The volcanic and magmatic evolution of Tongariro volcano (16/U735)

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Key words

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Summary

This study has produced a comprehensive database of whole-rock geochemical and geochronological analyses on the materials that comprise the edifice of Tongariro volcano. The database has been used to reconstruct Tongariro's volcanic and magmatic evolution over its ~300 kyr lifespan. Results here show changes in both vent locations and their longevity over Tongariro's lifespan: these become more widely dispersed and shorter-lived through time, particularly in the most recent 50 kyr. Patterns of enhanced volcanic activity at Tongariro appear to be coeval with activity at Taupo volcano and probably Ruapehu too. This finding provides evidence that tectonic processes are a primary control on the timing and styles of eruptive activity in the central and southern Taupo Volcanic Zone. Significant activity at any of these volcanoes may forewarn of impending activity at the others.

Introduction

With its eruptions in 2012, Tongariro abruptly reminded New Zealand that it is an active volcano, with the capability of causing significant disruption, damage and loss of life with even small eruptions. My recent fieldwork and that of Townsend et al. (2017) has shown that the pre-existing models for evolution and growth of the volcano are not detailed enough to define its overall history and hazards associated with the modern volcano. This study adopted a multi-disciplinary approach to understand Tongariro's evolution over its entire lifespan. A key goal of this study was to reconstruct the evolution of Tongariro's magma system.

Examination of Tongariro's volcanic and magmatic evolution was pursued by sampling and interpreting deposits from the entire volcano, with a particular emphasis on the parts erupted before the Holocene. These older volcanic units comprise about 95% of the volcano's lifespan and overall volume, yet less than half of these units had previously been sampled and interpreted. Using whole-rock geochemistry and geomorphic mapping, distinct packages of Tongariro's erupted materials were identified and grouped together. Radiometric $^{40}Ar/^{39}Ar$ age dating was then used to organise the deposits into chronological eruption order. Within the context of this eruptive chronology, features of Tongariro's varied magma compositions were examined through time.

Recent findings at Ruapehu (Conway et al., 2015) have required models for volcano growth at Tongariro (Hobden et al., 1996) to be reconsidered. Traditional views have implied that volcanic cones are constructed in periods of growth and then become inactive, at which point they are eroded by glaciers. This process is then repeated. In such a model, valleys in volcanic landscapes are purely erosional features. However, work at Ruapehu have shown that valleys on young stratovolcanoes (i.e., <0.5 Ma) are generally constructional landforms, where valley walls were built around ice (Conway et al., 2015). This result echoes previous work at other glaciated stratovolcanoes, such as Mount Rainier, USA (Lescinsky and Sisson, 1998) and contrasts with the traditional model where valleys are created by eroding pre-existing rock with glaciers. The newer model, which is consistent with new observations in this study, shows that stratovolcanoes such as Tongariro grow in starfish shapes, with the ridges between the valleys growing during glacial periods because they are preferential areas of lava emplacement and preservation. In parallel with this project, work by colleagues at the University of Otago has shown that Tongariro's upper-edifice landforms were constructed by eruptions that occurred in the presence of ice (Cole et al., 2018). An accurate understanding of Tongariro's growth styles has thus been fundamental to volcanic mapping and determining the locations of old vent locations in this study.

Objectives

1. *Collect samples of deposits from the entire volcano, primarily the parts that were erupted before the end of the last ice age. This may require as many as 400 sampling locations.*

Approximately 250 new samples of Tongariro's volcanic products were sampled over the course of this project (Fig. 1). This outcome is comparable to other similar studies, such as Dr Chris Conway's work on Ruapehu (~500 samples; cf. Conway, 2016; Conway et al., 2016). The smaller number of Tongariro samples reflects sampling that focussed on lower-elevation areas with more vegetation and less exposure of rock units than Ruapehu. The sampling density at Tongariro builds on the ~350 samples collected by Hobden (1997), ~80 by Wahyudin (1993) and another ~50 collected by co-investigators at GNS Science (Drs Graham Leonard, Dougal Townsend, Chris Conway and Mark Rattenbury: Fig. 1). The resultant sampling density has been appropriate for the goals of this study and has enabled a high-resolution map to be generated with 37 distinct units recognised over Tongariro's eruptive history. These units consist of 36 eruptive packages that are organised into ten eruptive formations, plus a single major debris flow unit (Te Whaiau Formation; Fig. 2).

2. *Conduct major and trace element whole-rock geochemistry analysis of a prioritised sub-set of samples, using XRF and ICP-MS techniques.*

Most of the ~300 new whole-rock samples obtained for this project were analysed for major elements by X-ray fluorescence (XRF). A sub-set of these (~80) were analysed for trace elements by solution inductively coupled plasma mass spectrometry (ICP-MS). About half of the samples analysed for trace elements were in turn analysed for their Sr-Nd-Pb isotope ratios by thermal ionisation mass spectrometry (TIMS). These data are presented in the context of their associated eruption ages in Fig. 3.

3. *Select and prepare targeted $^{40}Ar/^{39}Ar$ dating samples to establish the time sequence for the volcano's history.*

Approximately thirty ^{40}Ar/^{39}Ar age determinations were produced for Tongariro lavas. These have been instrumental in unravelling the volcano's eruptive history. Samples were prepared from fresh holocrystalline lava samples from which groundmass separates were obtained and analysed. The analyses were performed at the United States Geological Survey with the assistance of Drs Andrew Calvert and Graham Leonard. The age results are presented alongside whole-rock compositions in Fig. 3.

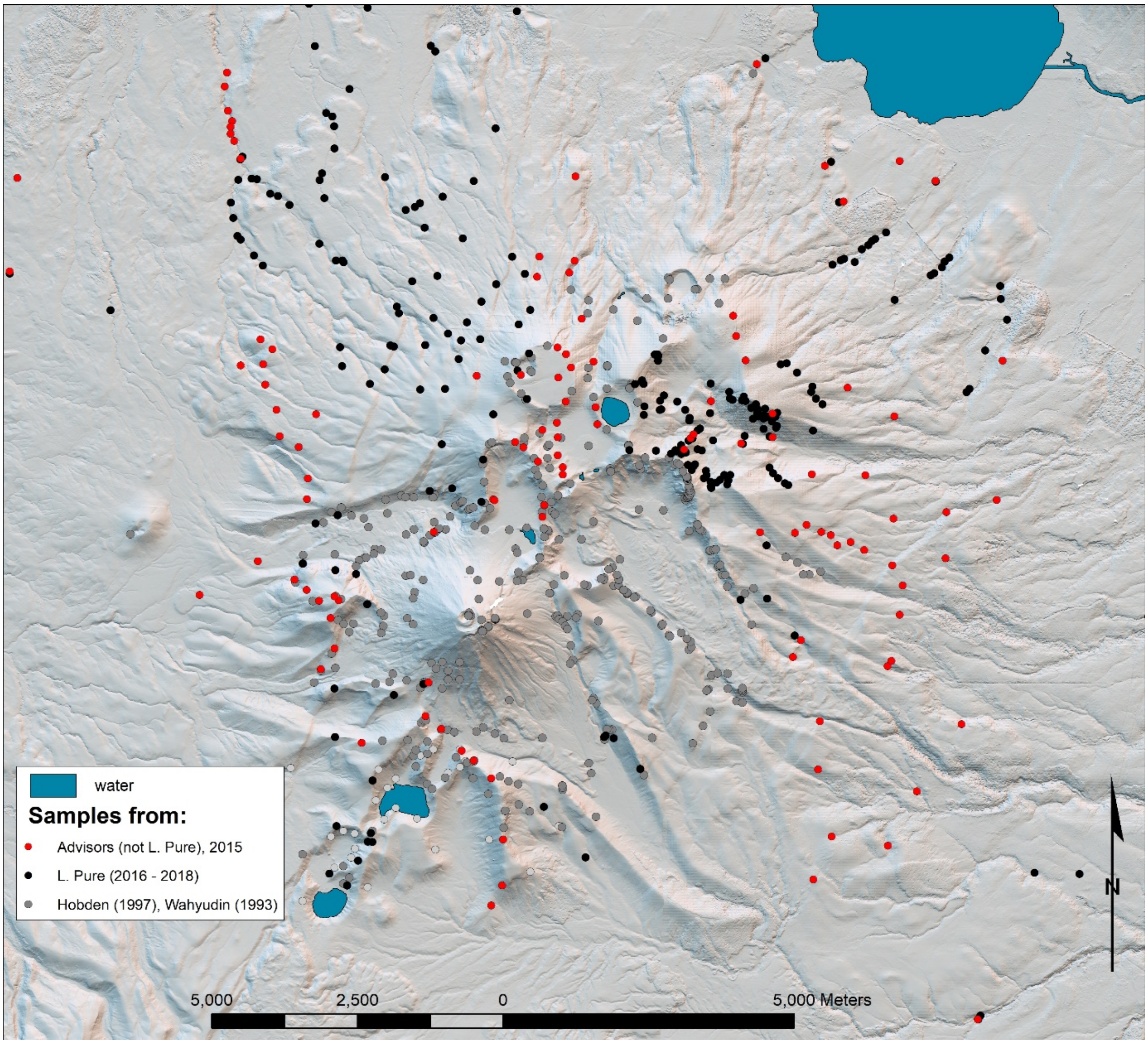

Figure 1. Sample locations for this study and previous work: Leo Pure's samples (2016 – 2018, black); samples from GNS personnel involved with this study (2015, red); samples from Hobden (1997) and Wahyudin (1993) (grey).

4. *Integrate whole-rock chemistry and ages (new and existing) with recently completed geomorphic mapping. Link deposits erupted from the same part of the magma system and a specific point in time.*

Whole-rock compositional data from Hobden (1997), Wahyudin (1993) and Cole (1978) were integrated with new data collected in this study for the purposes of volcano mapping (e.g., Fig. 1). However, for examining the evolution of Tongariro's magma compositions through time, only samples collected in this study with precisely-known ages (from $^{40}Ar/^{39}Ar$ dating) were used.

This was to ensure that geochemical trends are resolved in the greatest possible temporal detail and that geochemical observations accurately represent specific points in time.

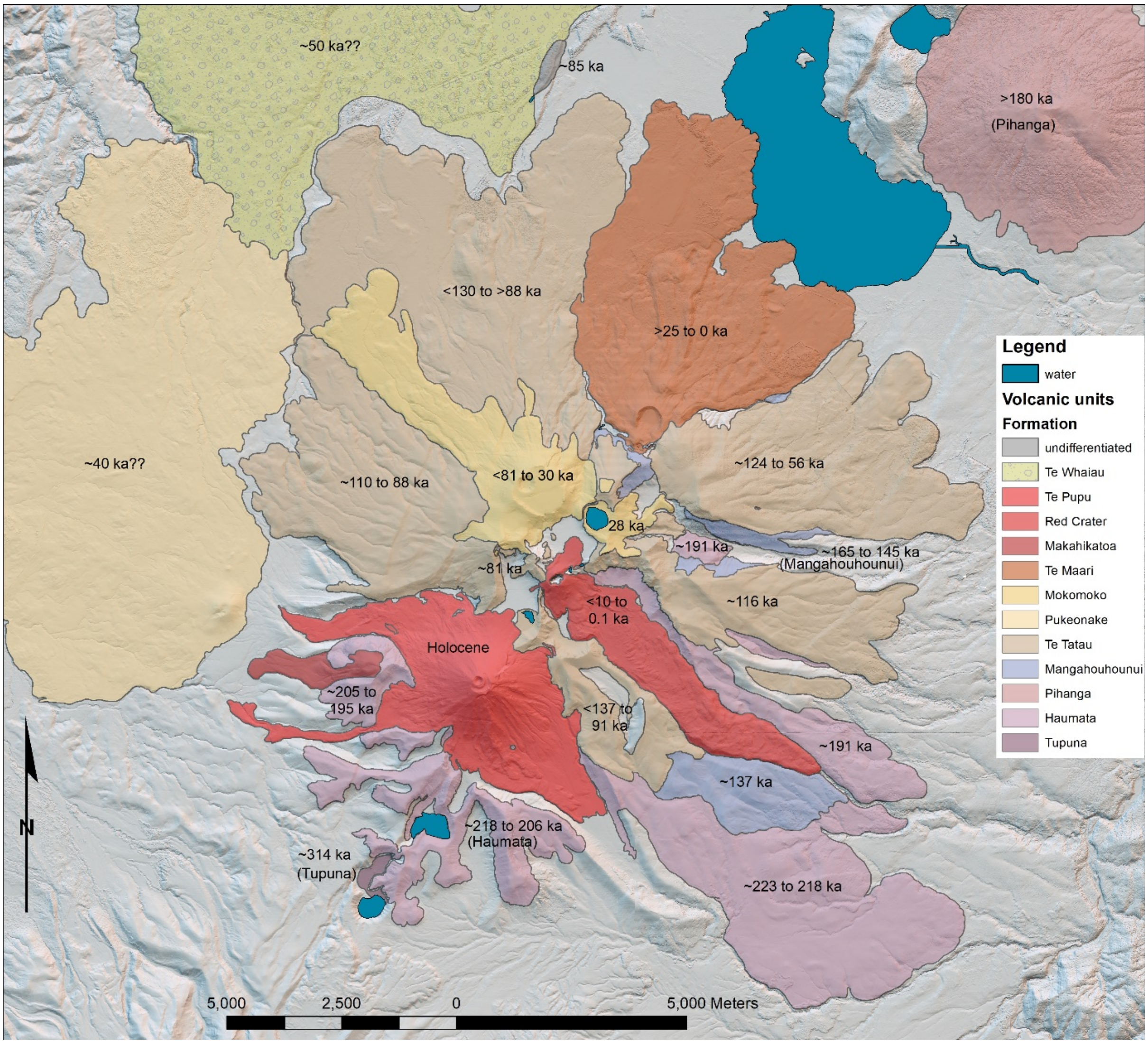

Figure 2. Tongariro (and Pihanga) formations with approximate ages, as indicated by new $^{40}Ar/^{39}Ar$ age data, supplemented by K/Ar ages of Hobden et al. (1996) that were inferred to be accurate.

Time-composition trends of Tongariro's magmas are shown in Fig. 3. The panels A-B show variations in the concentrations of K_2O and Zr with time. Also shown are $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios in panels C-D. In comparison, Panel E shows zircon crystallisation model-ages in eruptives from Taupo volcano, the vent locations for which are ≥50 km to the north of and are physically separated from Tongariro's magmas. Zircon crystallisation ages reflect magma assembly timescales and are shown here to examine whether contemporaneous magmatism occurs at physically separated volcanoes – if so, this would imply an external (e.g., tectonic) influence on the eruptive behaviour of volcanoes separated by tens of kilometres. Such an influence has previously been proposed for part of the recent activity at Tongariro and Taupo (Kohn and Topping, 1978).

Variations observed in Tongariro's erupted magma compositions imply changes in the magmatic plumbing system over the volcano's lifespan. First, incompatible element concentrations (K_2O and Zr) vary in similar fashion (Fig. 3). Up until ~150 ka, compositional variations are uniform and do not show high and low concentrations at the same time. This indicates a degree of uniformity in the magmatic system where the overall degree of crystal fractionation and/or crustal assimilation does not have strong variations over timescales of 5-10 kyr. After ~150 ka, greater short-term variation is observed in K_2O and Zr concentrations, which persists until the present day. During this period, uniform compositional evolution is not observed. This change probably reflects a change in the magma plumbing systems below Tongariro, allowing co-existing magmas to reach the surface and erupt independently, without homogenising and losing their compositional diversities. This interpretation is supported by field observations from this study and elsewhere that report significant rifting and down-faulting of Tongariro's edifice (e.g., Gómez-Vasconcelos et al., 2017). At Tongariro, volcanic vent foci appear to be aligned along major structural features. Two examples of this feature are the alignment of multiple vent foci that were active during the ~10 ka Pahoka-Mangamate tephra sequence (Nairn et al., 1998) and the juxtaposition of a flank vent on surficial fault ruptures, such as the Makahikatoa Formation flank vent on top of Pukekaikiore which straddles the Waihi Fault (Townsend et al., 2017). Hence, both field observations and time-composition trends indicate an increase in eruptions from flank vents at Tongariro in its recent lifespan (50 ka to now).

Second, the isotopic data collected ($^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values) imply that Tongariro's magmas have experienced many alternating periods of increased crustal residence and then elevated inputs of more 'primitive' mantle-derived magma. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values are distinct for meta-greywacke crustal rocks ($^{87}Sr/^{86}Sr$ = 0.706-0.711 and $^{143}Nd/^{144}Nd$ = 0.5123-0.5127; Price et al., 2015) and mantle-derived magmas ($^{87}Sr/^{86}Sr$ = 0.7035-0.7040 and $^{143}Nd/^{144}Nd$ = 0.5129-0.5131; Gamble et al., 1993). Hence, the relative mixing proportions of these materials, when also taken into consideration with the effects of crystals growing in the magmas and being extracted to form underground intrusive bodies, can be used to determine the percentage of mantle versus crustal material in Tongariro's magmas (e.g., DePaolo, 1981).

The data plotted in Fig. 3 show that $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values vary in roughly opposite directions with time. $^{87}Sr/^{86}Sr$ values are generally more scattered than $^{143}Nd/^{144}Nd$ values, which probably reflects the effects during crystallisation of the fact that Sr readily is taken up in plagioclase, which is abundant in most of Tongariro's magmas. In contrast, Nd is relatively incompatible for common phenocryst phases in Tongariro's magmas (i.e., mainly stays in the remaining melt) and is not buried in the crust like Sr is in plagioclase-rich intrusions. This feature suggests that $^{143}Nd/^{144}Nd$ values will more closely reflect the proportions of melted country-rock versus mantle-derived materials in Tongariro's magmas. Periods when magmas remain in the crust for longer are therefore reflected by lower $^{143}Nd/^{144}Nd$ values. In this situation, magmas will acquire lower $^{143}Nd/^{144}Nd$ values by one or more of:

(1) Crystallising Nd-poor minerals, which drives the remaining melt compositions to higher Nd concentrations
(2) Assimilating meta-greywacke materials with low $^{143}Nd/^{144}Nd$ values (0.5123-0.5127; Price et al., 2015)
(3) Not being mixed with hotter more primitive magmas with higher $^{143}Nd/^{144}Nd$ values (0.5129-0.5131; Gamble et al., 1993).

My results suggest that the largest volumes of more primitive mantle-like magmas were introduced to Tongariro's magmatic system before activities around ~225, ~100 and ~30 ka. Olivine- and clinopyroxene-dominant lavas with high MgO concentrations (5.5-9.5 wt%) were erupted from Tongariro at ~116 ka (Mangahouhouiti package) and ~40 ka (Pukeonake Formation) which are both upper-edifice and flank vent eruptives. Petrography shows that these mafic magmas did not intercept plagioclase-dominant magma reservoirs that more commonly feed eruptions from Tongariro's upper-edifice. The eruption ages (~116 and ~40 ka) occur ~10-15 kyr before minimum $^{143}Nd/^{144}Nd$ values are observed in plagioclase-dominant Tongariro eruptives at ~100 and ~30 ka. This relationship may indicate a delayed response before mantle-like isotopic signatures reappear in eruptible magmas in Tongariro's more established (plagioclase-dominant) magma reservoirs. In the absence of recent (≤10-15 kyr) significant mantle-derived input, Tongariro's magma compositions evolve back towards the $^{143}Nd/^{144}Nd$ values of meta-greywacke by progressive assimilation. Note that $^{143}Nd/^{144}Nd$ values do not correlate with incompatible element concentrations, such as K_2O and Zr, except for materials erupted before ~150 ka.

Of particular interest, the periods of $^{143}Nd/^{144}Nd$ minima (interpreted to reflect greater stagnation of magmas and melting of crustal materials) at Tongariro coincide with the antecrystic (~95 ka) and phenocrystic (~35 ka) zircon crystallisation age modes in Taupo volcano eruptives (Charlier et al., 2005), shown in panel E (Fig. 3). Zircon saturation modelling indicates that zircon crystallisation preferentially occurs in periods of prolonged crustal residence, without heating or reductions in magmatic Zr concentrations. Collectively, these observations suggest that a large-scale external force (e.g., tectonics associated with the rifting in the TVZ) may have influenced periods of increased crustal residence time that alternated with periods of elevated input of mantle-derived magma at both Tongariro and Taupo volcanoes.

5. *Explore the micro-geochemistry of the samples using EPMA microprobe and LA-ICP-MS on minerals, groundmass glass and melt inclusions within the crystals in order to assess the nature of the parental magma bodies as well as pre- and syn-eruptive processes.*

Because of time limitations, only limited micro-analytical measurements using electron probe micro-analysis (EPMA) on Tongariro's eruptives were made, and no laser ablation ICP-MS analyses were performed either. Instead, microscale analytical work focussed on trace element and isotope ratio measurements of groundmass separates and xenolith samples, using solution ICP-MS and TIMS techniques. Major elements were also analysed by XRF in some xenoliths where enough material was available (≥0.9 g). These analyses form a critical backbone for comparisons with future EPMA and LA-ICP-MS investigations on minerals, groundmass glass and melt inclusions that were not possible within the time-frame of this PhD study.

Collectively, trace element analyses and isotope ratio measurements of groundmass separates and xenoliths can be used to show the degrees of crustal assimilation involved in magma generation at Tongariro. The measurements also give indications as to which crustal materials have been assimilated. Isotope ratios of Sr and Nd in xenoliths suggest that three different suites of meta-greywacke materials have been melted and incorporated into Tongariro's magmas. These are the Pahau and Kaweka terranes (forming part of the Torlesse super group) and the Waipapa composite terrane (Mortimer et al., 2014). My results extend and modify previous studies that had indicated a role for a general Torlesse assimilant (Graham, 1987; Graham et al.,1988; Hobden, 1997). The results here also echo those of Charlier et al. (2010) who report Pahau and Kaweka terrane materials as a xenolith (Pahau) in the Rubbish Tip Dome (28 ka) and dispersed zircon crystals from both terranes in the Omega dacite (~20 ka) erupted from Taupo volcano. Work is currently ongoing to establish the percentages of crustal melting involved with generating Tongariro's magmas, and whether these percentages vary through time.

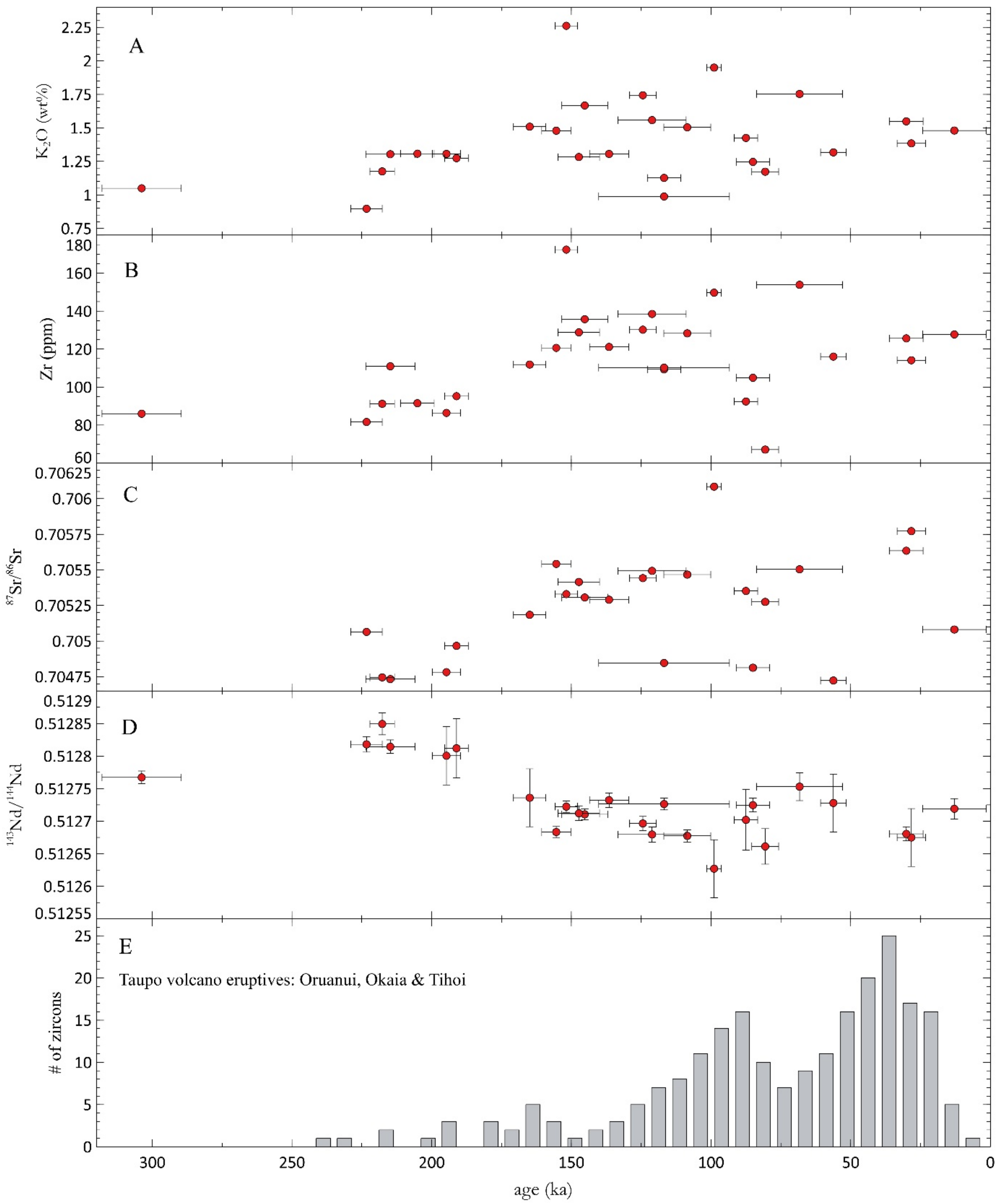

Figure 3. Time-composition relationships for Tongariro whole-rock samples that have $^{40}Ar/^{39}Ar$ age determinations (A-D). All error bars are 2σ (that is, the bar represents the 95 % confidence that the true value lies within those limits. Zircon model-age histograms for the Oruanui (25.4 ka, Vandergoes et al., 2013), Okaia (28.6 ka, Lowe et al., 2013) and Tihoi (~45 ka, Charlier et al., 2005) eruptives of Taupo volcano are shown for comparison in panel E (Charlier et al., 2005).

6. *Integrate all of these data to build a model for the development of the magma system below Tongariro, with consideration to maximising support for interpretations during the next volcanic eruption crisis at the volcano.*

This study contributes refined knowledge about the styles and sizes of volcanic eruptions that have occurred at Tongariro in both space (from separate volcanic vents) and time. It is almost certain that Tongariro will erupt again. The hazards associated with any future events will be best understood by examining trends in past behaviour to determine the processes governing how magmatism is expressed at Tongariro. By examining trends in past behaviour, it is possible to refine the expectations surrounding the sizes, locations and styles of future volcanic eruptions at Tongariro. General observations and suggestions about patterns and trends in Tongariro's volcanic activity are presented below.

First, the lifespans and ages of distinct vent areas at Tongariro are generally correlated (Fig. 4). Within the last 50 kyr (the most recent ~15% of Tongariro's lifespan), six distinct vent clusters of up to 1 km^2 in area that are more than 2 km apart have been active at Tongariro. Of these vent areas, two contain two or more vent foci each (Blue Lake and North Crater; Te Maari Craters). Where these vent areas have been active for more than 1 kyr, the styles of eruptive activity have differed substantially. Eruptions before 50 ka were sourced from only two areas: one in the present-day position of Ngauruhoe (~340 to ~195 ka; cf. Tost et al., 2016) and another in the present-day position of Central Crater (~191 to ~56 ka). However, the younger period, from 50 ka to now, is considered to be the most representative of future styles of activity at Tongariro. Information about the exact vent locations of pre-50 ka eruptions is also imprecise, and potentially less relevant to assessments of future volcanic hazards at Tongariro.

Second, for the period since 50 ka general similarities are noted between the longevity and behaviour of distinct vent areas. Mapping results suggest that volcanic activity can persist for at least 25 kyr at a particular vent area and hiatuses may exceed 10 kyr. However, in the past 50 kyr, it is more common for activity to last ≤10 kyr at a particular vent area. Examples of this are Ngauruhoe and Red Crater, which have been active for similar durations (~5-10 kyr) and were the most productive during their infancies. The largest lava flows from both Ngauruhoe and Red Crater were erupted before 1.8 ka (Stevens, 2002; Hobden et al., 2002) and subsequent activity has been of progressively smaller volumes through time. The smallest volume events have occurred since European arrival in New Zealand (Hobden et al., 2002; Greve et al., 2016).

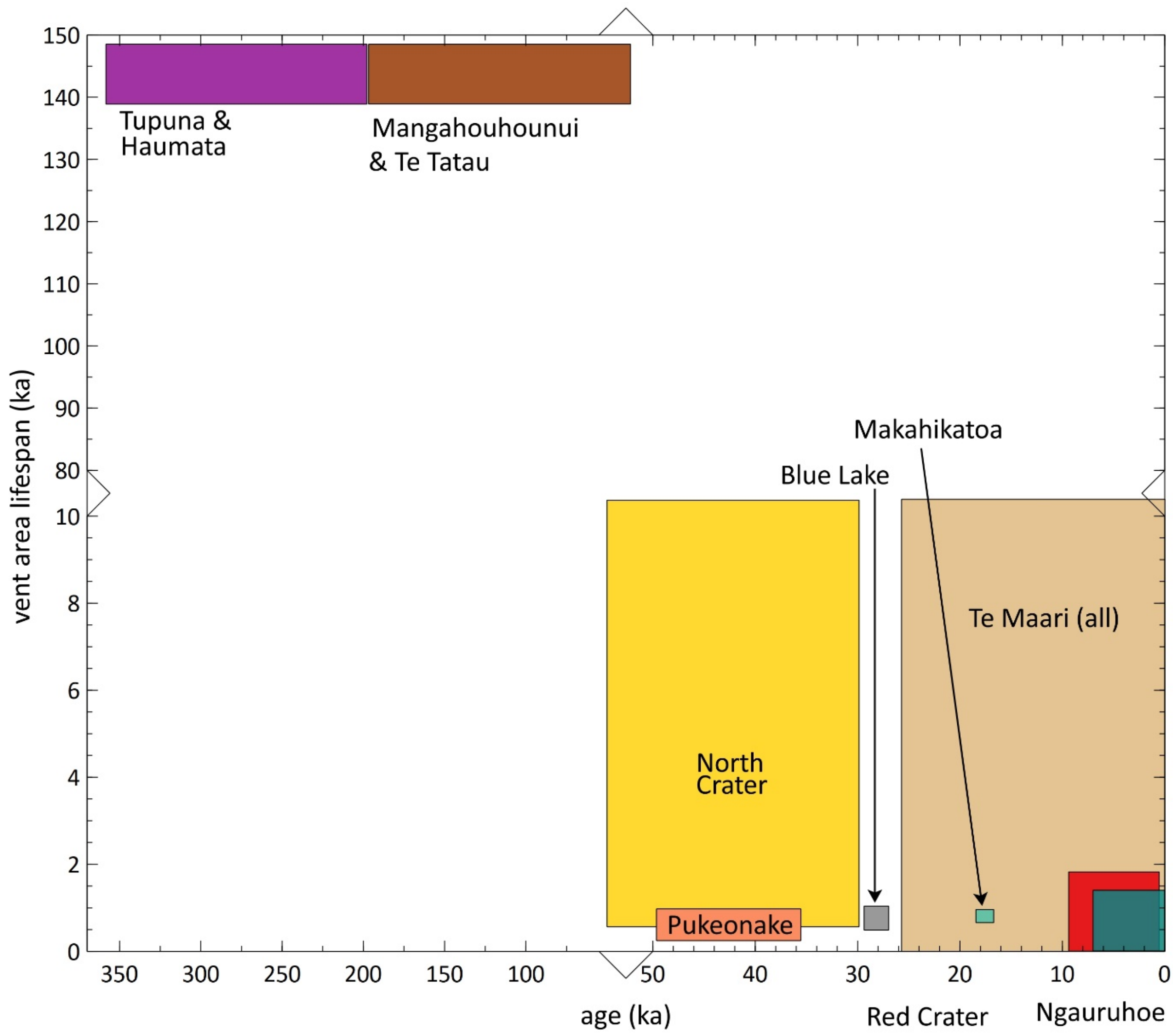

Figure 4. Tongariro eruptives grouped by vent area and approximate vent ages. Vents are <1 km^2 and ≥2 km away from any neighbouring vents, with the exception of Blue Lake and North Crater (~1 km separation). The vent area for the Tupuna and Haumata formations is beneath present-day Ngauruhoe. The vent area for the Mangahouhounui and Te Tatau formations is in the present-day location of Central Crater.

Broad similarities with initially vigorous activity that later progressively decreases is observed elsewhere, such as at North Crater. Large eruptions, with fire-fountaining several hundred metres into the air (Nairn, 1996) and a ~5 km lava that flowed to the NW, occurred between ~80 to ~30 ka, but probably closer to ~30 ka. Following this, a small explosion pit was formed in an eruption 10-100 times smaller at ~30 ka, which was the last activity at North Crater. Similar-composition magma was then erupted at ~28 ka from the present-day area of Blue Lake, which was probably sourced from the same parental magma body as the North Crater eruptives (grouped collectively as the Mokomoko Formation in my work, e.g., Fig. 2).

This behaviour is again generally similar to what is recorded for activity at Te Maari Craters. Te Maari Craters have four distinct vent foci within 1 km^2 that have been active intermittently from before 25 ka until now (Cronin, 1996; Lecointre et al., 2004; Townsend et al., 2017). The oldest activity from Te Maari Craters also erupted the largest volume of lava. Each phase of activity occurred around evidenced time-breaks, as shown by relations with regional tephra beds. These periods were before 25.4 ka, <25.4 to >17.5 ka, <9.0 to >3.3 ka and <0.5 ka to 2012 AD (Topping, 1974; Cronin, 1996; Nairn, 1996; Nairn et al., 1998; Lecointre et al., 2004; Lowe et al., 2013; Vandergoes et al., 2013; Scott and Potter, 2014; Townsend et al., 2017). Hence episodes of magmatic eruptions of decreasing volume occurred at intervals at least 2.5 kyr apart. During the most recent activity period, ~0.05 km^3 of basaltic-andesite lava was erupted from Upper Te Maari Crater at ~1500 AD (Topping, 1974). For a similar period since 1.8 ka, eruptives from Ngauruhoe are ~3-5 times more voluminous. During this period, Red Crater has been half as productive as Te Maari Craters.

Third, synchronicity is observed between magmatic and volcanic activity at Tongariro, Ruapehu and Taupo volcano. In the Taupo Volcanic Zone, the contemporaneity of spatially separated events has been suggested to arise from an external triggering force (i.e., tectonics), first proposed by Kohn and Topping (1978). Previous work has indicated contemporaneous activity between Tongariro, Ruapehu and Taupo volcano for the ~10 ka Pahoka-Mangamate eruptions (Tongariro and Ruapehu; Nairn et al., 1998) and the ~10 ka Unit B (Karapiti) and Unit C (Poronui) eruptions (Taupo volcano; Kohn and Topping, 1978; Wilson, 1993). This concept is extended further here with correlations between zircon crystallisation age modes for Taupo volcano eruptives and minimum $^{143}Nd/^{144}Nd$ whole-rock values in Tongariro's eruptives (see point 4 in the *Objectives* section and Fig. 3 D-E). The idea that broad-scale periods of elevated activity are linked is further supported by the eruption of magmas with high SiO_2, elevated radiogenic isotope ratios and high incompatible element concentrations in high-Mg andesites and dacites at Ruapehu at ~40 ka (Mangawhero Formation; Conway et al., 2018), which probably are coeval with the eruption from high-Mg basaltic-andesite from Pukeonake on Tongariro's flank (e.g., Fig. 2). It is therefore likely that eruptions of significant volume at Tongariro or Ruapehu or Taupo volcano should warn of potential volcanic activity at these other associated volcanoes.

Conclusions and key findings

Detailed mapping of Tongariro volcano has allowed the volcanic and magmatic evolution of the mountain to be reconstructed. The results of this study indicate that Tongariro's earliest activity (~340 to ~195 ka) persisted from a vent area beneath present-day Ngauruhoe. Later (~191 to

56 ka), eruptions were sourced from a new vent area in the region of present-day Central Crater. Since 50 ka, activity has occurred at six distinct vent areas (up to 1 km^2 and each ≥2 km apart), with some contemporaneous activity. In particular, three distinct magma systems have been contemporaneously active during the Holocene (Ngauruhoe, Red Crater and Te Maari Craters). This is in addition to another three independent post-50 ka magma systems (Makahikatoa, Pukeonake, North Crater-Blue Lake), which comprise four vent foci. The spacing of these vents areas is much more diverse than what is inferred for vent areas older than 50 ka at Tongariro.

Comparisons between Tongariro's magmatic activity and other regional volcanic events at Ruapehu and Taupo volcano indicate a probable tectonic influence on the timing and size of activity. This finding extends on previous work that demonstrated such a relationship in the early Holocene. Results here indicate contemporaneous/synchronised magmatism at Tongariro and Taupo volcano was occurring by ~100 ka, and possibly before at ~225 ka. This finding has major implications for possible volcano monitoring techniques and hazard management beyond Tongariro to across New Zealand's Taupo Volcanic Zone.

Impact

The findings of this study offer new considerations for hazard management at Tongariro:

- The evidence gained in this and previous studies is that tectonic processes regulate the size and timing of volcanic eruptions at Tongariro, Ruapehu and Taupo volcano on longer-term timescales. The data suggest that there should be attention paid to geophysical techniques that measure present values and changes in crustal stress states (e.g. Gerst and Savage, 2004; Johnson et al., 2011). Significant activity at one of these volcanoes may imply the possibility of impending unrest or activity at the others.
- If future volcanic activity at Tongariro involves flank eruptions, even if they are small volume events, they may distribute lava flows onto State Highways 1, 46 or 47. It may be worth considering the vulnerability of this infrastructure and contingency plans in the situation that one of these highways becomes unusable. Powerlines running parallel to State Highway 1 are at similar risk.
- It is unclear where and when future eruptions will occur from on Tongariro's upper edifice. The ages and sizes of Holocene eruptions indicate that one or more of Ngauruhoe, Red Crater, Upper Te Maari Crater or a new, yet-to-be-constructed volcanic vent are all possible future sites of activity.
- At least three independent magma systems have been contemporaneously active in the Holocene at Tongariro (Red Crater, Ngauruhoe, Te Maari Craters). Another three vent areas

have been active since 50 ka (North Crater-Blue Lake, Pukeonake, Makahikatoa). Each of these vent areas has erupted distinctly different magma compositions. This suggests that present-day volcano monitoring techniques should ideally resolve sub-surface activity at resolutions greater than the spacing between vents (i.e., better than 0.5-1.0 km), and not be restricted to Tongariro's upper edifice.

Future work

Mineral-specific investigations that quantify the timescales of magmatic processes preceding eruptions would be of great value here. Such ambitions have not been realised in this study due to the large volume of work needed to properly understand Tongariro's long-term volcanic and magmatic evolution, but are now beginning with the PhD studies of Kerstin Gruender at Victoria University. Ongoing work at Ruapehu by a colleague, Dr Chris Conway, has been highly successful with determining the time elapsed between mafic magma recharge events (which would be seismically visible) and subsequent large-volume effusive (and possibly also explosive) eruptions. Results indicate timescales of 1-100 days, but generally under two weeks. Similar work is viable on magnesium-rich eruptives at Tongariro and will be undertaken as part of Kerstin Gruender's future studies. In parallel, it would be advantageous if future studies examined the fine-scale structure and state of Tongariro's magma system with geophysical techniques, with comparisons to detailed geochemical analyses of recent (Holocene) eruptives and knowledge of the independent nature of the magma bodies feeding the widely spaced vent systems.

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Outputs and Dissemination

Five publishable outputs are planned for this work, although none are completed yet. They are four scientific publications on (1) Tongariro's eruptive history and stratigraphy, (2) meta-greywacke xenoliths found in Tongariro's erupted magmas, (3) the overall geochemical evolution of Tongariro's magma system over its lifespan and (4) a paper examining possible volcano-tectonic interactions that contemporaneously affect Tongariro, Ruapehu and Taupo volcanoes. The fifth publication is Leo Pure's Ph.D. thesis itself, which will be the culmination of these four studies. As with all VUW PhD theses that have no commercial content, the thesis will be available for public download once examined and accepted.

Links to publications/theses

Manuscripts for peer-reviewed journals and Leo Pure's Ph.D. thesis are currently being produced. These publications will acknowledge EQC's generous support of this study. The link to the lodged thesis will be sent to EQC in due course once the thesis is finally accepted.

List of key end users

DoC

Geonet

Iwi with oversight of lands within Tongariro National Park, specifically Ngati Tuwharetoa

CPVAG

Transpower (or whatever it is called these days)

Relevant District councils and regional councils