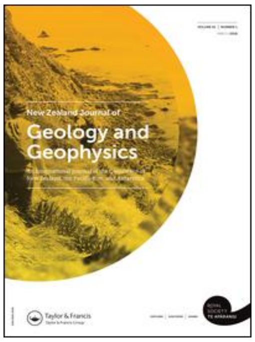

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RESEARCH ARTICLE

Auckland Volcanic Field magmatism, volcanism, and hazard: a review

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ABSTRACT
Auckland Volcanic Field (AVF) is a basaltic intraplate volcanic field in North Island, New Zealand, upon which >1.6 million people live. Seismic velocity tomography and geochemistry suggest a primary mantle source region at a depth of 70–90 km. Geochemical analysis indicates a range of magma compositions, and that melts ascend with little crustal interaction. Eruptions generally began with a phreatomagmatic phase forming maar and tuff rings with tephra fall, base surges, and ballistic projectiles as the main hazards. Subsequent magmatic phases formed scoria cones, and sometimes produced lava flows. Ages of 47 of the 53 volcanic centres reveal that the AVF first erupted ∼193 ka, and last erupted ∼500 yrs. BP. These geochronological constraints indicate repose periods ≤0.1–13 kyr, which have decreased since ∼60 ka. From known geological and exposure information, and using an interdisciplinary approach, eight future eruption scenarios have been developed for planning processes. Outstanding questions for the AVF concern the cause of mantle melting, the structure of the underlying lithosphere, magma ascent rates, controls on repose periods and eruptive volumes. Answering these questions may improve our understanding of warning periods, monitoring strategies, spatiotemporal risk profiles, and socio-economic impacts of volcanism on New Zealand's largest city.

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Intraplate; monogenetic volcanism; chronology; tephrochronology; volcanic hazard assessment; faulting; magma ascent rates; geochemistry; eruption scenarios; New Zealand

Introduction

Auckland Volcanic Field (AVF; Figure 1A) is a basaltic, intraplate volcanic field underlying New Zealand's most populated city, Auckland (population ∼1.6 M). It is one of 240+ known Holocene volcanic fields around the world (Cañón-Tapia 2016). Where volcanic fields overlap with population centres, eruptions pose significant hazard (e.g. base surges, ballistics, ash fall, lava flows) and associated risk (Lindsay et al. 2010; Lindsay 2016). While eruption volume, duration, and scale are generally much smaller than those at caldera or stratovolcanoes, eruptions in volcanic fields typically occur at a different vent location each time (Valentine and Connor 2015). Detailed holistic and field-wide studies are required to overcome this spatial distribution challenge for hazard assessments; however, these holistic studies are often infeasible due to limited resources, the number of vents, and/or the areal extent of the field (Valentine and Connor 2015). As the AVF is younger (∼193 ky) and contains fewer centres (53) than most volcanic fields globally, a comprehensive understanding of the whole system is more easily constructed.

The AVF was first recognised as a volcanic field and mapped by Heaphy (1860) and Von Hochstetter (1864). They identified 62 and 63 volcanic centres respectively, however, the number of discrete eruptive centres has been an ongoing matter of discussion (Figure 1B; Searle 1964b; Hayward, Murdoch, et al. 2011). In the 1990s, the accepted number of centres was 48 (Kermode 1992) but subsequent research identified a difference between volcanic centres and volcanic episodes (Smith and Allen 1993; Hayward, Kenny, et al. 2011; Hayward, Murdoch, et al. 2011, 2012). For example, Rangitoto exhibits two compositionally and temporally discrete eruption events (Rangitoto 1 and 2) that are spatially proximal (Figure 1B; Needham et al. 2011; McGee et al. 2013; Hopkins et al. 2017). In comparison, Purchas Hill/Te Tauoma and Mt Wellington/Maungarei (Figure 1B) are a compositionally distinct, geographically separate pair, but may have erupted in one episode. Within the last decade, new centres Boggust Park, Cemetery Hill, and Puhinui Craters (Figure 1B) were identified from new 0.5 m resolution Light Detection and Ranging (LiDAR) data. Currently, 53 centres are now recognised in the AVF (Hayward et al. 2012; Hayward 2019; Hayward and Hopkins 2019).

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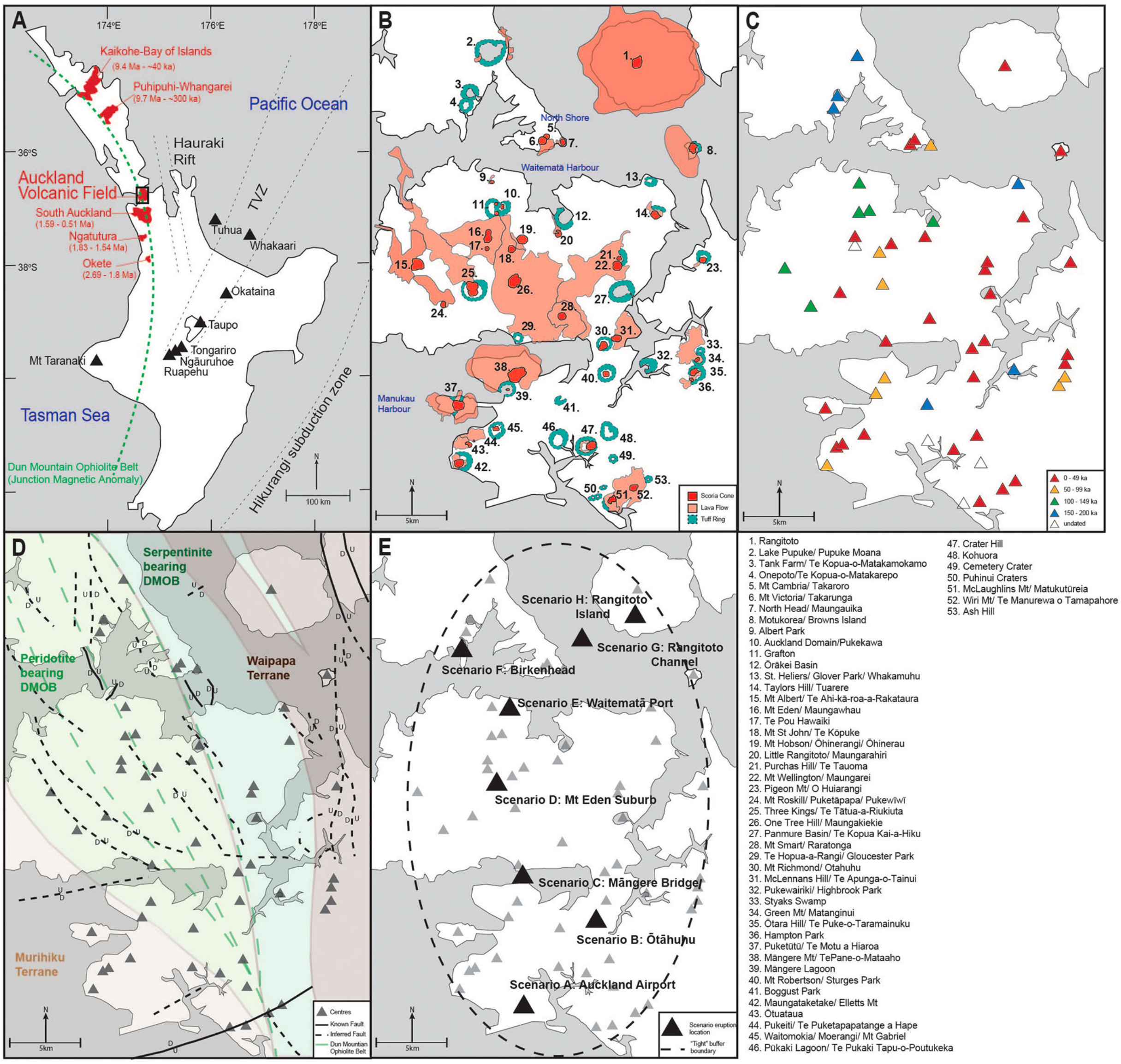

Figure 1. A, Location map for the Auckland Volcanic Field in the context of the North Island, New Zealand. Highlighted in red are all the volcanic fields of the North Island, black triangles show the other currently active volcanoes that could potentially impact Auckland. Green dashed line indicates the trace of the Dun Mountain Ophiolite Belt (DMOB), identified by the Junction Magnetic Anomaly (JMA). Black dashed lines indicate key tectonic traces discussed in the text. **B,** Location of the centres in the AVF, including their eruptive products and extents numbered from North to South, including their alternate names. **C,** Ages of the centres (c.f. Table 1 for details) coloured by 50 kyr groupings. **D,** Structural characteristics of the Auckland region, fault traces are from Kenny et al. (2012), trace of the DMOB from Eccles et al. (2005) and Spörli et al. (2015), diagram adapted from Kermode (1992), colouration shows differing geology described in the text; grey is Murihiku Terrane; brown is Waipapa Terrane; light green is Peridotite bearing DMOB; and dark green is Serpentinite bearing DMOB (from Eccles et al. 2005 and Spörli et al. 2015). **E,** Location of the 8 modelled DEVORA scenario eruption sites from Hayes et al. (2018) (see text and Table 2 for details), dashed line indicates the 'tight boundary' ellipse proposed for the extent of the field by Runge et al. (2015).

Regionally, the AVF is the most recently active in a series of volcanic fields trending northward to Auckland (from south to north: Okete [2.69–1.8 Ma]; Ngatutura [1.83–1.54 Ma]; South Auckland (SAVF) [1.59–0.51 Ma]; and Auckland [0.19 Ma – present]) (Figure 1A; Briggs et al. 1989, 1994; Cook et al. 2004). During the AVF's ~193 ka lifespan (Leonard et al. 2017; Figure 1C) small batches of basaltic magma (<<0.1–0.7 km^3 in volume; Kereszturi et al. 2013) rose from an inferred depth of 70–90 km and formed maars, tuff cones, tuff rings, scoria cones, lava flows and shield volcanoes (Figure 1B) within a ~30 × ~20 km elliptical area (Spörli and Eastwood 1997; Horspool et al. 2006; Kereszturi et al. 2013; Leonard et al. 2017). At present, there is no firm consensus on the geodynamic processes driving mantle melting and eruptions within the AVF, or the older volcanic fields in the Auckland Volcanic Province (Spörli and Eastwood 1997; Cook et al. 2004; Hoernle et al. 2006; Timm et al. 2010; Shane 2017; Van den Hove et al. 2017). Although most of the Holocene volcanic activity in New Zealand has taken place in the Taupō Volcanic Zone (TVZ; a

Table 1. Overview of the currently preferred ages for the Auckland Volcanic Field centres. An expanded version of this table can be found in SM Table 1. ^{14}C calibrations were done in 2011 by CalPal.

Centre name / Alternate name	Preferred Age (ka)	Error (2sd)	Method	Reference	Comments	Reliability Grouping
Albert Park	145.0	4.0	Tephrochronology	Hopkins et al. 2017		2
Ash Hill	31.8	0.4	14C	Hayward 2008		2
Boggust Park	>130[a]		Morphostratigraphy	Hayward and Hopkins 2019		5
Cemetery Crater	undated					5
Crater Hill	30.4	0.8	Tephrochronology	Hopkins et al. 2017		2
Auckland Domain / Pukekawa	106.0	8.0	Tephrochronology	Hopkins et al. 2017	See SM1	2
Grafton	106.5		Morphostratigraphy*	Hopkins et al. 2017	See SM1	3
Green Mt/Matanginui	19.6	6.6	Ar/Ar	Leonard et al. 2017		1
Hampton Park	57.0	32.0	Ar/Ar	Leonard et al. 2017		2
Te Hopua-a-Rangi/Gloucester Park	31.0		Tephrochronology & morphostratigraphy	Hopkins et al. 2017	See SM1	3
Kohuora	33.7	2.4	Tephrochronology	Hopkins et al. 2017		1
Little Rangitoto/Maungarahiri	24.6	0.6	Tephrochronology	Hopkins et al. 2017		1
Māngere Lagoon	59.5		Tephrochronology & morphostratigraphy*	Hopkins et al. 2017		3
Māngere Mt/Te Pane o Mataaho	59.0	20.0	Tephrochronology	Hopkins et al. 2017		4
Maungataketake/Elletts Mountain	88.9	4.8	Ar/Ar	Leonard et al. 2017	See SM1	2
McLaughlins Mt/Matukutūreia	48.2	6.4	Ar/Ar	Leonard et al. 2017		2
McLennan Hills/Te Apunga-o-Tainui	41.3	2.4	Morphostratigraphy & paleomagnetic	Hopkins et al. 2017		2
Motukorea / Brown's Island	24.4	0.6	tephrochronology	Hopkins et al. 2017		2
Mt Albert / Te Ahi-kā-roa-a-Rakataura	119.2	5.6	Ar/Ar	Leonard et al. 2017		1
Mt Cambria / Takaroro	42.3	22.0	Ar/Ar	Leonard et al. 2017		2
Mt Eden / Maungawhau	28.0	0.6	tephrochronology	Hopkins et al. 2017	See SM1	1
Mt Hobson / Ōhinerangi/Ōhinerau	34.2	1.8	Tephrochronology	Hopkins et al. 2017		4
Mt Richmond / Otahuhu	30.2	4.2	Tephrochronology	Hopkins et al. 2017		2
Mt Roskill / Puketāpapa/Pukewīwī	105.3	6.2	Ar/Ar	Leonard et al. 2017		2
Mt Smart / Raratonga	20.1	0.2	Tephrochronology	Hopkins et al. 2017		4
Mt St John / Te Kōpuke/Tītīkōpuke	75.3	3.4	Ar/Ar	Leonard et al. 2017		2
Mt Victoria/Takarunga	34.8	4.0	Tephrochronology	Hopkins et al. 2017		4
Mt Wellington/Maungarei	10.0	1.0	Tephrochronology	Hopkins et al. 2017		1
North Head/Maungauika	87.5	15.2	Ar/Ar	Leonard et al. 2017		2
One Tree Hill/Maungakiekie	67.0	12.0	Tephrochronology	Hopkins et al. 2017		2
Onepoto / Te Kopua-o-Matakarepo	187.6		Tephrochronology and morphostratigraphy	Hopkins et al. 2017	See SM1	2
Ōrākei	126.0	6.0	Tephrochronology	Hopkins et al. 2017		2
Otara Hill/Te Puke-o-Taramainuku	56.5		Morphostratigraphy*	Hopkins et al. 2017		3
Ōtuataua	24.2	1.8	Tephrochronology	Hopkins et al. 2017	See SM1	2
Panmure Basin/Te Kopua Kai-a-Hiku	25.2	1.8	Tephrochronology	Hopkins et al. 2017		2
Pigeon Mt / O Huiarangi	23.4	0.8	Tephrochronology	Hopkins et al. 2017		3
Puhinui Craters	undated					5
Pūkaki Lagoon / Te Pukaki Tapu-o-Poutukeka	>>45[c]		Tephrochronology	Shane 2005		3
Pukeiti/Te Puketapapatanga a Hape	23.7		Morphostratigraphy*	This paper	See SM1	4
Pukewairiki/Highbrook Park	>130[a]		Morphostratigraphy	Hayward and Hopkins 2019		3
Puketūtū/Te Motu a Hiaroa	29.8	4.4	Tephrochronology	Hopkins et al. 2017		2
Lake Pupuke / Pupuke Moana	193.2	5.6	Ar/Ar	Leonard et al. 2017	See SM1	1
Purchas Hill / Te Tauoma	10.9	0.2	14C	Lindsay et al. 2011		1
Rangitoto 2 (Upper Tephra or surface lava flows)	504 cal. yrs. BP	10 yrs	14C	Needham et al. 2011	See SM1	1
Rangitoto 1 (Lower Tephra)	553 cal. yrs. BP	14 yrs	14C	Needham et al. 2011		1
Mt Robertson/Sturges Park	24.3	0.8	Tephrochronology	Hopkins et al. 2017		3
St Heliers / Glover Park / Whakamuhu	161.0	36.0	Tephrochronology and morphostratigraphy	Hopkins et al. 2017		3
Styaks Swamp	19.1		Morphostratigraphy*	Hopkins et al. 2017		3
Tank Farm / Te Kopua-o-Matakamokamo	181.0	2.0	Tephrochronology	Hopkins et al. 2017	See SM1	2
Taylors Hill / Taurere	30.2	0.2	tephrochronology	Hopkins et al. 2017		2
Te Pou Hawaiki	>28.0		Morphostratigraphy	Affleck et al. 2001	See SM1	3
Three Kings / Te Tātua-a-Riukiuta	31.0	1.8	Tephrochronology	Hopkins et al. 2017		2
Waitomokia / Moerangi / Mt Gabriel	20.3	0.2	Tephrochronology	Hopkins et al. 2017	See SM1	2
Wiri Mt / Te Manurewa o Tamapahore	30.1 - 31.0		Ar/Ar	Cassata et al. 2008		1

[a]The age of 130 ka indicates geomorphological evidence that shows marine erosion during the last sea level high-stand related to the last interglacial at c. 130–120 ka.
[c]The age of 45 ka is related to the eruption of the Rotoehu tephra, which at present has an ambiguous age (see discussion in SM 1).
*indicates centres where morphostratigraphy suggests contemporaneous eruptions (for example no organic material between successive volcanic deposits); these are given an arbitrary difference in age of 500 years, based on a minimum time it takes to form soil horizons. Ambiguous or controversial ages highlighted in the table are discussed in SM1. Reliability grouping are assigned as per the characteristics outlined in SM Table 3.

rifted volcanic arc in the central North Island), driven by melts generated from the south-westerly subduction of the Pacific Plate under the Australian Plate (Figure 1A; Wilson 1996), there is no evidence linking this region of volcanic activity to the volcanism ~250 km northwest in Auckland.

An eruption in the AVF is a low probability event on human time-scales, but would have high consequences – Auckland is home to ~35% of New Zealand's total population, and generates 38% of the country's GDP (Lindsay 2010; McDonald et al. 2017). For this reason, future eruptions have been a long-recognised threat to the city (e.g. Searle 1961b, 1964a; Smith and Allen 1993; Molloy et al. 2009; Hurst and Smith 2010; Leonard et al. 2017). The dispersed nature of eruptions in volcanic fields and the wide range of factors involved mean that a large amount of data is needed to properly assess volcanic hazards and quantify volcanic risk.

Coordinated, transdisciplinary efforts, in consideration with emergency management and lifeline priorities, began in the AVF in the last few decades (e.g. Smith and Allen 1993; Deligne, Lindsay, et al. 2015). The focus of these studies include: potential melt generation triggers (McGee et al. 2011, 2012, 2013), erupted magma composition (Smith et al. 2008; McGee et al. 2012; Hopkins et al. 2017), degree of crustal contamination (McGee et al. 2013; Spörli et al. 2015; Hopkins et al. 2016), tectonic setting (Horspool et al. 2006; Cassidy and Locke 2010; Le Corvec, Bebbington, et al. 2013; Le Corvec, Spörli, et al. 2013), local mantle and crustal compositions and properties (Price et al. 2015; Spörli et al. 2015; Hopkins et al. 2016; Brenna et al. 2018), magma ascent rates (Brenna et al. 2018), magma volumes and fluxes (Kereszturi et al. 2013; McGee et al. 2013), local crustal structures and their effect on magmatic plumbing (e.g. Figure 1D; Eccles et al. 2005; Cassidy and Locke 2010; Kenny et al. 2012; Le Corvec, Bebbington, et al. 2013; Le Corvec, Spörli, et al. 2013), eruption recurrence rates and spatial patterns of eruptions (Hopkins et al. 2017; Leonard et al. 2017), and their styles, extent, duration, frequency, likelihood and environmental conditions (Lindsay 2010; Kereszturi et al. 2013; Kereszturi, Németh, et al. 2014; Agustín-Flores et al. 2015a, 2015b). The findings from these studies have fed into applied hazard and risk focused research including: scenario building and testing (Blake et al. 2017; Deligne, Fitzgerald, et al. 2017; Hayes et al. 2018, 2020); impact modelling (Deligne, Horspool, et al. 2017); clean-up and hazard response management (Dolan et al. 2003; Hayes et al. 2017); lava flow modelling and impact (Kereszturi, Cappello, et al. 2014; Tsang et al. 2019, In Review); qualifying and quantifying damage to infrastructure (Magill and Blong 2005a, 2005b; Houghton et al. 2006; Wilson et al. 2012, 2014; Deligne, Blake, et al. 2015; Deligne, Horspool, et al. 2017; Deligne, Fitzgerald, et al. 2017; McDonald et al. 2017; Williams et al. 2017), including transport networks (Blake et al. 2017); and volcanic hazard communication, education and outreach (Doyle et al. 2011; Wilson et al. 2014; Dohaney et al. 2015; Fitzgerald et al. 2016) and evacuation assessment and planning (Lindsay et al. 2010; Tomsen et al. 2014).

In this article, we detail the current understanding of the AVF with respect to its magmatism, volcanism, and hazards, and how researchers have collated and combined this information to create volcanic eruption scenarios, which can be used to forecast and plan for a range of plausible eruption locations, scales, and styles (Figure 1E).

Magmatism

Magma composition

Important insights about AVF mantle sources, melt generation, and ascent processes have been gleaned from petrographic observations and a large number of major, trace, and isotopic analyses of the eruptive products (an extensive geochemical database is available in Hopkins et al. 2017). AVF rocks are characteristically porphyritic, consisting mainly of olivine with subordinate clinopyroxene phenocrysts, in a groundmass of plagioclase, clinopyroxene, olivine and accessory iron-titanium oxides (Searle 1959a, 1959b, 1961a, 1961b, 1965; Heming and Barnet 1986). The most prominent feature observed in AVF major elements is a negative trend in SiO_2 vs. total alkalis, i.e. rocks vary from nephelinite through basanite to subalkaline basalt (TAS classification; Figure 2; McGee et al. 2013). Overall, trace element patterns reveal that AVF mantle sources have a similarity to ocean island basalt (OIB) trends, with high Nb and

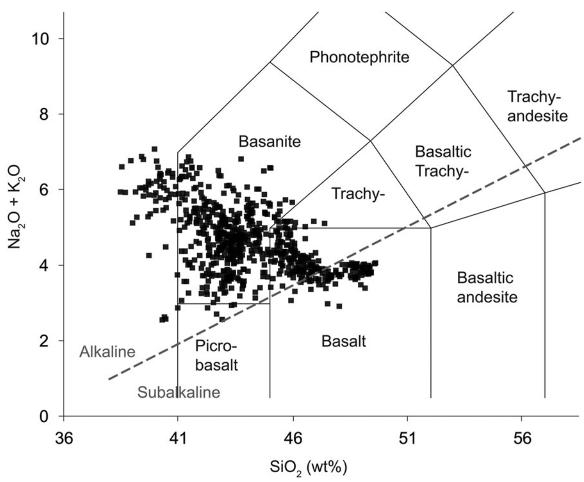

Figure 2. Total alkali (Na_2O + K_2O) vs. SiO_2 (after Le Maitre 2002) for all whole rock lava samples from centres in the AVF ($n = 755$) data from Hopkins et al. (2017) and references therein. Alkaline – subalkaline discrimination line from Irvine and Baragar (1971).

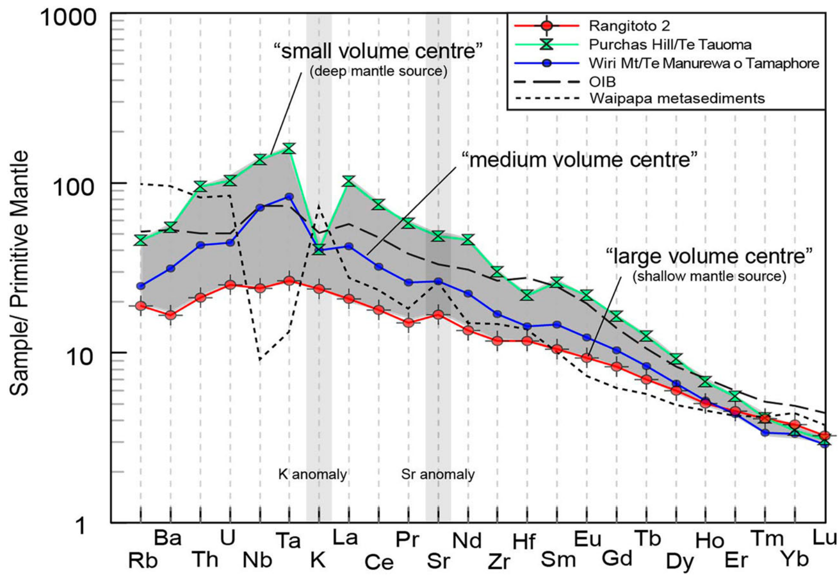

Figure 3. Primitive mantle-normalised multi-element patterns for whole rock lava samples from the AVF, normalisation values from McDonough and Sun (1995). All data shown by grey shaded region, three of the centres in the AVF are highlighted for their volume (based on DRE from Kereszturi et al. 2013); Rangitoto2 (large centre, red symbols), Wiri Mt/Te Manurewa o Tamapahore (medium centre, blue symbols), and Purchas Hill/Te Tauoma (small centre, green symbols). Also shown for comparison is the trace element composition of the Waipapa metasediments that make up some of the crustal structure beneath the AVF (data from Price et al. 2015), and typical OIB signature (data from Sun and McDonough 1989).

decreasing abundances of less incompatible elements (Figure 3; Huang et al. 1997; McGee et al. 2013; McDonough and Sun 1995). Trace element modelling (e.g. La/Yb and Gd/Yb ratios compared to typical MORB compositions; Figure 5) places melting dominantly in the garnet stability zone (i.e. >60 km deep and likely up to 100 km deep Figure 4; Smith et al. 2008; McGee et al. 2013). This is supported by the presence of ^{230}Th-excesses (^{230}Th/^{238}U > 1; Huang et al. 1997; McGee et al. 2011, 2013), and a broad low-velocity seismic zone at approximately 70–90 km depth under the Auckland region (Horspool et al. 2006).

Influences on magma composition

Detailed, field-wide studies of AVF lavas show that the field is compositionally heterogeneous (McGee et al. 2013, 2015). Two main processes explain the overall chemical variability found in the AVF. The first, and most influential, involves the probable interaction of melts from three different mantle sources (Figures 4 and 5) at variable degrees of melting, and the second involves minor evolution of the magma on ascent through assimilation, fractionation, and crystallisation (e.g. Smith et al. 2008; Hopkins et al. 2016). The three different mantle sources proposed by McGee et al. (2013, 2015) include: (1) fertile garnet peridotite which gives rise to the dominant compositions of LREE enriched, alkalic OIB-like basalts, (2) trace element enriched, possibly carbonated veins within the garnet peridotite that give a signature of relatively higher ^{206}Pb/^{204}Pb vs. ^{207}Pb/^{204}Pb and negative Zr-Hf anomalies, and (3) a shallower, cryptically-metasomatised mantle source indicated by positive Sr anomalies, higher fluid mobile/fluid immobile trace element ratios and relatively lower ^{206}Pb/^{204}Pb vs high ^{207}Pb/^{204}Pb in the resultant compositions (Figure 6; McGee et al. 2013, 2015). However, subsequent studies of mantle xenoliths thought to represent the lithospheric mantle composition of Southern Zealandia (e.g. Scott et al. 2016, 2020; Brenna et al. 2018) may mean that the geochemical data used by McGee et al. (2013, 2015) for mantle modelling in the AVF need updating or at least comparing to these new data. Such studies are immensely useful for the petrogenesis of the AVF where no definitive mantle xenoliths have so far been found. Although the Sr-Nd isotopic values for the AVF show very little variability, and are similar to the Otago lithospheric mantle region (Scott, Hodgkinson, et al. 2014; Scott, Waight, et al. 2014; McCoy-West et al. 2016; Scott et al. 2016, 2020), AVF Pb isotope ratios are less radiogenic than basalts from the South Island intraplate volcanic fields (e.g. Scott et al. 2016). McGee et al. (2013) used the variability in Pb-isotopes combined with trace element ratio modelling to suggest the interaction of three mantle sources (Figure 6D). This variability is not observed in the South Island volcanic products. There are therefore some apparent differences in the products of the South Island eruptives in comparison to the AVF, and, although feasible to hypothesise that they would have similar mantle characteristics, this topic needs further investigation before mantle models developed for the South Island can be applied to the AVF, particularly considering the heterogeneity of the mantle beneath Zealandia (e.g. Dalton et al. 2017; Scott et al. 2019)

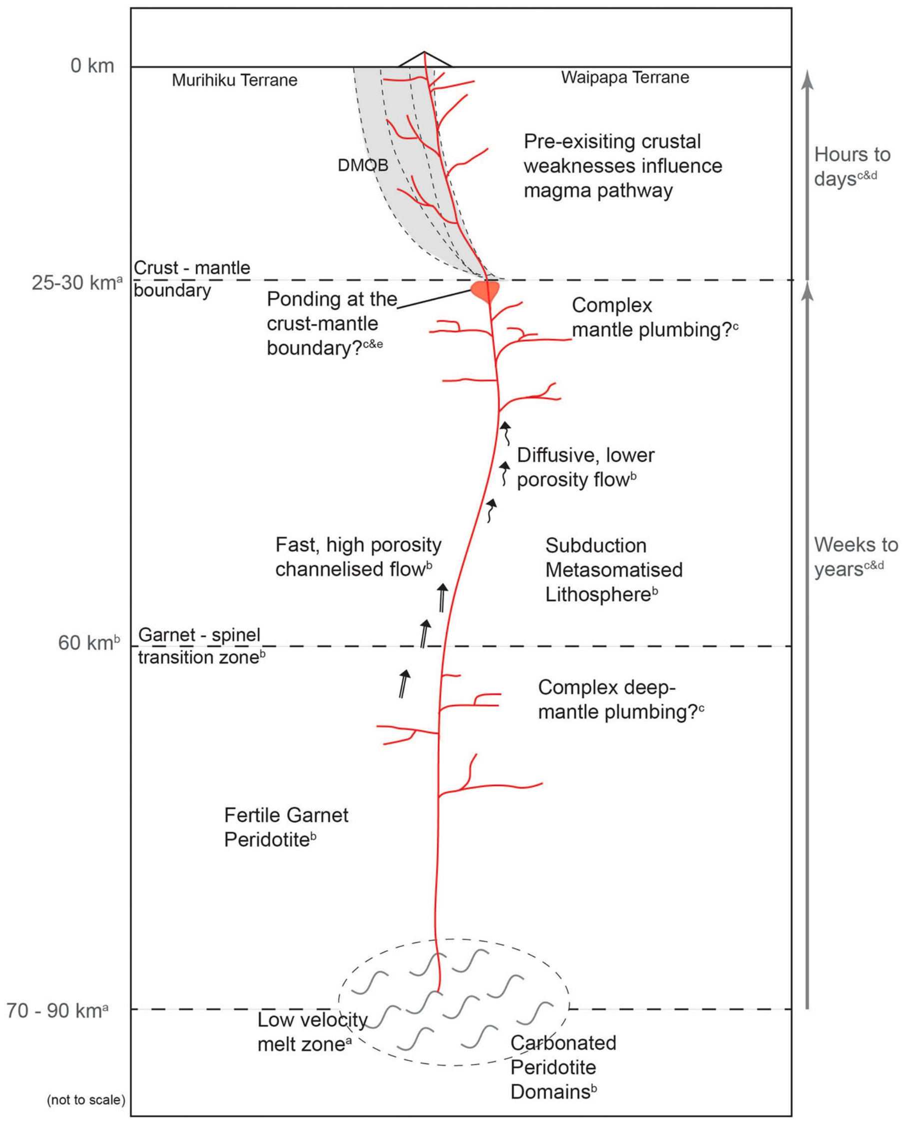

Figure 4. Schematic diagram of our current understanding of the mantle processes associated with an eruption in the AVF. Depths on the left of the figure are approximate and supported by geophysical (low velocity zone under MKAZ station, see Figures 8 and 10; (a) Horspool et al. 2006) and geochemical evidence ((b) McGee et al. 2013). Similarly, time frames of ascent on the right of the figure are also approximate, based on diffusion modelling in AVF xenocrystic olivines ((c) Brenna et al. 2018) and evidence from analogue volcanic fields ((d) Blake et al. 2006). Complex plumbing systems and ascent in both the deep and shallow mantle are proposed with evidence from crustal contamination studies (e.g. (e) Hopkins et al. 2016), geochemical modelling (McGee et al. 2011; Brenna et al. 2018), or comparisons to other fields globally (e.g. Muirhead et al. 2016). Studies on crustal composition and magma ascent through the crust indicate the importance of the DMOB as a potential weakness exploited by the ascending melt. Finally, in the upper crust, magma ascent has been suggested to be influenced by pre-existing faulting or weaknesses, which can impact the final location of the eruptive centre at the surface.

Meticulous sampling through the sequence of volcanic deposits at select, individual AVF centres reveals that the compositional variability found across the field can be seen within single centres (Smith et al. 2008; Needham et al. 2011; McGee et al. 2012; Linnell et al. 2016). Studies of single centres, combined with the field-wide geochemical database, have been used to better understand eruptive processes in the AVF. For example, at Motukorea/Browns Island, complex geochemical trends through the eruption sequence are explained by exhaustion of mantle components during the melting event (McGee et al. 2012). At Rangitoto, petrologic work by Needham et al. (2011) importantly revealed that the far larger, subalkaline lava-producing phase of the eruption was preceded by a small volume, alkaline cone-forming eruption. These results hint at the control that mantle source compositions exert on the eventual eruption, and the hazards it produces.

Mantle source composition-volume links

McGee et al. (2013) combined geochemical characteristics with eruption volume estimates (Kereszturi et al. 2013) and found a correlation between mantle sources and the size of eruptive centres (Figure 7). Multi-element plots of large, lava-dominated centres versus small, tuff-dominated centres show that

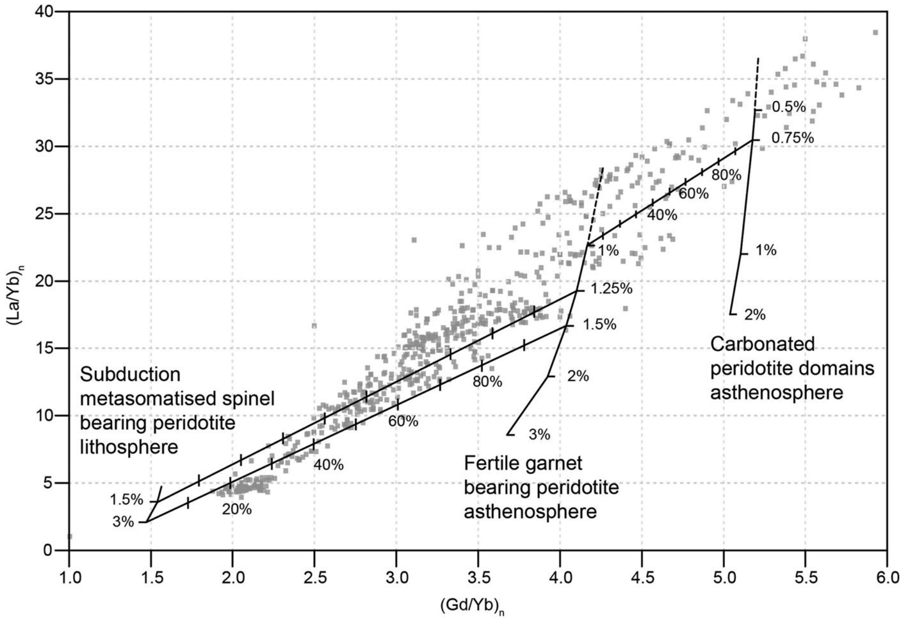

Figure 5. All AVF whole rock lava samples analysed for trace elements using solution-ICP-MS. Modelled parameters of three heterogeneous mantle sources after McGee et al. (2013, 2015), normalisation values from McDonough and Sun (1995). Horizontal tick marks show the % partial melting of the individual sources, and vertical tick marks show the % mixing between these partially melted sources.

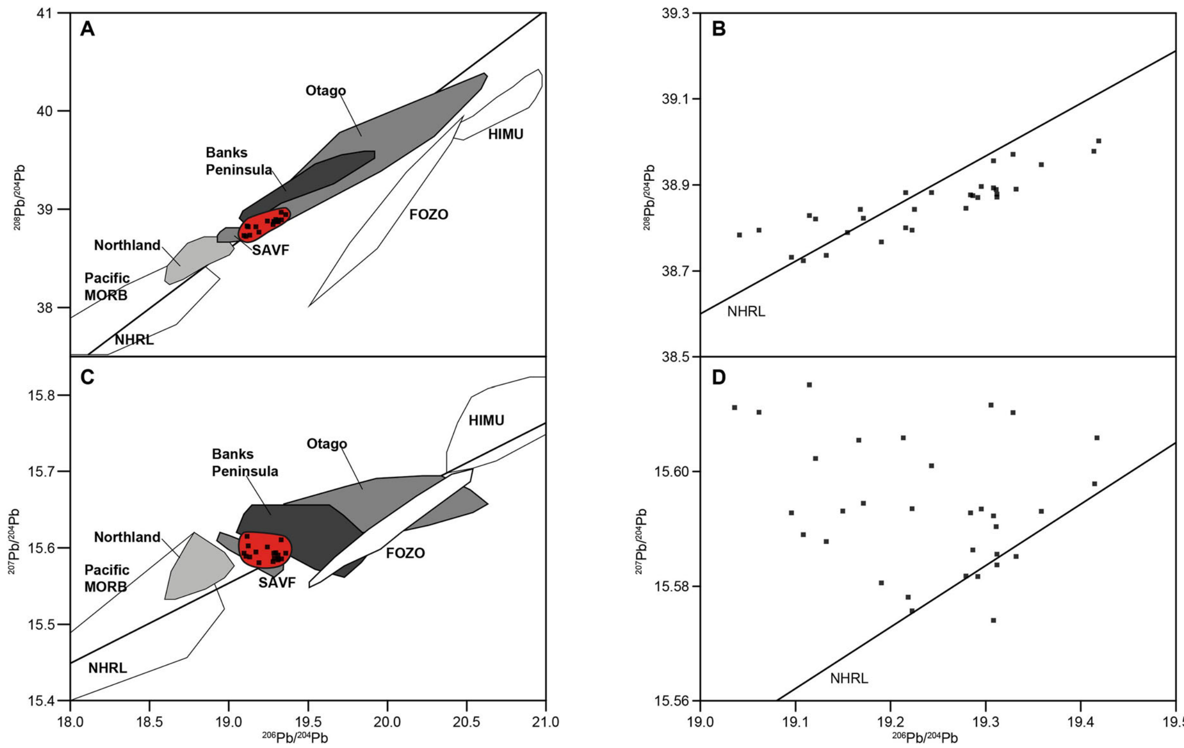

Figure 6. Pb-isotope compositions for the AVF whole rock lava samples (highlighted in red in panels **A** and **C**), panels **B** and **D** show the AVF data, enlarged to allow the detail in the data to be seen. Northern Hemisphere Reference Line (NHRL) calculated after Hart (1984), analytical errors are smaller than symbol size and therefore not shown. White areas on panels **A** and **C** show key mantle domains from Stracke et al. (2005). Shaded areas show data for other intraplate basaltic volcanic fields and complexes in New Zealand, data from Scott, Hodgkinson, et al. (2014); Scott, Waight, et al. (2014); Scott et al. (2016, 2020); McGee et al. (2013) and references therein. Two areas are from the east coast of the South Island; Banks Peninsular includes volcanic fields and the Akaroa shield volcano on the east coast of the South Island, and the Otago data includes volcanic fields, the Dunedin shield volcano, Dunedin Volcanic Group, and the Westland Alpine dyke swarm. Two areas are from the west coast of the North Island; SAVF, South Auckland Volcanic Field, and Northland volcanic field (located on Figure 1A).

mantle-derived signals such as negative Zr-Hf anomalies and shallower features such as positive Sr and K anomalies become diluted or prominent respectively, with increasing size of eruptive centre (Figure 3; McGee et al. 2013). In a follow-up study, McGee et al. (2015), identified a link between degree of melting, involvement of mantle sources and melting rate. McGee et al. (2015) proposed that smaller centres, generally nephelinites, were produced by the smallest degrees of melting at lower melting rates from a deeper source, and larger centres resulted when these melts also incorporated shallower melts with higher degrees of melting (Figure 4). This relationship was not only applied to the AVF but also proposed to provide a general model for other small monogenetic fields (e.g. the Wudalianchi volcanic field, China; McGee et al. 2015). The AVF is one of the few volcanic fields in which we are able to explore a geochemical-eruptive volume relationship, as there is a lack of extensive volume data in other fields, coupled with the dwindling accuracy of estimating volumes as erosion degrades the volcanic landforms over time (McGee et al. 2015; McGee and Smith 2016).

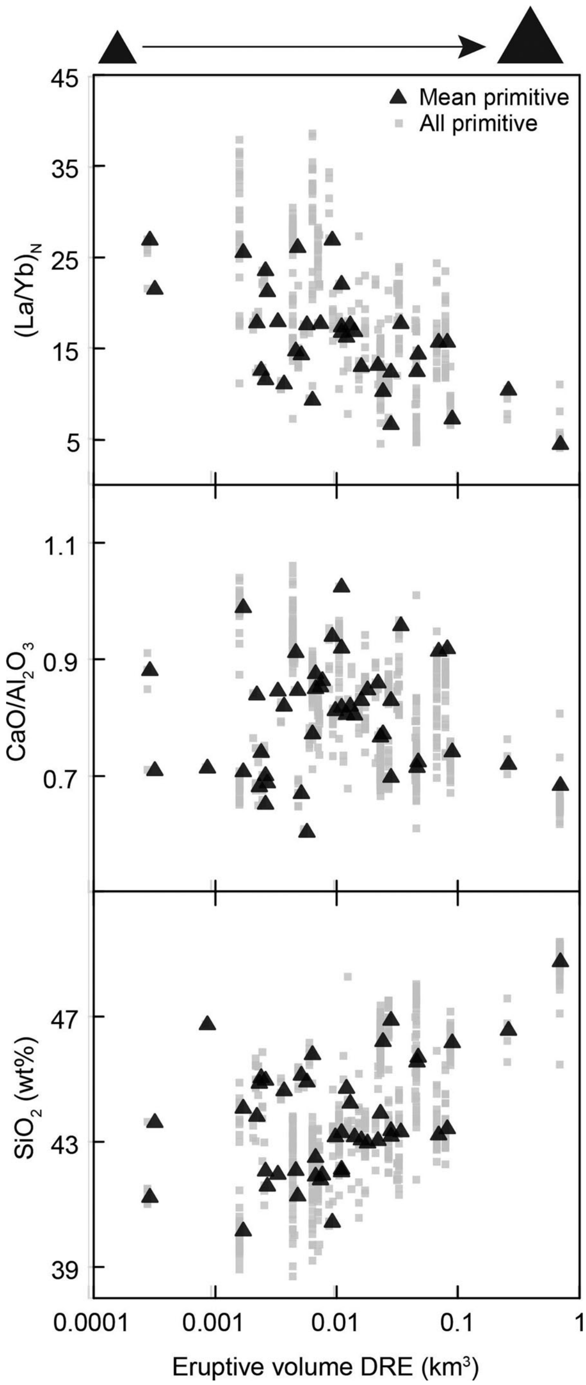

Figure 7. Geochemistry vs. volume plot after McGee et al. (2015) and Hopkins et al. (2017). Volume estimates from Kereszturi et al. (2013), geochemical data for the most primitive samples (i.e. those containing, e.g. Mg# ≥60) from Hopkins et al. (2017) and references therein.

Magma ascent

While mantle source compositions have been shown to have a large influence on the final chemistry of erupted AVF products, additional studies have indicated that the modification of parental magmas by fractionation, crystallisation, and crustal assimilation play a much lesser, secondary role (Smith et al. 2008; McGee et al. 2013; Hopkins et al. 2016). Geochemical studies of these processes also provide important insights regarding magma ascent dynamics, crustal lithologies, and ascent pathways. For example, Smith et al. (2008) found that compositional variations within the Crater Hill eruption sequence match those expected by deep 'near source' clinopyroxene fractionation, shallow olivine and augite fractionation, and concluded that the magma erupted via a dyke rather than stalling in a magma chamber. The geochemical evidence shows that individual magma batches in the AVF are generated and ascend through the mantle via complex ascent processes in isolation, even from successive eruptions within the same volcanic centre (Figure 4). For example, ^{230}Th and ^{226}Ra excesses were observed in both Rangitoto's earlier-erupted alkaline and later-erupted subalkaline magmas, although negatively correlated (McGee et al. 2011). In order to generate these large ^{230}Th excesses but small ^{226}Ra excesses in the earlier alkali basalt (notably, one of the highest found in the literature for continental intraplate and OIB), it was suggested that the melts ascended quickly from depths of ≥80 km and that they suffer minimal overprinting by crustal processing via flow in high porosity channels (Huang et al. 2000; McGee et al. 2013). In contrast, the later, more voluminous subalkaline basalt was proposed to ascend from a shallower melting region via slower, diffuse melt movement which would allow greater ingrowth of ^{226}Ra (Figure 4).

Complex ascent histories for Auckland magmas were also suggested by Brenna et al. (2018), who examined water and major element diffusion in mantle-derived xenocrystic olivines in Lake Pupuke/Pupuke Moana lavas. Major element diffusion profiles indicate that the xenocrysts were entrained in the magma during deep crustal or mantle storage on timescales

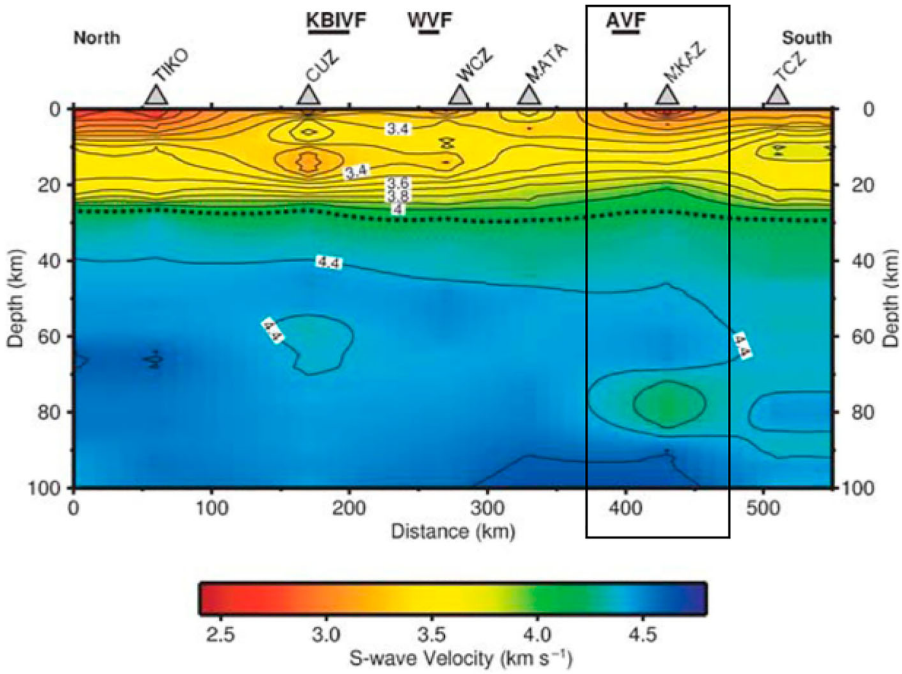

Figure 8. Shear wave velocity profile for northern New Zealand, originally published as the top panel of Figure 11 in Horspool et al. (2006). The profile is created from interpolation between sparse 1D profiles at broadband stations indicated by triangles. Locations of intraplate basalt fields (black bars) are projected onto the profile at top: Kaikohe-Bay of Islands Volcanic Field (KBIVF), Whangarei Volcanic Field (WVF) and Auckland Volcanic Field (AVF). Note the region of low seismic velocity below MKAZ at ~70–90 km depths, interpreted to be a region of partially molten mantle is located ~20 km to the south east of the AVF. The interpreted Moho is indicated by the blacked dotted line showing the crustal thickness varies between 25–30 km, and the cross section represented in Figure 4 is outlined by the black box. The seismic stations are show by grey triangles with their name abbreviation station codes defined, for example MKAZ – Moumoukai.

varying from one month up to several years at depths 27–80 km, thereafter rising to the surface over ~30–40 days, giving a relatively slow average ascent rate of 0.01–0.03 m/s. In contrast, water diffusion profiles in the dehydrated rims of the same xenocrystic olivines indicate that Lake Pupuke/Pupuke Moana magmas rose more rapidly through the crust from 1–2 km depth over <12 h, at speeds of 1–10 m/s (Figure 4). This demonstrates that a single magma batch may ascend at variable rates as it rises through the mantle and crust.

There is no clear evidence for crustal magma storage in the AVF, past or present, which is interpreted to mean shallow magma ascent rates are too quick to support stalling for significant periods of time (Lindsay et al. 2010; Mazot et al. 2013; Hopkins et al. 2016). Several physical observations also support the idea of rapid crustal magma ascent for example; Houghton et al. (1999) inferred fast magma ascent at Crater Hill, as indicated by deposits from Hawaiian-style fire fountaining, an eruption style primarily controlled by magma ascent rate; and Kereszturi, Németh, et al. (2014) noted that using an ascent rate of 0.1 m/s at the vent opening in lava flow models resulted in lava flow lengths and thicknesses similar to those observed in the AVF.

The presence of rare crustal xenocrysts and crustal xenoliths in Auckland lavas, combined with analogue models of xenolith settling rates and dike propagation, have also been proposed as evidence for fast ascent (0.01–6.0 m/s from 100 km depth, taking ~10–100 d; Cassidy et al. 1986; Blake et al. 2006; Spörli et al. 2015; Brenna et al. 2018). Xenoliths are uncommon in the AVF, however, where found they are mostly distinct populations of lithic cargo within phreatomagmatic tuff ring deposits (e.g. Searle 1959b, 1962; Brothers and Rodgers 1969; Jones 2007; Spörli and Black 2013; Spörli et al. 2015; Brenna et al. 2018). For example, at Lake Pupuke/Pupuke Moana (Figure 1B), xenocrysts are exclusively olivine-rich ultramafic inclusions, proposed to have been assimilated in the upper mantle (e.g. Brothers and Rodgers 1969; Brenna et al. 2018). In comparison, Mesozoic and Cenozoic sedimentary clasts linked to shallow-level crustal Waitemata, Te Kuiti and Waipapa Group sediments are found in several tuff ring deposits throughout the field (Spörli et al. 2015), and mafic schistose and non-schistose, amphibolite-grade metabasite xenoliths have been found at St Heliers/Glover Park/Whakamuhu and Taylors Hill/Taurere indicative of interaction of ascending magma with melange formation along the eastern boundary of the DMOB in the crust (Spörli et al. 2015). The xenoliths at some centres show evidence of reaction rims indicating high temperature interactions (e.g. at Mt Wellington/Maungarei; Figure 1B), but this evidence is absent in others (e.g. at

St Heliers/Glover Park/Whakamuhu; Figure 1B) (Spörli et al. 2015).

Rapid shallow-crustal ascent is also supported by whole rock major and trace element modelling, which has confirmed that crustal assimilation has very little influence on the geochemical variations seen in the AVF (McGee et al. 2013). More specifically, Hopkins et al. (2016) analysed Sr-Nd-Pb-Os-Re isotopes in primitive lavas and found that, while Sr-Nd-Pb systems show very little variability, the more sensitive Re-Os isotopes suggest interaction with two main types of crust: metasediments of the Waipapa and Murihiku terrains and dunite-dominated ultramafic rocks of the Dun Mountain – Maitai terranes, commonly referred to as the Dun Mountain Ophiolite Belt (DMOB) (Figure 1D; Figure 4; Hopkins et al. 2016). The input from these sources was modelled to be ≤1%, which precludes detection in the traditional major, trace or isotope (Sr, Nd, and Pb) systems (Hopkins et al. 2016). While the geochemical composition of both the lavas and their cargo (e.g. minerals and xenoliths) can tell us much about the source compositions of melts and subsurface processes acting on the magma, details about the tectonic setting as well as the geophysical structure of the mantle and crust are needed to complete a conceptual eruptive model for the AVF.

Structure

Tectonic setting

Several events in Auckland's tectonic history influence magma chemistry and perhaps the location of the AVF. Subduction occurred directly beneath the Auckland area during the Miocene, and is the presumed cause for the presence of slab fluid-metasomatized lithospheric mantle, which comprises one of the three hypothesised mantle sources (McGee et al. 2013). Auckland magmas erupt through late Palaeozoic to Mesozoic metasedimentary basement terranes which accreted on the Gondwana margin (Bradshaw 1989). These are overlain by dominantly deep-water Miocene Waitemata Basin sandstones and mudstones, in addition to some Pliocene to Quaternary shallow marine to terrestrial (fluvio-lacustrine) sediments. The total crustal thickness in Auckland is ~25–30 km, as indicated by shear velocity gradients, see Figure 8 (Horspool et al. 2006).

Currently, the AVF occurs distal (>400 km) to the Hikurangi subduction zone (Figure 1A), where the Pacific Plate (to the southeast) is subducting beneath the Australian Plate (to the northwest) and, more proximally, to the west of a zone of geodetically resolved oblique extension associated with the Hauraki Rift axis (Figure 1A; Pickle 2019). The axis of extension of the Hauraki Rift parallels the accreted basement fabric delineated by the Junction Magnetic Anomaly (JMA; Figure 1A) (Kenny et al. 2012), a significant geophysical marker throughout New Zealand (Figure 9). The NNW-SSE trending JMA is interpreted to comprise the intra-crustal trace of the ultramafic DMOB succession (Hatherton 1967; Hatherton and Sibson 1970; Eccles et al. 2005), which contrasts with those of the accreted forearc Murihiku Terrane to the west (Briggs et al. 2004) and silicic succession of the Waipapa Terrane to the east (e.g. Figure 1D; Spörli et al. 1989). As a result of this, the DMOB is clearly observed in ambient noise-derived velocity models (Ensing et al. 2017) and total magnetic intensity anomaly maps (Figure 9; Cassidy and Locke 2010). These models show that under the AVF, the DMOB takes a complex, sinuous form of eastward dipping shear zones and likely transects the crust (Figure 1D), with its influence seen in the topology of the Moho and lithospheric mantle structure. Therefore, it is hypothesised to represent a zone of weakness connecting the mantle to the surface; additionally, the bounding faults associated with the DMOB have been proposed to exert control over the E-W surface expression and AVF boundary (Figure 4; e.g. Hatherton and Sibson 1970; Spörli and Eastwood 1997; Eccles et al. 2005; Williams et al. 2006; Cassidy and Locke 2010; Kenny et al. 2012; Spörli et al. 2015; Hopkins et al. 2016). More regionally, intraplate volcanism in northern New Zealand shows some spatial correlation to the location of the DMOB; the AVF and SAVF are located directly on it, however, the other fields (Okete and Ngatutura) are offset to the west (Figure 1A).

Causes for melting under Auckland

Researchers commonly rely on local geophysical measurements of seismicity, as well as the gravitational and magnetic field, to make inferences about the subsurface structure, properties, and origin of melting in a volcanic field. However, in the Auckland region, urbanisation, infrastructure density, and a lack of high-resolution local sources for seismic tomography have reduced the ability to utilise traditional geophysical methods. For example, Figure 10 displays the epicentres of the 118 earthquakes recorded by Geonet (https://www.geonet.org.nz/data) in the Auckland region over the past 30 years. Of those earthquakes, only four had a magnitude greater than M3 and very few even sit within the proposed boundary of the AVF. As a result of this, high-resolution geophysical images of the subsurface under the AVF generally terminate in the shallow crust (Davy 2008; Cassidy and Locke 2010), and geophysical investigations of the deeper structure under the AVF lack clear resolution (Mooney 1970; Eccles et al. 2005; Horspool et al. 2006; Eberhart-Phillips et al. 2010).

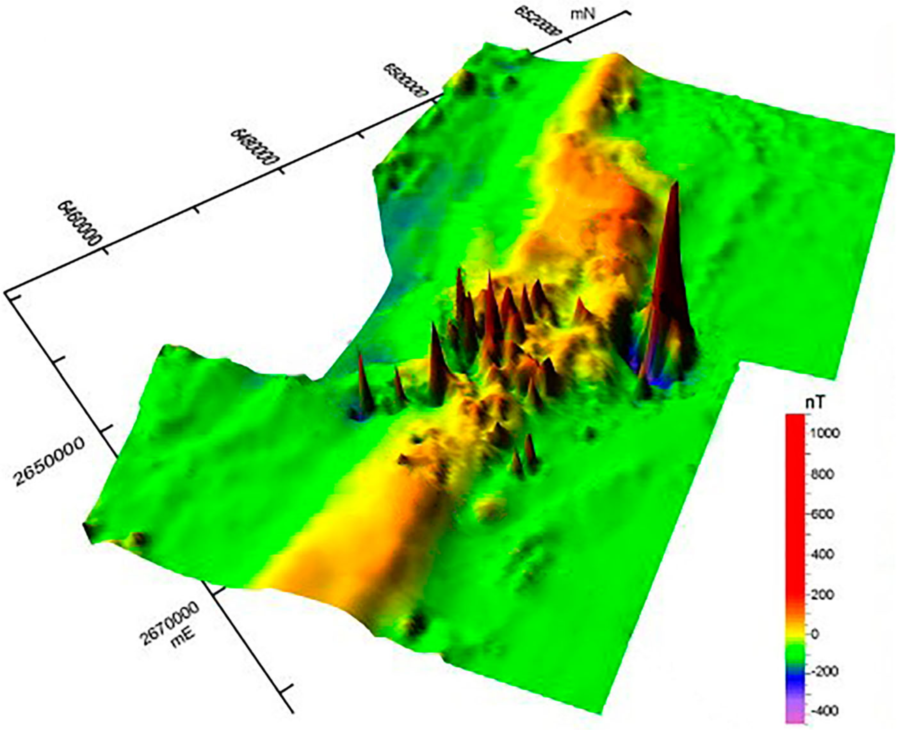

Figure 9. Total magnetic intensity (TMI) anomaly map of the Auckland region at 430 m above sea level. The orange to yellow, sub-linear, long-wavelength magnetic high running the length of the figure represents the Junction Magnetic Anomaly (JMA), caused by the DMOB (see text for discussion). Short wavelength anomalies (positive, dark red peaks and adjacent negative, dark blue-purple troughs) represent the often bipolar anomalies associated with volcanic centres. Figure modified from Cassidy and Locke (2010).

Our current understanding of the crust and mantle under the AVF is captured in a 2D model that traverses the upper North Island of New Zealand (Horspool et al. 2006). Surface waves and receiver functions from teleseismic earthquakes were converted to 1D profiles under an array of seismic stations to reveal a zone of low seismic shear-wave velocity at approximately 70–90 km depth beneath Auckland (Figure 8). This was interpreted by Horspool et al. (2006) as a potential zone of partial melt, supported by geochemical observations (McGee et al. 2013), suggesting that erupted materials stem from magma sources at a similar depth (~80 km; Figure 4). However, this image is based on data from a single station (MKAZ) ~20 km the south-east of the AVF (Figure 10). Consequently, we have not yet been able to identify the dominant controls on regional upwelling flow beneath the AVF and can only infer potential causes by comparing the AVF to other intraplate fields in NZ (e.g. Hoernle et al. 2006; Timm et al. 2010; Scott et al. 2020) and around the world (e.g. Conrad et al. 2010, 2011; Putirka et al. 2012; Davies and Rawlinson 2014; Kaislaniemi and van Hunen 2014; Brenna et al. 2018). The interplay between magma fluxes and regional tectonic stresses in particular seem to have a large influence on the predictability of eruptions (either temporally or volumetrically) in some volcanic fields (e.g. Demidjuk et al. 2007; Valentine and Perry 2007; Conrad et al. 2010; Aranda-Gómez et al. 2013; Brenna et al. 2015). Explanations for melting under Auckland most closely match those in time-predictable fields, specifically those that involve disturbances in mantle flow patterns and/or delamination, which in turn induce melting and upwelling (Hodder 1984; Spörli et al. 2015). However, eruptions in the AVF are neither strictly time- nor volume-predictable and the cause of melting remains enigmatic (Hopkins et al. 2017; Mortimer and Scott 2020).

In order to localise melting and volcanism, some degree of entrainment of enriched material may be required (Demidjuk et al. 2007), or 3D regional lithospheric structure, plate motion and background mantle flow must combine to localise upwelling flow (McGee et al. 2011, 2013; Davies and Rawlinson 2014). The outstanding questions for the AVF are whether edge-driven flow (i.e. flow excited by crustal delamination or lateral variations in lithospheric thickness), and/or shear-driven flow (i.e. movement in response to regional plate motion), play an important role in the melt origins (Hodder 1984; Spörli et al. 2015). Although no chemical evidence exists to support this idea, it is possible that factors influencing regional mantle flow patterns (e.g. subduction east of the North Island) are inducing upwelling under the AVF, similar to the mechanisms proposed by Brenna et al. (2015) at the Jeju volcanic field.

Where local seismicity is lacking (as in Auckland; Figure 10), researchers are employing newly developed crustal imaging techniques, such as the inversion of ambient seismic noise (e.g. ocean waves; Ensing et al. 2017), a method that has proven very effective for

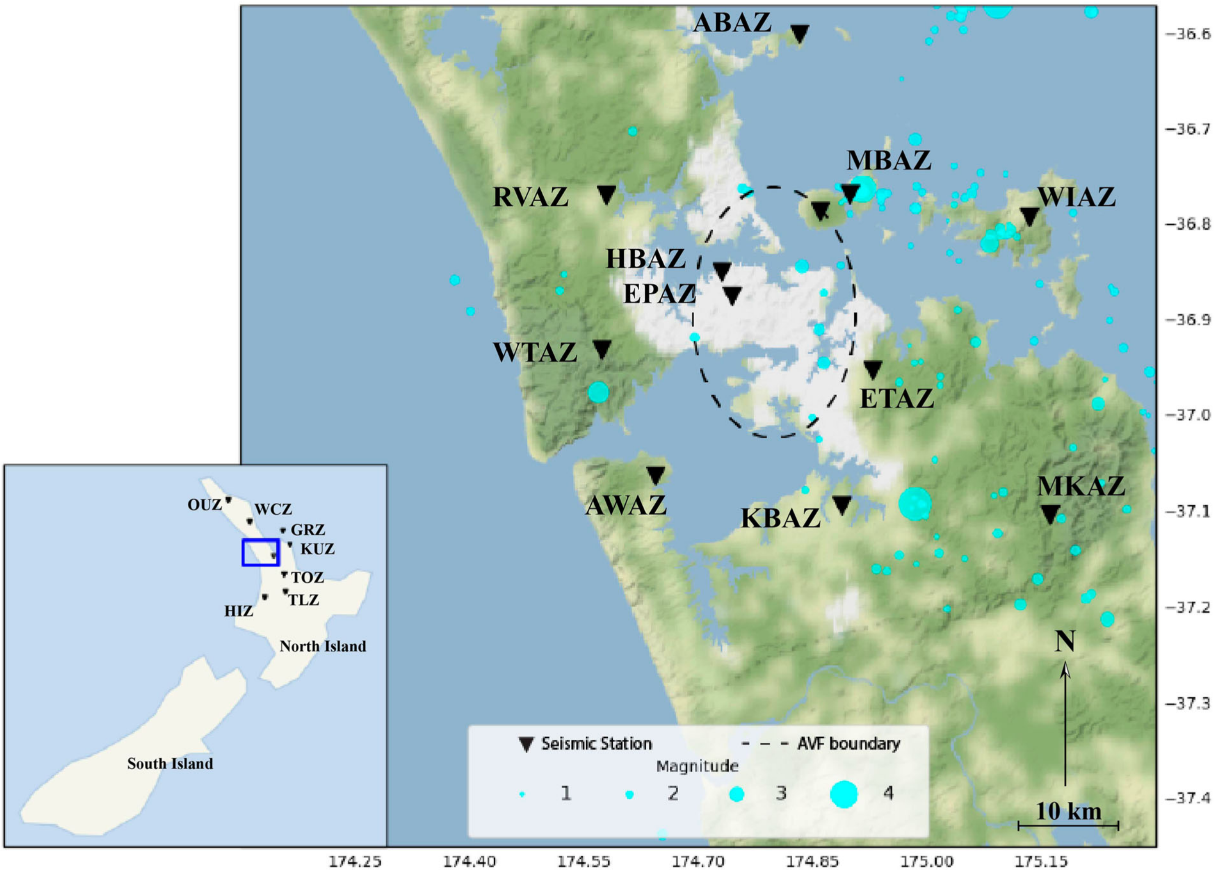

Figure 10. Map of the Auckland region with the epicentres of all 118 catalogued earthquakes in cyan circles (from Geonet catalogue (https://www.geonet.org.nz/data) in the last 30 years). Magnitude of earthquakes corresponds with circle size shown in the key. Black triangles indicate seismic stations with their station codes detailed, for example MKAZ – Moumoukai (Figure 8). The light shaded area shows the extent of the urban Auckland area. The AVF boundary (see also Figure 1E) is marked by the dashed ellipse.

shallow targets (e.g. Shapiro et al. 2005; Brenguier et al. 2007; Lin et al. 2007; Li et al. 2009). Preliminary results from the correlation of ambient ocean noise confirm the AVF crust is not only strongly heterogeneous, but they also provide a first insight in a subsurface projection of the contact between oceanic and continental lithosphere that underlies the AVF (Ensing et al. 2017). These deep crustal heterogeneities and structures (such as the ultramafic DMOB, Figure 9) seem to provide a conduit for magma to the surface, while shallow faults offer some control on the final vent locations of individual centres (Spörli and Eastwood 1997; Magill et al. 2005; Le Corvec, Spörli, et al. 2013).

Shallow tectonic influences on volcanism

The cause and nature of shallow structural control on the AVF eruptions has been difficult to determine (Spörli and Eastwood 1997; Le Corvec, Bebbington, et al. 2013). The elliptical pattern of volcanic vents within the AVF form on a N-S oriented long axis (Figure 1E; Spörli and Eastwood 1997), it is interpreted to describe the mantle source geometry at depth, and the influence of the DMOB's bounding faults to the east and west (Spörli and Eastwood 1997; Kenny et al. 2012; Le Corvec, Spörli, et al. 2013). However, studies have shown that individual vent locations within the field are predominantly influenced by the location of shallow fractures or faults (Le Corvec, Spörli, et al. 2013) or variations in the stress fields toward the surface. For example, Magill et al. (2005) speculated that there are groups and alignments of vents in largely NW-SE and SW-NE orientations, reflecting dominant fractures and faulting within the basement structure. However, fault identification within the Auckland region is challenging due to the sedimentary, volcanic and urban cover and the low rates of tectonic deformation and associated seismicity far-field to the plate boundary, as discussed above (e.g. Figure 10; Stirling et al. 2012). In order to resolve this challenge, Kenny et al. (2012) utilised exposed geology, topography and the Auckland regional borehole database (Howe et al. 2011; now expanded into the New Zealand Geotechnical Database [https://www.nzgd.org.nz/]) to identify offsets in the Waitemata Group surface. They inferred 64 obscured fractures or faults that cannot be geologically mapped at the surface. Many of these faults have NNW-SSE, WSW-ENE or N-S orientations as seen in Figure 1D. Kenny et al. (2012) reveal that most AVF volcanic centres are located within 500 m of these newly inferred fractures or faults, supporting the theory that ascending magma

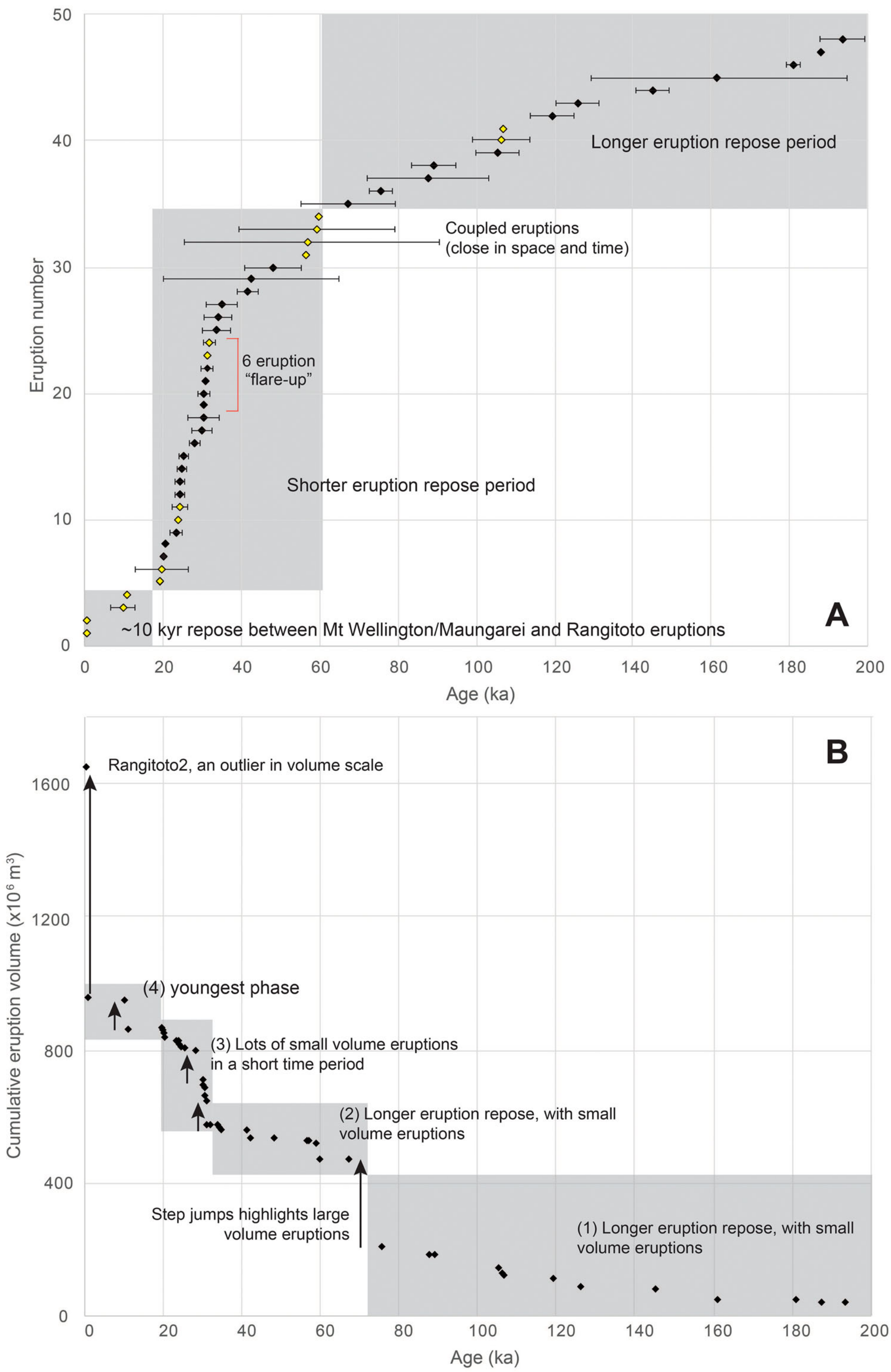

Figure 11. A, Relationship between age (including 2sd error bars), grey shading delineates different temporal eruption periods (discussed in the text). All data is reported in Table 1, proposed coupled eruptions are coloured in yellow, and flare up is highlighted by red bars, see text for discussion. **B,** Relationship between age (excluding error for clarity) and cumulative volume (minimum volumes, in dense rock equivalence (DRE) from Kereszturi et al. 2013). As with panel **A**, grey shading shows periods of variable volume vs. time relationships, black arrows show large volume increases, showing a stepped sequence with smaller-volume eruptions punctuated by a few large-volume eruptions. This cumulative age pattern can be split into four phases: (1) the oldest phase between 200 and 270 ka where a slow progression of small-volume eruptions built up a cumulative volume of 220×10^6 m^3 over 130 ka (1.7×10^6 m^3/kyr), (2) an older middle phase between 70–~30 ka, including the large-volume eruption of One Tree Hill/Maungakiekie, giving a total cumulative eruptive volume of 363×10^6 m^3 over 40 ka (9×10^6 m^3/kyr), (3) a younger middle phase from ~30–20 ka, which began with a large-volume eruption at Three Kings/Te Tātua-a-Riukiuta, and includes multiple small volume eruptions within a short time frame (the 'flare-up') during which 275×10^6 m^3 of material erupted over 10 ka (27.5×106 m^3/kyr), and (4) the youngest phase during which the volume increases to 795×10^6 m^3 over 20 ka (40×10^6 m^3/kyr), and includes the eruption of Rangitoto. Figures adapted from Leonard et al. 2017.

exploits shallow level weaknesses in the crust. At present, however, any direct geophysical expression of the magmatic plumbing, and how for example dyke propagation may utilise the pre-existing structural pathways, has yet to be resolved.

Magnitude and frequency of AVF eruptions

Temporal eruptive patterns

Over the last decade, researchers have made significant advances in determining the numerical ages of the centres in the AVF (Supplementary Material (SM) Table 1). For a full review of the dating methods, see Lindsay and Leonard (2009) and Lindsay et al. (2011), and for critical advances in some of the dating techniques since these publications, see SM 1. In Table 1 we present the currently recognised ages of each of the 53 volcanic centres in the AVF. We highlight our preferred age based on reconciliation of all data published to date, and include a reliability grouping, following the approach originally proposed by Lindsay et al. (2011), but modified slightly to include recent advances in dating techniques (refer to discussions in SM 1 and SM Table 1 and SM Table 2 for full details). Combining the results from all past studies brings the total number of dated centres in the AVF up from 12 (Lindsay et al. 2011) to 47 (Figure 11; Hopkins et al. 2017; Leonard et al. 2017) out of 53, with only six centres with no direct ages (Hopkins et al. 2017; Hayward and Hopkins 2019). With eruption ages for most volcanic centres, we have constructed one of the most complete chronologies for a volcanic field in the world, and from this, the spatial and temporal evolution of the field can be assessed.

The oldest recognised centre in the field is Pupuke/Pupuke Moana at 193.2 ± 2.8 ka ($^{40}Ar/^{39}Ar$ analysis; Leonard et al. 2017), and the youngest is Rangitoto (2) at 504 ± 5 yrs. BP (^{14}C analysis; Needham et al. 2011). Hopkins et al. (2017) and Leonard et al. (2017) highlighted a number of key findings by combining their results with previous research (Figure 11A), including: (1) a flare-up in activity ca. 28–35 ka; (2) a ≤ 10 kyr hiatus between the youngest and penultimate eruptions; (3) evidence for grouping or coupling of eruptions; (4) multiple eruptions occurring during paleomagnetic excursions; (5) preference for eruptions to occur on pre-existing faults (Figure 1D); (6) repose periods that vary between $\leq$0.1 and 13 kyrs, with 23 of the 47 centres (~49%) showing repose periods of <1000 yrs.; and (7) an overall increase in the rate of volcanism since ca. 60 ka.

Eruption styles and magnitudes

Eruptive styles in the AVF reflect both magmatic (composition, volume, and flux of the ascending melt) and environmental variables (the presence/quantity or absence of water and the type of country rock and geologic structures the magma encounters along the ascent pathway) (Németh et al. 2012; Kereszturi, Németh, et al. 2014). In volcanic fields, where the magma volume can vary and vent location is generally not static, the relative importance of these factors can be highly changeable between eruptions. Therefore, constraining the ranges of the variables involved in past eruptions, through detailed field studies, allows us to more robustly forecast future eruption characteristics (e.g. Kereszturi, Németh, et al. 2014; Hayes et al. 2017; Kereszturi et al. 2017; Ang 2019). See SM Table 3 for a detailed overview of likely AVF eruption hazards, summary of characteristics, and considerations and requirements for hazard and risk assessments.

Past studies have shown environmental influences on the style of AVF eruptions are possibly more significant than magmatic influences (e.g. Allen and Smith 1994; Kereszturi, Németh, et al. 2014). In particular, Kereszturi, Németh, et al. (2014) highlight the prominence of phreatomagmatic phases in the AVF, and suggest this is due to the presence of underlying water-saturated sediments and a shallow groundwater table in the Auckland region, especially in the south of the field. They note that while unpredictable internal forces (e.g. magma supply) influence eruption style and transitions, the geographical mapping of external influences (e.g. groundwater distribution) can inform susceptibility maps in advance of eruptions, aiding hazard assessments (Kereszturi et al. 2017).

In the AVF, approximately 83% of eruptions are known to have begun with a 'wet' phreatomagmatic vent-opening phase (e.g. Allen and Smith 1994; Kereszturi, Németh, et al. 2014), where the ascending magma interacted explosively with ground- and/or surface-water. This is then sometimes followed by a 'dry' magmatic explosive or effusive phase once magma-water interaction has stopped either through exhaustion or exclusion of available water source(s). The phreatomagmatic phases of an AVF eruption generate low eruption columns (Kereszturi, Németh, et al. 2014) and are associated with base surges (e.g. Brand et al. 2014), and the creation of maar craters and tuff rings (e.g. Németh et al. 2012), and relatively widespread tephra dispersal (e.g. Hopkins et al. 2015, 2017) (Figure 1B, SM Table 3). The magmatic phases range from Hawaiian (lava fountaining) to Strombolian (explosive) styles, and generally form scoria cones, scoriaceous tephra fall and lava flows (e.g. Németh et al. 2012) (Figure 1B, SM Table 3). There is minimal evidence in the AVF for '*sensu stricto*' Surtseyan style eruptions (e.g. Agustín-Flores et al. 2015a; Cronin et al. 2018), where the initial stages of the eruption occurred in shallow standing water, suggesting that external water was abundant at least during the onset of the eruptions (Kokelaar 1983). Nevertheless, with ~35% of the field area in Auckland currently covered by ≤30 m of water, combined with future sea-level rise, the Surtseyan style of volcanism could potentially become increasingly prevalent in Auckland (Agustín-Flores et al. 2015a).

Estimates for the volume of individual eruptions reported by Allen and Smith (1994) and Kermode (1992) were updated by Kereszturi et al. (2013) using volcano geology-based geometrical considerations, pre-existing size data and a LiDAR survey-based Digital Surface Model, taking into account all types of erupted material (excluding distal tephra deposits). A minimum volume of magmatic material for the field of 1.7 km^3 is reported in Dense Rock Equivalent (DRE), composed of ~78% lava flows, ~6% of scoria cones, ~6% of crater lava infill, ~5% in tephra/tuff rings, and ~4% phreatomagmatic crater lava infills (Kereszturi et al. 2013). The smallest centre has a calculated volume of 0.000076 km^3 (Ash Hill); the largest centre (Rangitoto) is nearly four orders of magnitude larger at 0.70 km^3, and comprises ~41% of the field's total volume. When the volume estimates are plotted against the new temporal reconstruction, a stepped sequence is seen (Figure 11B), highlighting that most eruptions are small-volume, punctuated by a few large-volume eruptions. Although our understanding of the chronology of the AVF eruptions is remarkably detailed, there are no clear patterns in the spatio-temporal eruptive behaviour (Figure 1C). As a result, we remain unable to forecast the timing, volume, or location of a future eruption. We do however understand many fundamental details about the characteristics of the eruptions, and what potentially influences the sizes and styles of the eruption. This information informs scenario modelling (discussed below) and provides critical constraints to complex modelling parameters.

Volcanic hazards in the AVF

History of scenario-based planning in the AVF

Due to the city of Auckland's large population, economic value, and its identity as a key node for critical infrastructure, robust assessment and management of volcanic risk has been a major focus for New Zealand scientists and government (Lloyd's City Risk Index 2019). A challenge has been translating the complex and evolving volcanic science into useful and useable formats for disaster risk management planning. One important tool has been the development and application of 'scenarios' (research-informed, postulated sequences of events during a future eruption), which can be used to summarise multidisciplinary volcanology science in a usable format to inform risk management. Eruption scenarios have been used extensively to manage and plan for a future AVF eruption. In 1997, five eruption scenarios were produced for the Auckland Regional Council (ARC; now Auckland Council [AC]) to assist with contingency planning (Johnston et al. 1997). These scenarios featured both phreatomagmatic and magmatic eruption styles and were used to demonstrate the variety of impacts that could occur to the built environment. They were primarily qualitative, with extensive scenario narratives and accompanying maps of hazardous phenomena, but gave limited consideration to varying unrest sequences that could occur (all scenarios included a generic 25-day precursory seismic sequence). However, subsequent research has shown there is considerable uncertainty associated with seismic unrest sequences in the AVF (Blake et al. 2006; Sherburn et al. 2007; Brenna et al. 2018).

In 2008, an 'all-of-nation' emergency management exercise was held using a hypothetical AVF eruption scenario termed 'Exercise Rūaumoko' (MCDEM 2008; Lindsay et al. 2010; Deligne, Fitzgerald, et al. 2017). It simulated an eruption lead-up, and tested the protocols and response of the Auckland Volcano Science Advisory Group (AVSAG; MCDEM 2008; Doyle et al. 2011). The results from this scenario testing coupled with further studies showed: (1) the need for increased scope for disaster response and recovery planning (Brunsdon and Park 2009); (2) a demonstration of how Bayesian Event Tree modelling could be utilised for real-time eruption forecasting during a future AVF eruption (Lindsay et al. 2010), and (3) an economic model, which found that the direct economic costs of business inoperability would cost between NZ $1–$10B, with indirect effects potentially much greater (McDonald et al. 2017). Exercise Rūaumoko scenario has subsequently been further developed into an educational and outreach tool used for training and eruption scenario simulation (Dohaney et al. 2015; Fitzgerald et al. 2016). Knowledge developed through Exercise Rūaumoko, the long-term transdisciplinary Determining Volcanic Risk in Auckland (DEVORA) research programme, and other studies on the AVF have allowed for more complex eruption scenarios and decision-making tools to be developed that are better aligned with contemporary emergency management needs.

The DEVORA Scenarios

As part of the DEVORA research programme a new suite of eight scenarios (the 'DEVORA Scenarios'; Figure 1E) were developed (Hayes et al. 2018, 2020) (Table 2). They include complex spatio-temporal eruption sequences using scenario narratives and quantitative geospatial hazard layers (Figure 1E). To ensure the scenarios were both credible and useful, a wide variety of stakeholders (physical volcanologists, geophysicists, geochemists, disaster risk researchers, policy advisors,

Table 2. The DEVORA Scenarios, their key characteristics, and the purpose for their development.

Scenario	Purpose	Eruption Style	Lead time (Days)	Duration (days)	Bulk Volume (km^3)
A – Auckland Airport	A short-lived eruption directly affecting Auckland Airport	Phreatomagmatic	8	4	1.8×10^{-2}
B – Ōtāhuhu	An eruption affecting an important critical infrastructure node that passes through the Auckland isthmus.	Phreatomagmatic – magmatic	13	32	3.4×10^{-2}
C – Mangere Bridge	An eruption that includes a wide variety of eruption phenomena that would affect many urban assets.	Phreatomagmatic – magmatic	28	28	1×10^{-1}
D – Mt. Eden Suburb	A large volume eruption that directly impacts a predominantly residential area with a long-lived eruption sequence.	Magmatic	45	240	1.3×10^{-1}
E – Waitematā Port	An eruption of both phreatomagmatic and Strombolian styles that directly impacts the Waitematā Port.	Phreatomagmatic – magmatic	3	27	1.2×10^{-2}
F – Birkenhead	An eruption that directly affects the Auckland Harbour Bridge.	Phreatomagmatic – magmatic	15	160	1.9×10^{-2}
G – Rangitoto Channel	An eruption that considers implications of a Surtseyan style eruption that affects the main shipping channel.	Surtseyan	10	8	1.4×10^{-2}
H – Rangitoto Island	An eruption that occurs near the location of the most recent eruption within the AVF. Also considers a protracted unrest sequence.	Phreatomagmatic – magmatic	660	109	1.8×10^{-1}

geotechnical engineers, infrastructure managers, and emergency management officials) were engaged and embedded throughout the design and development of the scenario suite (Hayes et al. 2020). The scenarios can be used for diverse disaster risk reduction activities such as table-top exercises, educational/outreach activities, and economic loss modelling (Hayes et al. 2018).

In each of the eight scenarios, eruption volume, duration, lead time, volcanic centre location, and volcanic hazards were varied within a credible range for the AVF, excluding, in its current iteration, another 'Rangitoto shield-building' scenario as this is complex and highly atypical in the field's history (Table 2). The locations of the scenarios were chosen based on four key criteria, these included; being located in the 'tight' elliptical field boundary limits (Runge et al. 2015; Figure 1E); being geographically spread across Auckland; allowing the exploration of different eruption styles and hazards (see SM Table 3); and allowing the exploration of impacts to different exposed assets (Hayes et al. 2018; Figure 1E). Details of the scenario locations and names can be found on Figure 1E, and an overview of the different components attributed to each scenario is detailed in Table 2. Each of the scenarios were allowed to play out to produce hazard footprints of the associated hazards (details in SM Table 3), their duration, and volume (Hayes et al. 2018).

An example of the use of the scenarios can be seen in the Māngere Bridge scenario (Scenario C; Figure 1E), which models an eruption in a shallow estuarine setting, and is placed so the eruption impacts a wide variety of urban assets including critical transport links (road, rail, air), water systems, electricity supplies, industrial, and residential dwellings (Blake et al. 2017; Deligne, Fitzgerald, et al. 2017). This scenario is discussed in detail in Deligne, Fitzgerald, et al. (2017), who use the hazard map produced to model evacuation zone designation and evaluate the consequences of an eruption on the electricity service provisions for Auckland city. A companion publication was also produced to discuss the impacts to transportation (Blake et al. 2017) for this scenario. The eruption spans 10 weeks (two weeks of non-activity, four weeks of unrest, and four weeks of eruptive activity), and is comparable to that of Maungataketake (Deligne, Fitzgerald, et al. 2017). The key outcomes indicate that infrastructure will be severely damaged, but will likely still be able to provide a partial service. Outage duration for a number of key critical infrastructure services are also estimated, with outage duration for electricity >1 year (Deligne, Fitzgerald, et al. 2017); telecommunications <2 weeks (Deligne, Fitzgerald, et al. 2017); roads and rail outages >7 weeks (Blake et al. 2017); and aviation impacted for ~3 months (Blake et al. 2017).

Future hazard and risk research directions

The applications of the scenarios for hazard and risk planning have provided insights into the potential complexity associated with managing and recovering from a future AVF eruption. Loss and impact results can be heavily influenced by assumptions relating to a selected scenario's characteristics. Thus, characterisation of the uncertainty associated with the impacts of AVF eruptions through probabilistic methodologies is the necessary next step. This has begun with research to derive probabilities for the DEVORA eruption scenarios at every location in the AVF, which are dependent on local environmental conditions. The inclusion of hazard footprints for end users, investigations into evacuation planning strategies in the context of variable locations, the detection of eruption warning signals, development of tools to support rapid crisis decision-making, and examinations into the effects of an eruption on the many aspects of New Zealand life and environment (e.g. social, financial, political, cultural), amongst numerous other considerations, are also essential and comprise future plans to inform effective AVF risk management. An AVF unrest and eruption will be a major event requiring considerable resources to manage, so it is necessary to consider strategic planning issues in advance, including risk governance, to avoid doing this under duress during the actual crisis.

Finally, we stress the overriding importance of maintaining and extending (a) effective science coordination to ensure fit-for-purpose knowledge, capacity and capability is available and continues to advance; and (b) strong science-practitioner-policy relationships and structures (both formal and informal) that ensure science effectively interfaces with disaster risk management structures to continuously improve the ability to inform effective AVF risk management (Daly and Johnston 2015; Fearnley and Beaven 2018).

Conclusions

In the 60 years since in-depth geological research on the AVF began, the field has become one of the most well-studied in the world. High-resolution mapping and reliable, comprehensive age and geochemical data has allowed us to examine spatio-temporal, geochemical, and volume patterns over the field's lifetime. Detailed field studies have revealed a strong environmental control (e.g. presence of groundwater) on the hazards produced. Geophysical investigations thus far, though hampered by the lack of seismicity in the Auckland region, have shown a low-velocity melt zone at ~70–90 km depth under Auckland, potentially indicating the depth of initial melting.

Improving our understanding of the source to surface processes that govern the formation and evolution of the AVF has been critical, however, the way in which these results are fed into hazard, risk and social studies is also a vitally important aspect of on-going research. This holistic approach is highly unique and has resulted in, among many other research products, eruption scenarios detailing the ranges of hazard styles and scales in various locations around the city. These valuable tools have provided a strategy to estimate damage and impacts from future eruptions.

Overall, we have a unique and detailed knowledge of the AVF, however, many unknowns still exist and remain to be investigated, including the processes causing melting under Auckland, the relationship of the older volcanic fields within the North Island to the AVF, the drivers for increases in eruption volumes and eruption rates over the field's lifetime, and why the last eruption was volumetrically much larger than other eruptions in the field's history. Additional questions remain about magma ascent through the crust and its impact on warning times, as well as the composition and structure of the mantle and crust and how it controls ascending magma. Finally, we highlight the need to improve our knowledge of the potential volcanic hazards (particularly tephra fall, volcanic earthquakes, land deformation, shockwaves, volcanic tsunami, ballistic projectiles and fire) associated with a future Auckland eruption to improve eruption scenarios, risk assessments, and disaster risk reduction efforts. With continued and sustained efforts to address these gaps in our knowledge, a quantitative risk assessment for Auckland is likely to become a reality in the coming years.

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