally ≤ 100 years apart). Of the 53 centres found in the AVF, sixteen are identified as coupled, meaning that 30% of the eruptions show this characteristic.

Our research identified that these coupled eruptions also show a relationship in their geochemical composition, suggesting that they are not only linked in space and time, but also in their magma source (defined by geochemical composition). Our results show that the geochemical relationship between the first and second eruptions of the couplets can be explained through a variable amount of melting in the mantle, mixing together three distinct sources. The geochemistry suggests that there is limited stalling on ascent of the magma through the mantle and crust, as no evidence for contamination from these sources is identified.

We also see evidence for a structural control on the location of the centres and the couplets. For every couplet the first and second eruptions sit on a bearing NNE-SSW of each other. There is no consistency for which eruption is located further north or south, although this orientation alone allows the site of a second eruption in a couplet to be predictable to two locations at ≤ 1 km from the site of the first eruption.

This research has improved our knowledge of the physical and geochemical characteristics of the eruptions of the AVF. By increasing our knowledge of the past eruptions, we can better inform our predictions of the characteristics of a future eruption. Our results highlight the importance of considering eruptions that potentially will move location, and that future eruptive scenarios may not be as simple as a single, stationary centre. The geochemical data can also be used to predict the potential volume of the eruptible magma through assessing the volume of partial melt responsible for the melt batch. Both these factors combined can help to inform the evacuation and hazard zones linked to a potential future eruption. As a result, we hope that this information will help to reduce the impact on the people and property in proximity to a future eruption from the AVF.

Coupled eruptions in the Auckland volcanic field: are we underestimating the volcanic threat to our city?

Scientific Abstract

We present a detailed review of "coupled eruptions" identified in the Auckland volcanic field (AVF), New Zealand. Coupled eruptions are defined here as those that have occurred close in space (≤ 1km apart) and time (≤1 kyr apart, but most commonly ≤ 100 yrs apart). We show that of the fifty-three currently identified "monogenetic" eruptions in the AVF, twenty appear to show this coupled relationship. In order to investigate this relationship further we present the results of new geochemical, and Sr-, Nd-, and Pb-isotopic data to investigate the geochemical, and hence mantle source relationships and ascent dynamics between the coupled volcanic centres.

The ten couplets are initially split into four groups, which are then reduced to two groups by further investigation. Group 1 includes those couplets which show a consistent and systematic evolution from the first eruption (with a more primitive geochemical signature) to the second eruption (with a more evolved geochemical signature, e.g. SiO_2 eruption 1 > eruption 2, $(La/Yb)_N$ eruption 1 > eruption 2). Group 2 includes couplets have the same geochemical signatures between the first and second eruptions, with no systematic variation in major, trace or isotopic concentrations.

We consider two hypotheses for the source and ascent dynamics that could be used to explain these groupings and investigate these hypotheses using the geochemical signatures identified. Our results indicate that differences between the geochemical signatures of the first and second eruptions for the couplets in groups 1 and 2 cannot be explained simply by fractional crystallization and/or crustal assimilation or simple partial melting processes. Instead these geochemical relationships are attributed to variabilities in partial melting linked to differing heterogeneous mantle sources.

In addition to the geochemical characteristics indicative of the mantle source dynamics, we also identify two overprinted structural controls on the ascent dynamics of the rising magmas. The interaction of the Dun Mountain Ophiolite Belt with perpendicular E-W trending faults is proposed to provide the pathway between the crust-mantle boundary which the magma can exploit as it ascends from the mantle. Then, in the shallow crust, the NNE-SSW trending faults of the underlying basement material (Murihiku and Waipapa terranes) provide the shallow weaknesses that the ascending melt uses to arrive at the surface. The latter control is identified through the consistent relationship of the coupled centres lying on a NNE-SSW trend.

We therefore conclude that coupled eruptions are indeed linked both spatially, temporally and geochemically, and are not an uncommon occurrence in the Auckland volcanic field. This has major implications for hazard and risk models of a future eruption, which at present only model a single source centre rather than one which has the potential to migrate laterally on a potentially predictable trajectory.