Volcanic hazard from the Auckland Volcanic Field

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ABSTRACT

The Auckland Volcanic Field, which last erupted ~600 years ago, is a late Quaternary monogenetic basaltic volcanic field of approximately 500 km^2. A recent study (Leonard et al., 2017) has improved the accuracy of eruption dates for 23 of the eruptive centres. Previously only 12 of the 53 had been reliably dated. This new data illustrates a complex episodic eruption history with large variations in the eruption volumes and changes in the rate of eruptions over time. Such non-uniformity shows that averaging the number of eruptions over the lifespan of the field to give a mean eruption rate is overly simplistic. In particular, the rate of volcanism in the Auckland Volcanic Field has increased since 60 ka, suggesting that the field is still in its infancy.

This paper summarises the findings of this research and considers the implications for the future development of Auckland.

1 INTRODUCTION

Auckland is the largest city in New Zealand. Recent strong population growth is expected to continue, and according to the 2006 Census projections the population will reach 1.93 million by 2031, a 25% increase over current numbers (Statistics New Zealand, 2012).

As a result of its location and geological setting Auckland is exposed to a number of natural hazards including volcanic eruption. As the population grows the exposure to these natural hazards will increase. A priority within the Auckland Plan is to 'build resilience to natural hazards'. Understanding the likelihood of future eruptions is critical to accurately assessing these risks and building resilience.

1.1 The Auckland Volcanic Field

Auckland lies on an active basaltic volcanic field that contains at least 50 volcanoes (the exact number depends on the definition of 'volcano'). It sits on continental crust approximately 400 km west of the Hikurangi trench, where the Pacific Plate is being actively subducted below the Australian Plate, and approximately 200 km west of the active volcanic arc.

Approximately 3 km^3 of material has been erupted periodically over the last 200,000 years, covering a total area of approximately 100 km^2. Most of the erupted material is olivine basalt, although there are significant deposits of associated material including scoria cones, ash and lapilli mantles, and tuff-ring deposits.

The Auckland Volcanic Field volcanoes are normally considered to be monogenetic (each volcano usually only erupts once with further eruptions occurring at a new location). There is debate about whether the volcanoes are truly monogenetic because of evidence for multiple events of contrasting chemistry from essentially the same centre (particularly Rangitoto: Needham et al., 2011; Linnell et al., 2016). The field as a whole is not monogenetic as it comprises many volcanic centres.

To the south of the AVF are older basalt volcanic fields; in turn, the South Auckland Volcanic Field, active from 1.6 to 0.5 Ma (Briggs et al., 1994) and the Ngatutura and Alexandra fields, active from ca. 2.7-1.5 Ma (Briggs et al., 1989). The South Auckland Volcanic Field may represent a precursor field to the AVF, but there is a distinct 300 ka hiatus in eruption ages, and a > 10 km gap between the closest vents, implying that they represent separate volcanic fields (Le Corvec et al., 2013).

Based on a comparison of centre numbers, eruptive volume estimates, geochemical evolution, and age ranges between the AVF and the South Auckland Volcanic Field, Allen and Smith (1994) proposed that the AVF is likely still in its infancy.

2 AGE OF THE AUCKLAND VOLCANIC FIELD

Previous estimates of the earliest volcanic eruption in the Auckland Volcanic Field have been up to 250,000 years ago; the most recent volcanic eruption, which was witnessed by Māori living on Motutapu Island, occurred approximately 600 years ago and produced Rangitoto.

2.1 Challenges in dating the Auckland Volcanic Field

The AVF is typical of basaltic volcanic fields, with spatially scattered vents erupting infrequently and relatively small volumes of magma in single eruptions (Connor and Conway, 2000). Unlike in polygenetic volcanoes, the wide dispersal of vents within volcanic fields means that often there are limited overlapping field relationships amongst deposits on which to base chronostratigraphic frameworks (Leonard et al, 2017).

For basaltic fields like the AVF where stratigraphic successions are ambiguous and thus relative sequencing of eruptive histories are difficult, the ability to directly date young basalts by radiometric methods is essential. Accurate dating allows a chronostratigraphic framework to be developed, which underpins all aspects of hazard and frequency forecasting.

Young basaltic rocks are difficult to directly date radiometrically. Their lack of zircon precludes U-series or U-Pb dating, and their low radiogenic argon have often precluded reliable K-Ar or ^{40}Ar/^{39}Ar dating. Historically, many studies have used conventional K-Ar dating, but these ages can be inaccurate due to excess argon issues (e.g. McDougall et al., 1969). Improvements in ^{40}Ar/^{39}Ar analytical techniques, coupled with ultrasensitive rare-gas mass spectrometers, have surplanted the K-Ar method (e.g. Fleck et al., 2014).

Lindsay et al. (2011) reviewed previous age data for the AVF and assessed these for reliability and consistency, rating only eleven centres as reasonably reliably and accurately dated. The youngest centres are constrained by ^{14}C dating, but many of the older ages were at the limits of the technique when analysed, and are now considered anomalous.

2.2 New results for the Auckland Volcanic Field

A recent study (Leonard et al., 2017) has improved the accuracy of eruption dates for 23 of the eruptive centres. Fifteen of the 23 new analyses are younger than 60 ka, but the remaining eight older analyses are particularly important because most of these eruptive centres had no previous age control. In total nine of the 23 new centres analysed had no previous ages associated with them. The full age data is presented in Leonard et al., 2017, and summarised in Figure 1.

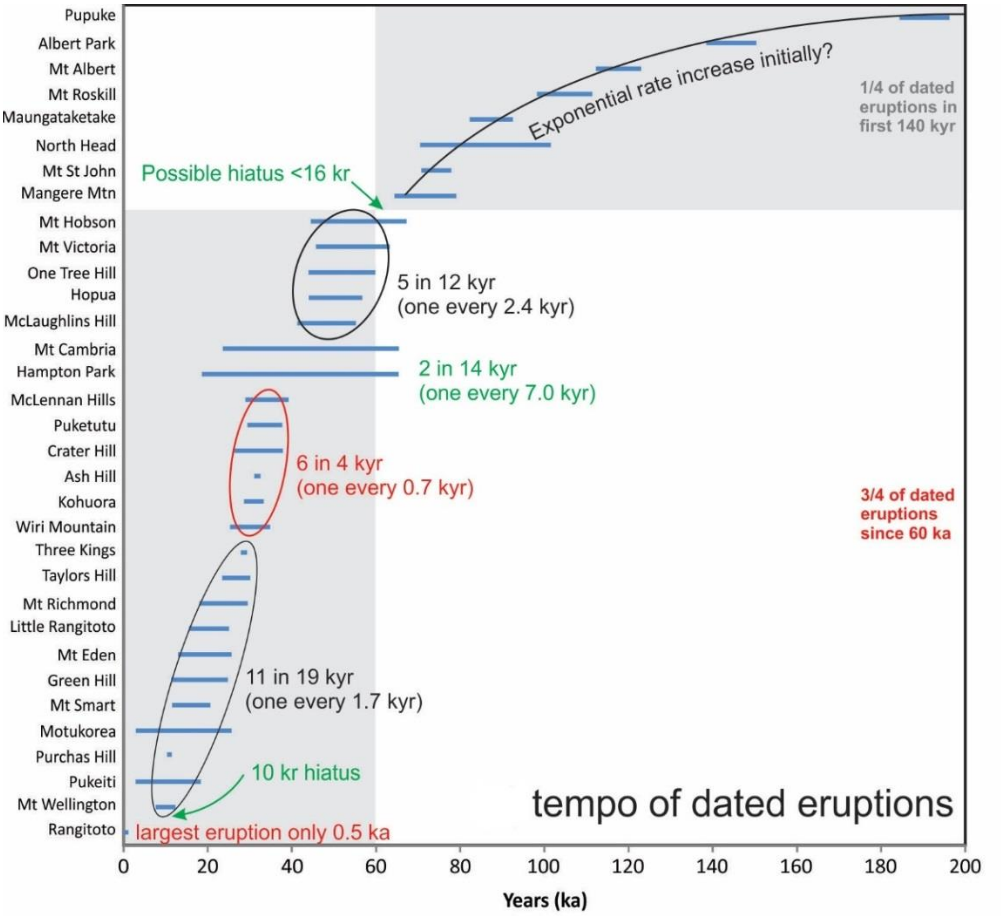

Figure 1: AVF volcanoes ordered in eruptive sequence by their ages, showing only volcanoes with radiometric dates, with annotation describing the complex tempo of post 60 ka eruptions (after Leonard, 2017)

3 IMPLICATIONS OF AGE DATA FOR BEHAVIOUR OF THE AVF

3.1 Frequency of eruptions

The gaps between eruptions (repose periods) have ranged from approximately 50 to 10,000 years. A simplistic approach of averaging the 53 volcanoes across the 193 ka history gives an average rate of one eruption every 3,600 years. Overall increases in eruptive frequency and volume over time have previously been proposed by Allen and Smith (1994) and Kerszturi et al. (2013), respectively. The new data (Leonard et al, 2017) show that at least 26 AVF centres have erupted since 60 ka, supporting the previous assumptions that there is a hinge point in AVF behaviour around that time. Different eruption frequency distributions can be suggested for the overall AVF depending on the ages adopted for the 20 volcanoes that remain undated. Two end-member approaches are presented in Figure 2, illustrating the range of possible eruption rates:

1. Approach 1: Assume a minimum eruption rate since 60 ka. In this approach all volcanoes with a documented maximum age from stratigraphy or geomorphology (see Lindsay et al., 2011) are assigned that age. Undated volcanoes are placed in the period prior to 60 ka. This yields an eruption rate of one per 2.6 kyr for the last 60 ka.

2. Approach 2: Assume a maximum eruption rate since 60 ka. In this approach all volcanoes with a documented minimum age from stratigraphy or geomorphology (Lindsay et al., 2011) are assigned that age. Undated volcanoes are placed within the last 60 ka. This yields an eruption rate of one per 1.5 kyr for the last 60 ka.

The real post-60 ka eruption tempo lies somewhere between these two end members (one per 2.6 - 1.5 kyr) but, regardless, has increased markedly compared to the rate prior to 60 ka (one per 13-5.2 kyr). Whether the increase in rate has been a gradual change or a sharp shift requires the remaining 20 undated volcanoes to be dated, coupled with more precise ages and absolute sequencing for those already dated.

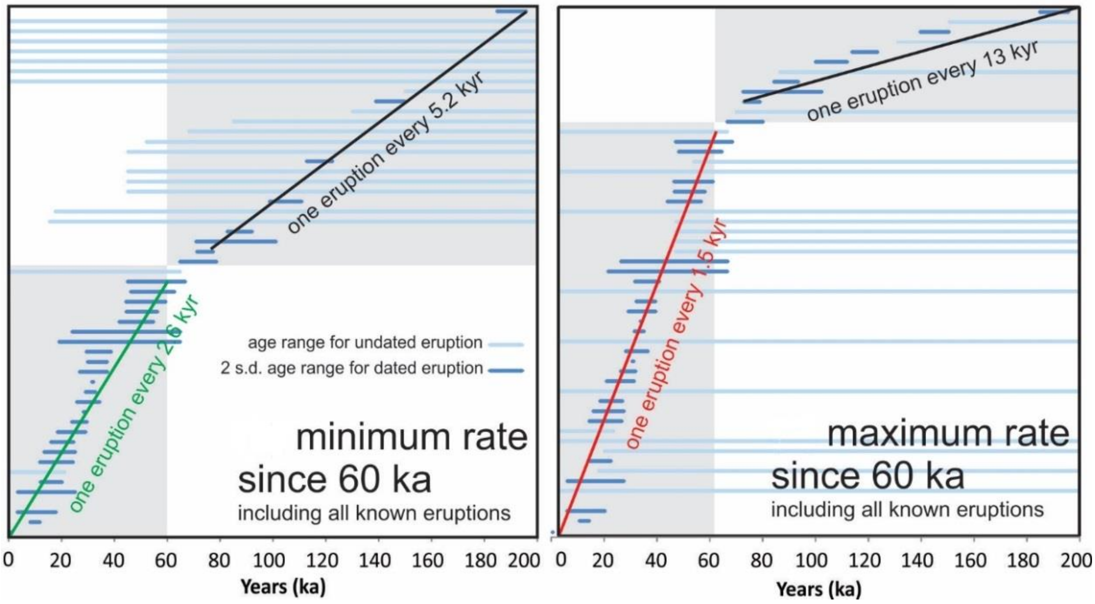

Figure 2: Volcanoes ordered in eruptive sequence by age, showing those with radiometric dates in bold (after Leonard, 2017). Radiometric ages depicted as 2SD error bars. LEFT: Approach 1 (minimum recent rate). RIGHT: Approach 2 (maximum recent rate).

3.2 Location of eruptions

The oldest five eruptions from the AVF show a spatial progression from north to south (Fig. 3) from 193 to 105 ka. After this period, the progression of ages appears to be random, but this may also reflect the fact that the age errors for the volcanoes overlap more in the younger $^{40}Ar/^{39}Ar$ data.

3.3 Volume and style of eruptions

The total Dense Rock Equivalent (DRE) volume for dated volcanoes is 1.5 km^3 (Kereszturi et al., 2013). This represents 96% of the total volume erupted in the AVF, so volume can be reckoned well from these dated centres. When plotted against dates there is no clear trend in eruption volume over time, but the five largest dated eruptions have occurred since 60 ka and the two largest eruptions (One Tree Hill, Rangitoto 2) have occurred following two long repose periods, as also noted by Kereszturi et al. (2013). However, another identified long repose period was followed by a relatively small volume eruption (Mt Hobson).

Most of the dated predominantly phreatomagmatic eruptions (producing little or no scoria cone or lava flow volume) have occurred post 60 ka. Only two eruptions so far have had volumes between 0.1 and 1 km^3 so forecasts of the largest size are limited by the number of events of this magnitude to extrapolate from. The magnitude-frequency relationship for the Auckland eruption sequence (Figure 4) shows variation over five orders of magnitude, but with the majority of the 53 eruptions between 0.001 and 0.03 km^3.

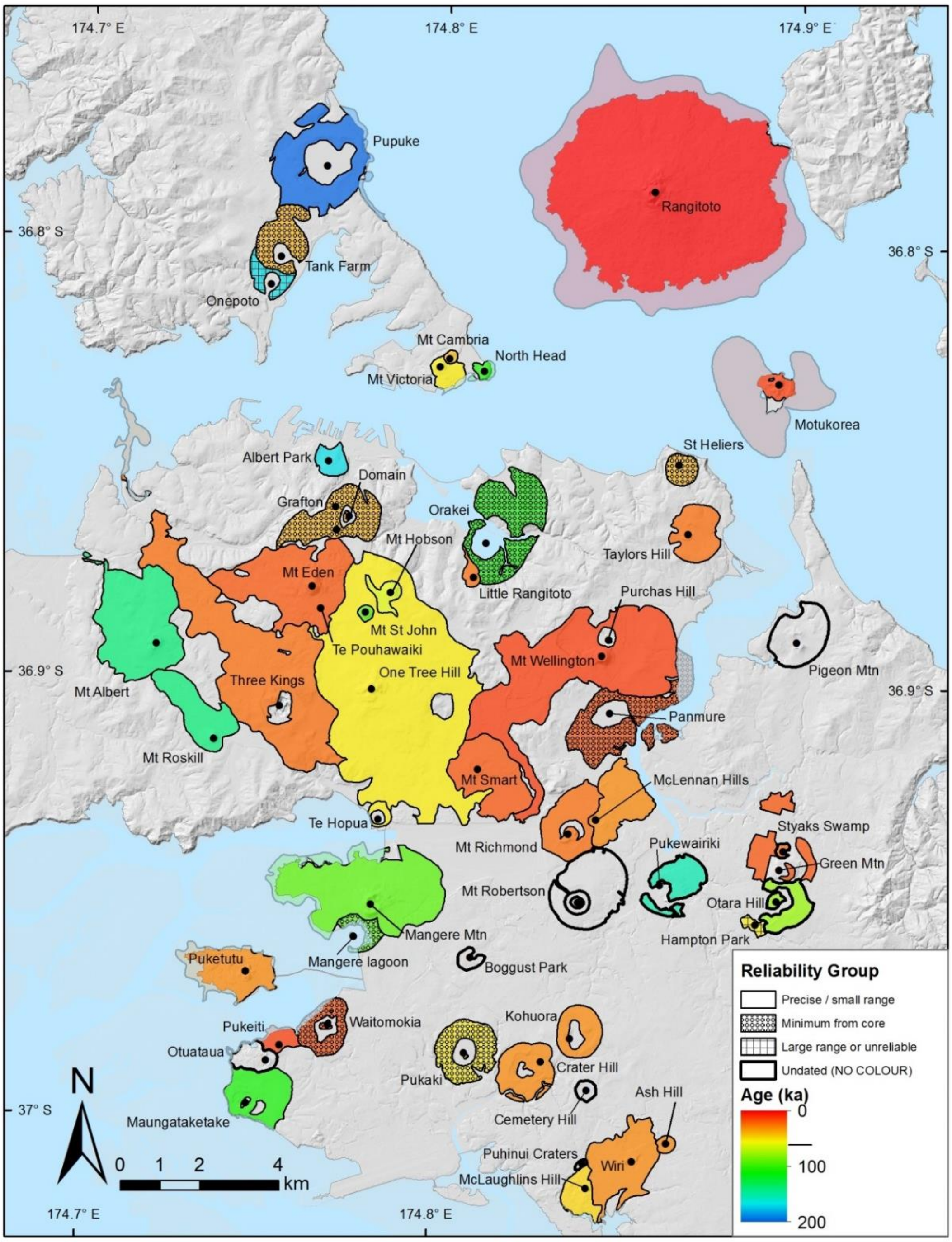

Figure 3: The volcanic deposits of the Auckland Volcanic Field centres, coloured by their interpreted ages. Hatching indicates grouped age reliability (after Leonard et al, 2017).

It should be noted that magmatic volume is not the most relevant hazard metric for phreatic eruptions, where the threat is posed by explosive but primarily non-magmatic fragments. However, it still may be of value in assessing the potential area of damage for loss estimation for scoria and lava.

4 THE RANGITOTO PARADOX

The most recent eruption in the AVF was unusual. It was much larger than any previous eruption (up to nearly four times larger than the next largest: Kereszturi et al., 2013) and it is one of only two eruptions that exhibits a sub-alkaline basaltic geochemical signature, along with Pupuke, the oldest dated volcanic centre (Needham et al., 2011; McGee et al., 2013).

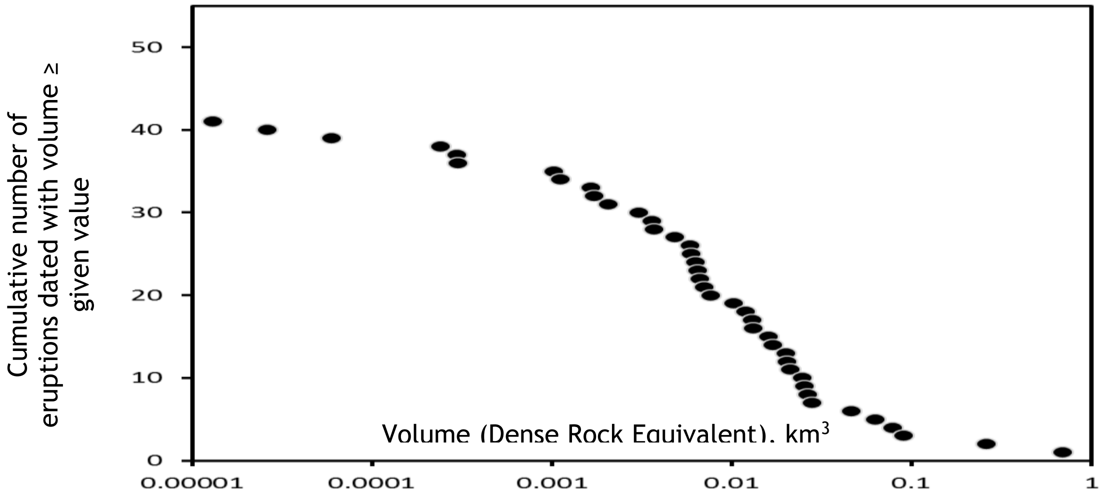

Figure 4: Magnitude-frequency plot for all radiometrically dated eruptions from the AVF (volumes from Kereszturi et al., 2013).

The combined Rangitoto episodes were preceded by one of the two longest repose periods in the AVF since 72 ka (Lindsay et al., 201 1; Needham et al., 2011). However, the other apparently long repose was followed by a relatively small volume eruption (Mt Hobson). There are other eruptives buried within Rangitoto that may be older than 600 years ago (Linnell et al., 2016) – research is ongoing. Spatially, the Rangitoto eruptions do not appear to follow any temporal trends within the wider field, highlighted by their proximity to the oldest centre (Pupuke).

5 REDUCING THE RISK

Although a future eruption in Auckland would be relatively small, its effects would be devastating to the economy of New Zealand (Lindsay, 2010). Hazard avoidance through land use planning is generally not feasible given the population size, and extent of economic and urban development (Becker et al, 2010). Most societal effort to mitigate the risk is put into contingency planning (e.g. evacuation). However, some of the risks can be reduced with careful planning and engineering. Lava flow susceptibility can be assessed (e.g. Kereszturi et al, 2012), and buried services within these zones kept at a depth that would limit damage to them as the flow passes over. Critical infrastructure diverted away from at-risk zones, or be designed to be bypassed or relocated. Buildings can be designed to resist loadings from volcanic ash, and to provide filtered air to reduce the impact of ash on the people inside.

6 CONCLUSIONS

Prior to Leonard et al. (2017), 12 volcanoes in the AVF were well dated. With the addition of 23 new ages this has been increased to 35 out of the 53 known volcanoes. This new data shows that since 60 ka the average rate of eruption has been between one every 1.5 and 2.6 kyr.

The use of a single frequency rate may be misleading for forecasting future events. Repose periods have ranged from ca. 50 to 10,000 years, volumes from ca. 0.001 km^3 to 0.7 km^3, and vent locations are distributed with no clear trend. There are thus no grounds on which the duration of the current repose period or the site of the next eruption can be forecast. The fact that the most recent eruption episode (ca. 600 years ago) was anomalous, i.e. included an eruption nearly four times larger than any previous eruptions in the field, erupted magma of a different chemistry, and occurred after an unusual 10 ka hiatus, highlights the difficulty in forecasting.

Given these difficulties it is not currently realistic to reduce the risk to Auckland by changing the location of proposed development within the city. However, the new range of frequency rates and illustrations of clustering and pauses proposed by Leonard et al (2017) can provide a useful starting point for the assessment of relative risk when compared with other natural hazards. The long-term frequency of Auckland eruptions is probably similar to mega-tsunami, but less regular. However, the location of the next eruption is unknown within the field. This makes it very hard to land-use plan for eruptions, but it is very important to contingency plan for them. This includes considerations for emergency management, and design of infrastructure and urban growth to limit vulnerability and pinch points.

Geotechnical professionals are well placed to advise developers and infrastructure owners on the volcanic hazard in Auckland, and to propose engineering options to reduce the vulnerability of our society. The assessment of the likelihood of eruption presented in this paper can be used as a basis for building a business case to engineer more resilient infrastructure and buildings.

7 ACKNOWLEDGEMENTS

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