The evolution of past and present magmatic systems in the north Taupo area: Implications for modern hazards? (EQC grant 18/U776)

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Summary and results highlights

Lava dome eruptions have been more frequent in the north Taupō area than previously thought and their vents have shifted spatially through time over a widespread 80 x 40 km area. New ^{40}Ar-^{39}Ar geochronology data show the vents become younger from the Northwest Dome Complex (NWDC, north of the Waikato River) to the current Lake Taupō configuration, which aligns with current understanding. The ^{40}Ar-^{39}Ar dates show that lava dome eruptions have been a continuous feature of the volcanism over ~400,000 years. There were quieter periods with few eruptions, and "busier" periods of more frequent eruptions. Whether a caldera volcano is better characterized by frequent small volume eruptions interspersed by large ignimbrite forming eruptions is yet to be decided.

Lavas along the western border of the study (Western Dome Belt, WDB), previously thought to pre-date the Whakamaru supereruption and resulting caldera collapse, are now recognised to in part predate these events by up to 100,000 years. This result suggests that the magma systems involved in WDB eruptions were not completely destroyed by the Whakamaru events. The magma system that fed the WDB lavas is separate to those that supplied the Whakamaru eruption. The ^{40}Ar-^{39}Ar age data support Brown's (1994) hypothesis that a series of magma chambers or an irregular chamber would let separate magma batches at varying stages of evolution co-exist and erupt. This hypothesis would account for the presence of the highly evolved NWDC lavas to the north of the inferred Whakamaru caldera rim (which are dated as the oldest). A revision to the Whakamaru caldera structure would further help us understand how modern hazards are affected by rift faulting.

The whole rock geochemistry shows a clear distinction between magma types from different eruptions. The magma types change in crystal content and Sr values further south towards Lake Taupō. There is a steady progression in magma types, however this is not reflected in a sequential manner in the 25,000 – 350,000 years ago time period as the most evolved magma type (NWDC) is the oldest. The central Maroa lava domes and NWDC lava domes are both derived from the same magma source, whilst the WDB lavas are a mixture of at least three magma types from two magma systems. ^{87}Sr/^{86}Sr isotope ratios reveal the presence of two large-scale deep crustal magma systems controlling the isotopic characteristics of most of the eruptives studied. These magma systems co-existed up to ~50,000 years ago and appear to lead into the two modern systems under the area but with a shift in vent areas and an intense focusing of activity into an area beneath the modern Lake Taupō. Two magmatic systems are currently viable for unrest or eruption: the highly productive system submerged beneath Lake Taupō, active in its current configuration since ~25,000 years ago and a less frequently active system beneath the Wairakei-Tauhara area that has been active since ~45,000 years ago.

Introduction

How magma chambers evolve and assemble large bodies of crystal-poor magma to supply supereruptions (>~450 km^3 of magma erupted) and what happens in between such vast events is a widely debated question in volcanology. This project focuses on this topic using a defined time period bracketed between two supereruptions that occurred in the central Taupō Volcanic Zone (TVZ). The central TVZ was host to four of the thirteen supereruptions known worldwide in the Quaternary (Wilson et al., 2009). How volcanic systems behave in between these vast events is not well constrained yet is important in determining the factors that lead to supereruptions. This project investigates the volcanic products erupted between the ~ 350 ka Whakamaru and 25.4 ka Oruanui supereruptions to understand how magma systems in the North Taupo-Maroa area were organised and evolved.

The surficial record of volcanism in the broader Taupō area extends from ~250 CE back to overlap the Whakamaru Caldera and the associated Whakamaru Group eruptions at ~350-340 ka (Wilson et al., 2006; Wilson, 1993; Leonard, 2003; Leonard et al., 2010; Downs et al., 2014a). This broader area of about 80 x 40 km is much larger than that attributed today to 'Taupō volcano', and hence there is the need to consider what we define as Taupō volcano, both the structure and when it came into existence. The 25.4 ka Oruanui caldera forming eruption that defines the lake outline is thought to represent the current incarnation of the modern Taupō volcano (Barker et al., 2021). Destruction by caldera collapse, tectonic subsidence and obscuration by younger deposits, and an incomplete chronology for the Taupō area, are issues that have obscured interpretations. Studies by Sutton et al. (1995) and Charlier & Wilson (2009) documented that eruptions from 25,000 years to 65,000 years old could be separated into discrete magma batches, with two systems being prominent (Figure 1). The first (e.g. the ~45 ka Tihoi and ~28.5 ka Okaia eruptions) had characteristics similar to the Oruanui magma, whilst the second (e.g. the ~47 ka Ngangiho and ~27.5 ka Poihipi eruptions) were distinctively different and were labelled the NE dome system (Figure 1). Sutton et al. (1995) ascribed the chemical and isotopic variations in the rhyolites to mean they did not originate from a single magma chamber, but rather distinct batches of magma were sourced geographically (over a large area) or were time dependent. Leonard (2003), Wilson et al. (1986) and Brown (1994; 1998) provided further evidence for older magmatic systems.

The work in this project is designed to integrate the pre-existing studies with a new framework of geochronological and geochemical data in order to place the evolution of the broader Taupō area into context with respect to the viability of modern, potentially active systems. This aim has been accomplished through the following work. First, collection of a new suite of ^{40}Ar-^{39}Ar age data to add to and compare with earlier data (Houghton et al., 1991 [by K-Ar]; Leonard, 2003) so as to arrive at a comprehensive data base of ages of the surficial eruptives. Second, by collection of geochemical (major elements by X-Ray Fluorescence, trace elements by solution Inductively Coupled Plasma Mass Spectrometry) and isotopic ($^{87}Sr/^{86}Sr$ by Thermal Ionisation Mass Spectrometry) data to couple with earlier data (Brown, 1994; Sutton et al., 1995, 2000) to form a complete data base of compositional characteristics of eruptives in the area. Third, by collecting new petrographic observations and mineral compositional data by Electron Probe Microanalysis to link with existing data (Ewart, 1968; Brown, 1994; Sutton, 1995), again to bring together a comprehensive data base of the characteristics of the eruption products. The first of these pieces of work has been completed, the second is completed but the data have yet to be compiled, and the third is approaching completion.

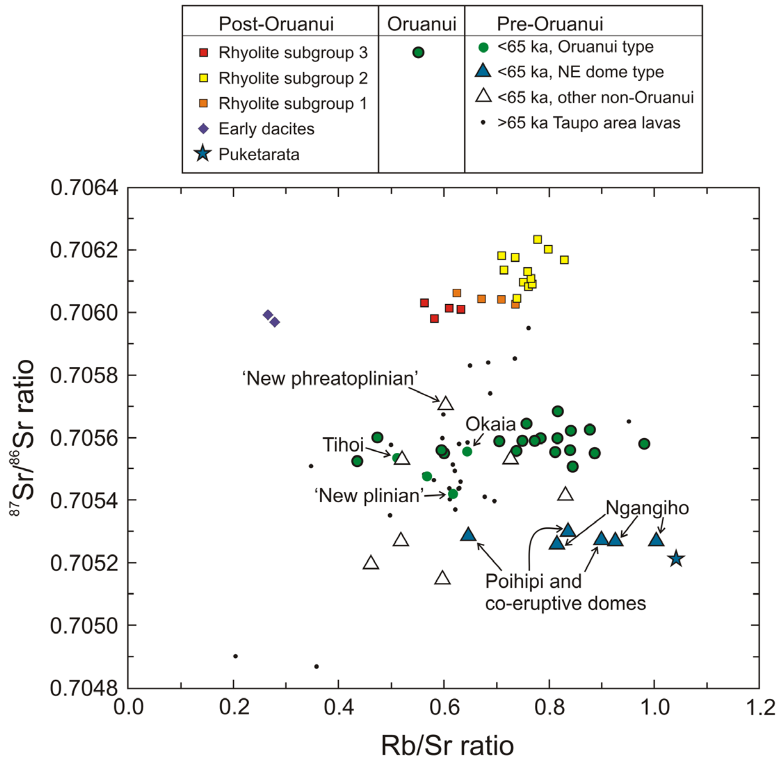

Figure 1. Summary of isotopic and geochemical compositions of pre- Oruanui and post-Oruanui eruptives (Wilson & Charlier, 2009). The $^{87}Sr/^{86}Sr$ ratio increases with the amount of interaction of magmas with the greywacke basement, while the Rb/Sr ratio increases with the geochemical evolution of the magmas. Magmas from a common system plot as horizontal arrays in this figure.

Objectives

The objectives that were linked to this funding request were to:

1) Collect samples of pyroclastic deposits and lavas from eruptions that post-date the Rotoehu marker horizon (ca. 50-55 ka).
2) Conduct major and trace element whole-rock geochemistry analysis of these samples, using XRF, electron microprobe (for fine-grained tephras) and ICP-MS techniques to arrive at a common data base.
3) Select and prepare targeted Ar-Ar dating samples to establish the time sequence context for the younger volcanic history of the north Taupō area.
4) Integrate the whole-rock chemistry and ages (new and existing) with the existing mapping data to provide an overview of the context of young, potentially viable volcanic activity in the north Taupō area.
5) Explore the micro-geochemistry of the samples using EMPA microprobe and LA-ICPMS 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.
6) In the thesis, integrate all of these data to build a model for the location and duration of magma systems below the north Taupō area, with particular consideration to maximizing information on the location and status of magmatic systems capable of erupting in this area.

Conclusions and Key findings

GEOCHRONOLOGY

A summary map of the age data is shown in Figure 2, and time snapshots are given in figures 3 and 4. Main findings from the age data collected as part of this project are as follows. Lavas along the western border of the study area (western dome belt, WDB) in part predate, rather than wholly post-date, the major 350,000 year old Whakamaru super-eruption and its caldera collapse (cf. Wilson et al., 1986). The ^{40}Ar-^{39}Ar dates show that rather than being restricted to the period between the Oruanui eruption at 25,000 years to the Whakamaru caldera collapse at ~350,000 years, lava dome eruptions occurred over a period of ~400,000 years. These lava dome eruptions are in places also accompanied by pyroclastic flow deposits (e.g. the Whakaroa Dome Complex, WDC) and cover an area of 80 x 40 km, from beyond the Waikato River in the north where the northwestern dome complex (NWDC) is located, to the southern shores of Lake Taupō where the southwestern group of domes are located (Figure 5).

The new ^{40}Ar-^{39}Ar dates supplement the existing geochronology of the area by Leonard (2003) and Houghton et al. (1991). Lava dome eruptions are more frequent at Taupō than previously thought and their vents are shifting with time over a ~80 x 40 km area. Figures 2-4 illustrate how these lava dome eruptions have shifted spatially over time, with different vents. Although described by some workers (Kósik et al., 2020) as essentially monogenetic (the silicic counterpart to the Auckland Volcanic Field), there are patterns of age and compositional clustering that imply small-scale but organised magmatic systems existed in this area for period of thousands to tens of thousands of years. For example, the Whakaroa complex appears to be a compound accumulation of lava flows of two to three magma types erupting from overlapping vent sites. The age and geographic distributions of the eruptive units raise the question over how to describe the character of this style of sporadic and dispersed activity, and whether a caldera volcano is better characterized by frequent small volume eruptions interspersed by large ignimbrite forming eruptions.

The Western dome belt lavas (WDB, Figure 5, green and grey colours) consistently returned ^{40}Ar-^{39}Ar eruption ages of up to 100,000 years before the Whakamaru eruption. This suggests the WDB, which lies on the western rim of the Whakamaru caldera (dashed black line, northwest, Figures 5-7), was active prior to the Whakamaru caldera forming eruption and continued afterwards, indicating a system that has been operating over 150 kyr or more. The Whakamaru eruption represents the single largest eruption in the TVZ (~350,000 years ago: Downs et al., 2014a) evacuating over 1500 km^3 of magma (Brown, 1994; Wilson et al., 2009) and marks the onset of the "young TVZ" (Wilson et al., 1995) that continues today. This project is concerned with the relationships between the Whakamaru magma systems (Brown et al., 1998) and those feeding the WDB, as the degree of geographical or compositional overlap has implications for the geographic footprint of the Whakamaru caldera and associated magmatic systems. The catastrophic nature of the Whakamaru eruption suggests that magma systems would be destroyed, or at least in part, reset, yet the ^{40}Ar-^{39}Ar dates imply that the magma system feeding the WDB were not affected. The magma systems feeding the WDB lavas thus appears to have been independent of the Whakamaru systems.

The NWDC lavas which lie to the north of the inferred Whakamaru caldera were reported by Brown (1994) to be predominantly highly evolved compositions at various stages of fractionation. Because the most evolved lavas were not erupted last, it was inferred that an irregularly shaped chamber, or series of chambers would allow separate batches to coexist and be erupted in a sequence, which would then be dependent on the delivery/conduit system. The ^{40}Ar-^{39}Ar dates obtained in this study support this hypothesis. As a result, substantial revision is required to our models of the Whakamaru caldera structure that have relevance to understanding the development of the modern magmatic systems and their hazards in the area.

Further south towards Lake Taupō, the ages become progressively younger from the NWDC to the northern shores of Lake Taupō. The lava domes on the northern shores are dated at 150-100 ka. Domes southwest of the lake span a wide range of ages, despite forming a coherent line of domes. It is uncertain, however, whether there were domes extending from the southwest area around the lake across to its north shore as all evidence was destroyed by collapse of the Oruanui caldera. The most recent dome-building eruptions, at Motutaiko Island, and at Acacia Bay and along the Ouaha ridge are established from correlations with radiocarbon dated pyroclastic deposits to be in the 12-0 ka time period (Wilson, 1993).

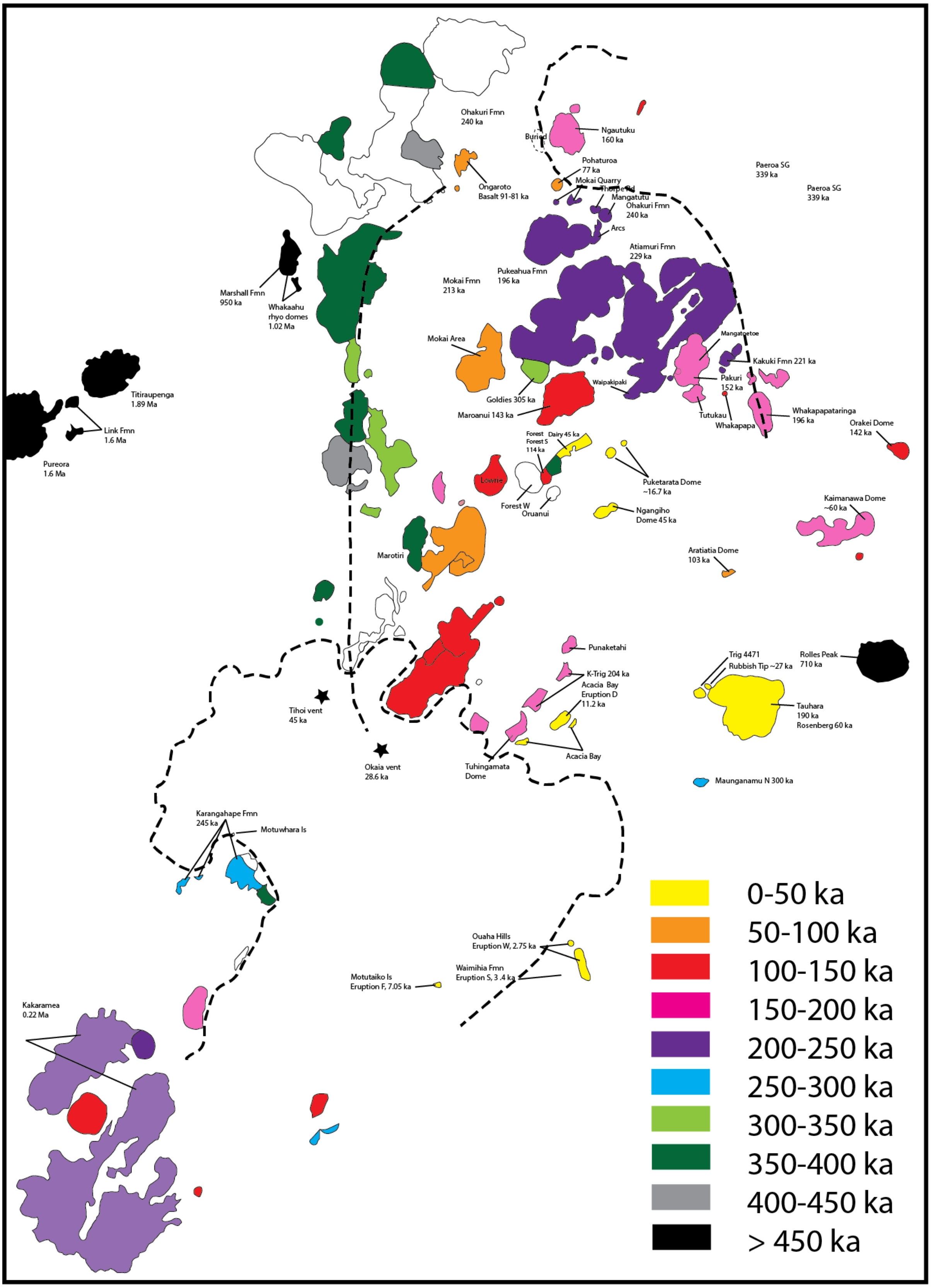

Figure 2. Map of rhyolite lava dome eruptions from the present to approximately over 450 ka. The grey and green colours are the Western dome belt rhyolite lava eruptions. The purple lavas in the northeast are the Maroa dome complex rhyolite lavas. Outlined domes are those for which age data are not available or are still being collected. Dashed lines mark the boundaries of the Ohakuri (264 ka), Whakamaru (350 ka) and Oruanui (25.5 ka) calderas, respectively (from Leonard et al., 2010)..

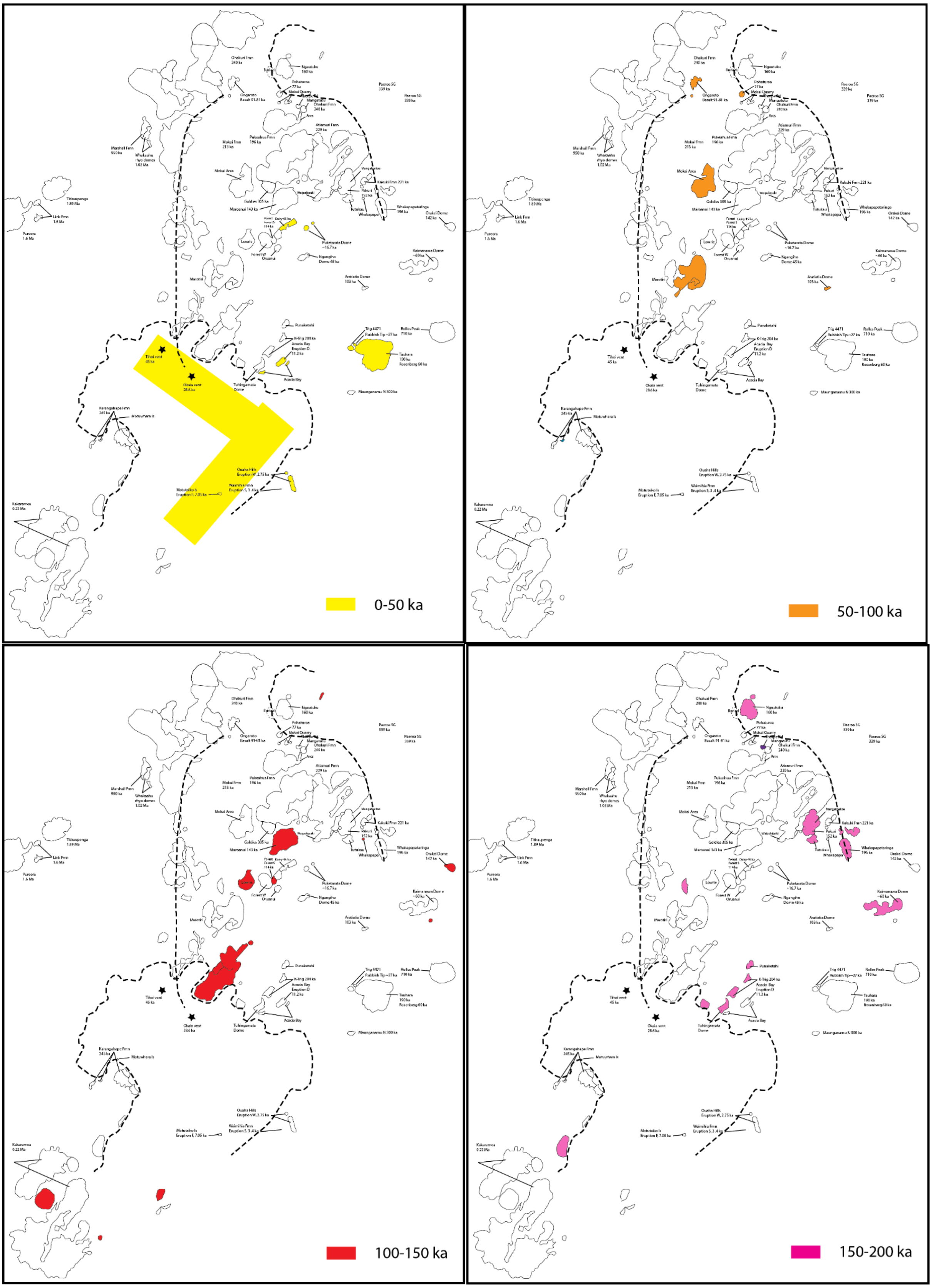

Figure 3. Maps from 0-50 ka, 50-100 ka, 100-150 ka and 150-200 ka illustrating the rhyolite lava dome eruptions through time.

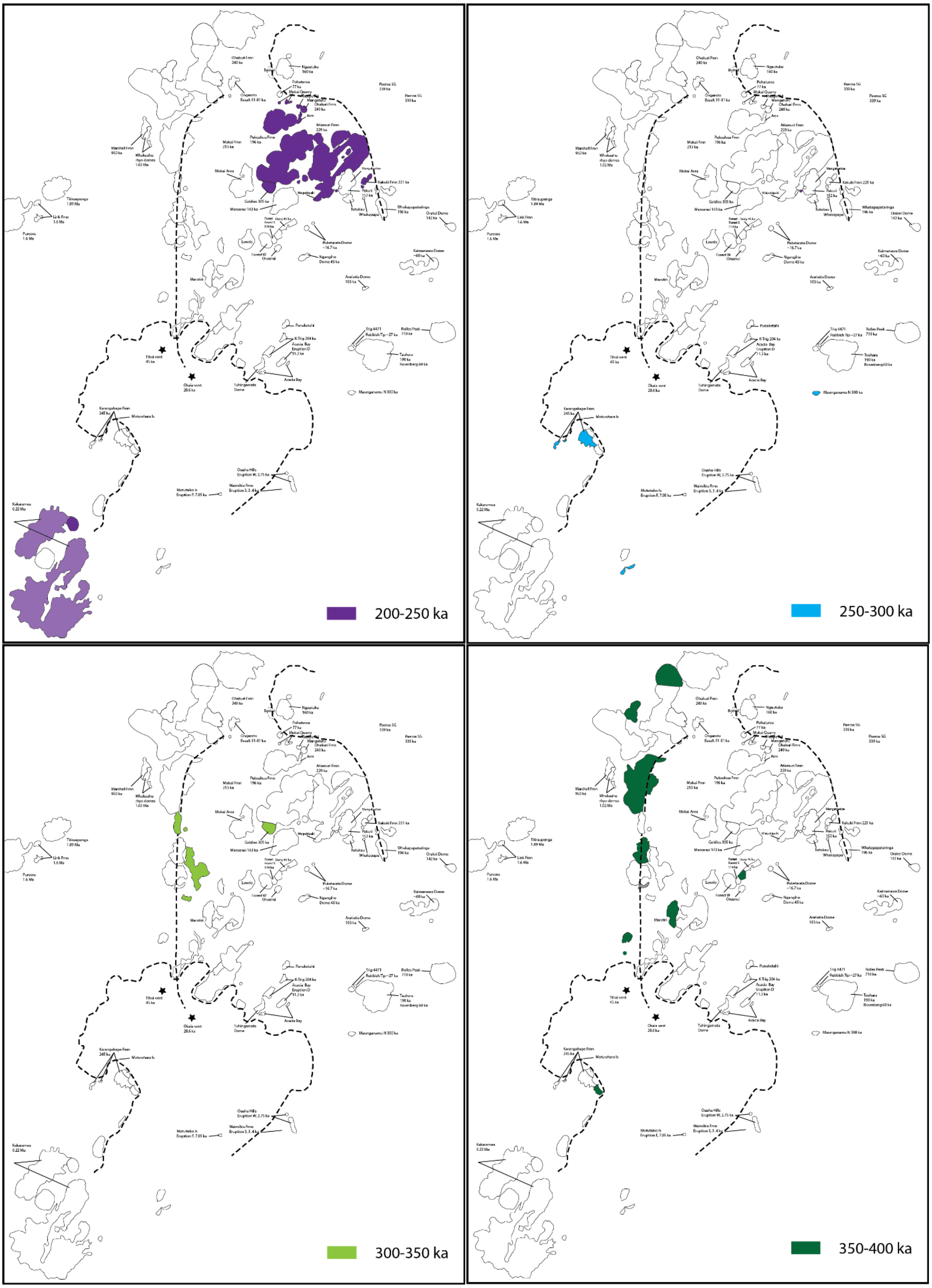

Figure 4. Maps from 200-250 ka, 250-300 ka, 300-350 ka and 350-400 ka illustrating the rhyolite lava dome eruptions through time.

GEOCHEMISTRY

Petrographic thin section mineral descriptions showed that the NWDC lavas to the north of the Waikato River contain a different mineral assemblage to the Western Dome Belt (WDB). This difference is coupled with the older ages recovered from the NWDC lavas, which are now confirmed to have been erupted prior to the Whakamaru eruption. The whole rock geochemical data confirm these distinctions and shows consistent differences between magma types from different eruptions.

Some of the samples collected fit into the magma groupings outlined by Leonard (2003) whilst others, such as the NWDC, represent a newly recognised, more evolved magma type. Data shown in Figure 5 imply that the Maroa lava domes (red diamonds) are derived from a source with the same Sr-isotopic characteristics as the more evolved and older NWDC lava domes (green diamonds). One sample (Skyline W, KMR072b) is the most radiogenic ($^{87}Sr/^{86}Sr$ = 0.706028) and of a higher crystal content compared to others in the NWDC (Ewart, 1968; Figure 6). In contrast, the WDB lavas (light blue diamonds) are a mixture of at least three magma types, originating from two magma systems. The southwestern lavas (purple diamonds) form a tight cluster from the higher isotopic ratio magma system. Overall, there is a steady progression in magma types, however, this is not reflected in a sequential manner in the 350,000 to 25,500 time period as the most evolved magma type (NWDC) is the oldest. The magma types do change in total crystal content and Sr values further south towards Lake Taupō, and some are focused in certain areas (e.g. Maroa dome complex) reflecting some spatial influence.

$^{87}Sr/^{86}Sr$ isotope ratios reveal that two large-scale deep crustal magma systems were operating in the area studied for the period up to 50,000-25,000 years ago. These systems are represented by two broad trends (Figure 6), one with a lower $^{87}Sr/^{86}Sr$ isotopic ratios from 0.7052-0.7054 and one with a more radiogenic signature from 0.7056 to 0.7060, implying either an increased crustal contribution (form a uniformly radiogenic source) or the presence of two slightly contrasting crustal domains. When the two main groups are plotted in map view, the northern part of the Taupō region is dominated by the lower isotopic signature, whilst the southern half is dominated by the more radiogenic signature (Figure 7). These two systems appear to lead geochemically and isotopically into the two modern systems under the area, but with a shift in vent areas and an intense focusing of activity to an area beneath the modern Lake Taupō (compare Barker et al., 2020). To a first order, the Oruanui magma type, erupted from ~60,000-25,500 years ago Sutton et al., 1995; Wilson & Charlier, 2009), is descended from the higher $^{87}Sr/^{86}Sr$ isotopic signature, whilst the modern NE magma system supplying domes/eruptives northeast of Lake Taupō near the Wairakei-Tauhara area is the successor to the lower $^{87}Sr/^{86}Sr$ isotopic signature magma system. However, the post-Oruanui activity at Taupo represents a break from the Oruanui magmatic system (Barker et al., 2014, 2015) along a new higher-$^{87}Sr/^{86}Sr$ trend (Barker et al., 2015) following thermal re-setting of the trans-crustal magmatic system below the volcano (Barker et al., 2014). As such, the modern magmatic system under Lake Taupō represents a new entity which, as emphasized in the 2019 unrest events (Illsley-Kemp et al., 2021), represents the current major source of hazards associated with unrest and/or eruption in this area.

This work raises issues of: how we define the modern Taupō volcano - spatially, or by characteristic chemistry or magma composition? The presently 'alive' but less vigorous system (that fed the NE domes: Sutton et al., 1995) in the Wairakei-Tauhara area northeast of Lake Taupō represents the latest example of the shifting, small-volume magma-generating areas that have been present over the wider area for ~400,000 years. As such, it represents the possibility of future eruptions outside the area considered as “Taupō volcano”. This is of interest and concern in that current monitoring efforts are primarily focused on the system beneath the lake and not on whether or not there is magma under the Wairakei-Tauhara area, providing the thermal roots to the Wairakei-Tauhara geothermal system (Rosenberg et al., 2020). Although eruptions from this system are sparse (5 in ~45,000 years, including the magma fed into the Oruanui eruption: Allan et al., 2012) the influence of this magmatic system on the stability of hydrothermal fluid flows within the Wairakei-Tauhara Geothermal Field will need to be taken into account in future utilization of the geothermal resource. The present state of the magmatic system is unknown.

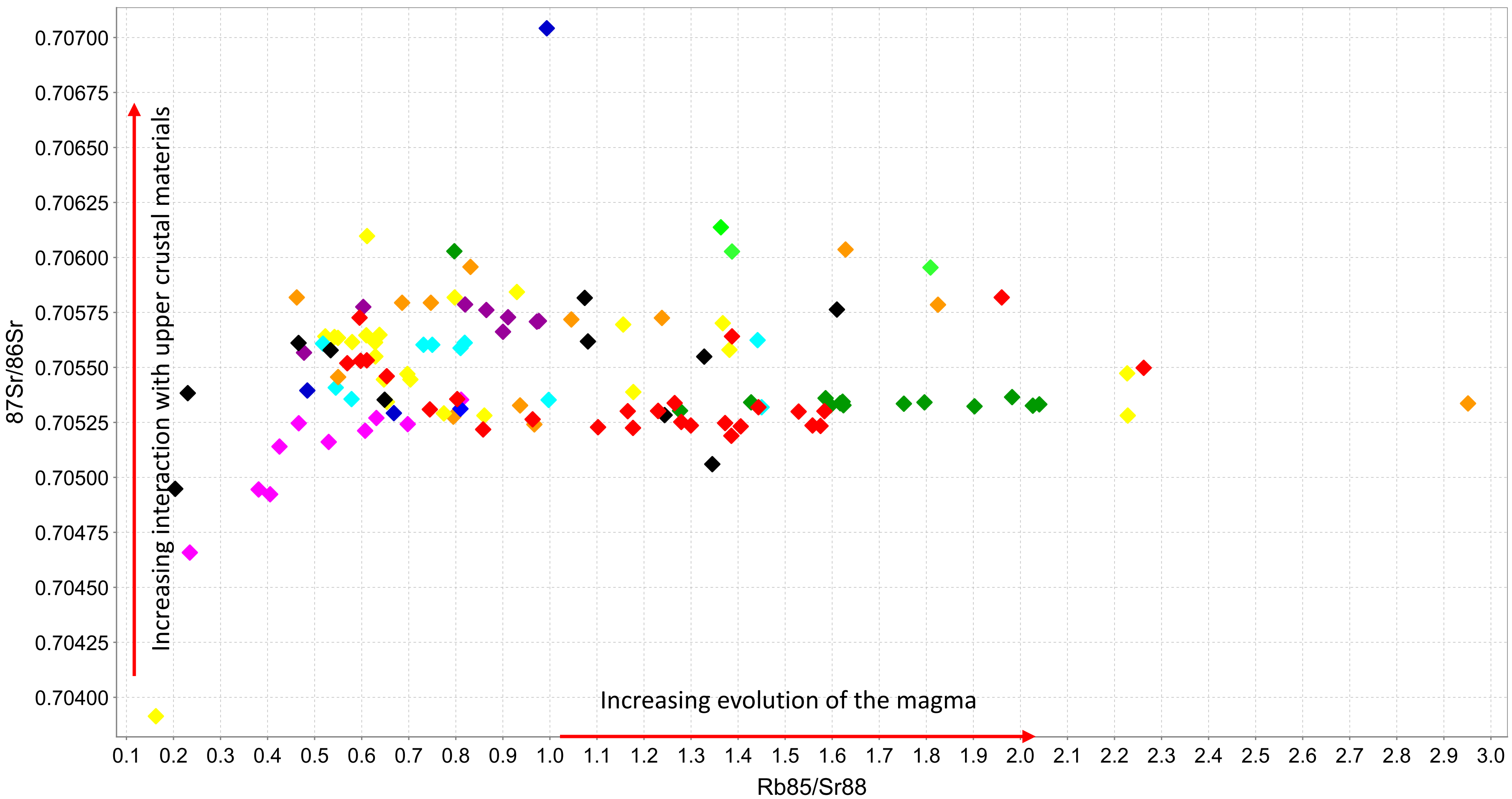

Figure 5. Plot of $^{87}Sr/^{86}Sr$ ratios (higher values reflect an increased component of crustal greywacke material in the magmas) versus $^{85}Rb/^{88}Sr$ ratios (higher values reflect increasing degrees of evolution of the magmas). Orange dots are widespread individual domes. Yellow symbols are domes or tephra close to the north shore of Taupō. Purple symbols are southwest dome lavas. Light blue symbols are the western dome belt (WDB) lavas. Red symbols are the central Maroa complex dome lavas. Green symbols are the northwestern dome complex (NWDC) lavas. Dark blue symbols are rhyolite lava domes on the eastern side of the lake. Magenta symbols are ~50 ka pyroclastic units from north Taupo. Black symbols represent those samples that are not yet classified.

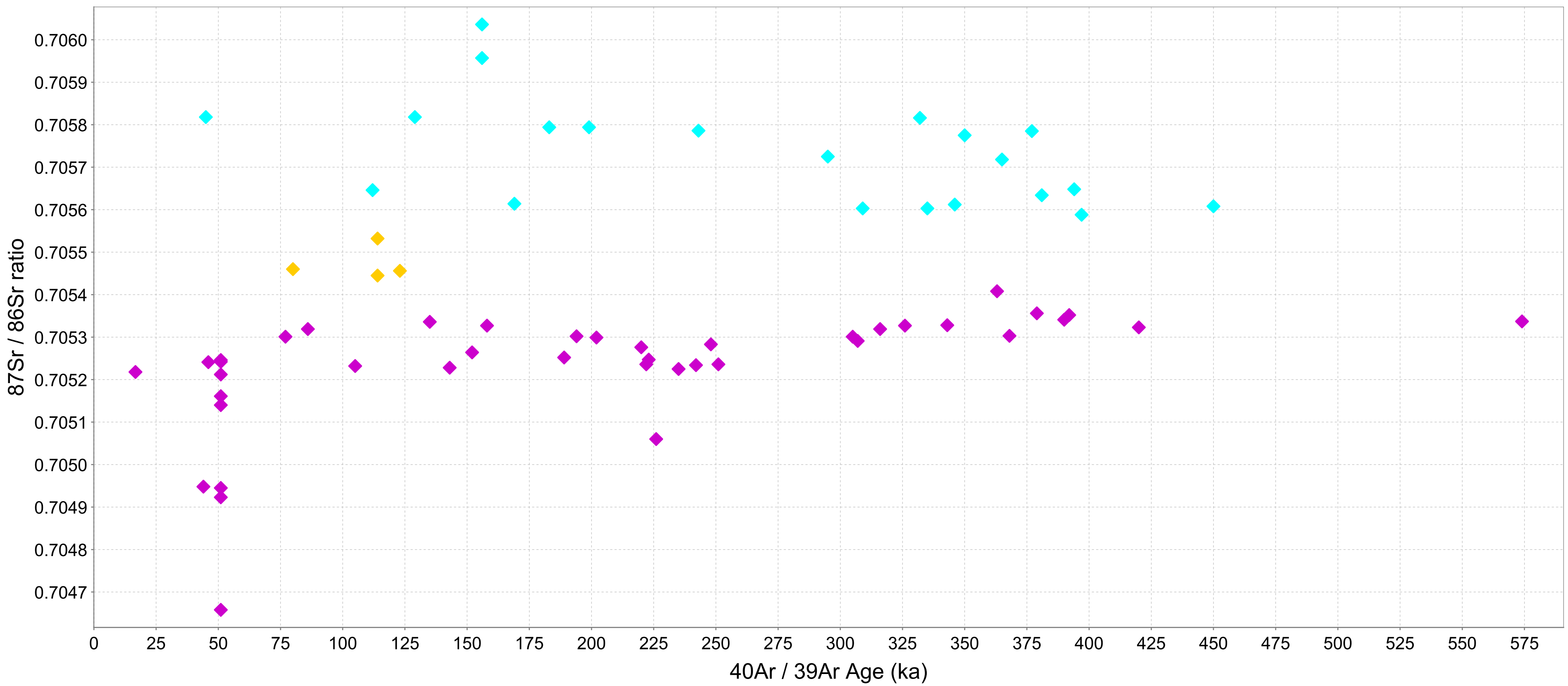

Figure 6. Plot of $^{87}Sr/^{86}Sr$ ratios versus $^{40}Ar/^{39}Ar$ age (ka) (from this work plus Leonard, 2003, and Houghton et al., 1991) showing the two broad trends of strontium isotopic ratios at $^{87}Sr/^{86}Sr$ = 0.7052-0.7053 (magenta) and 0.7056-0.7060 (blue). Yellow represents an intermediate category.

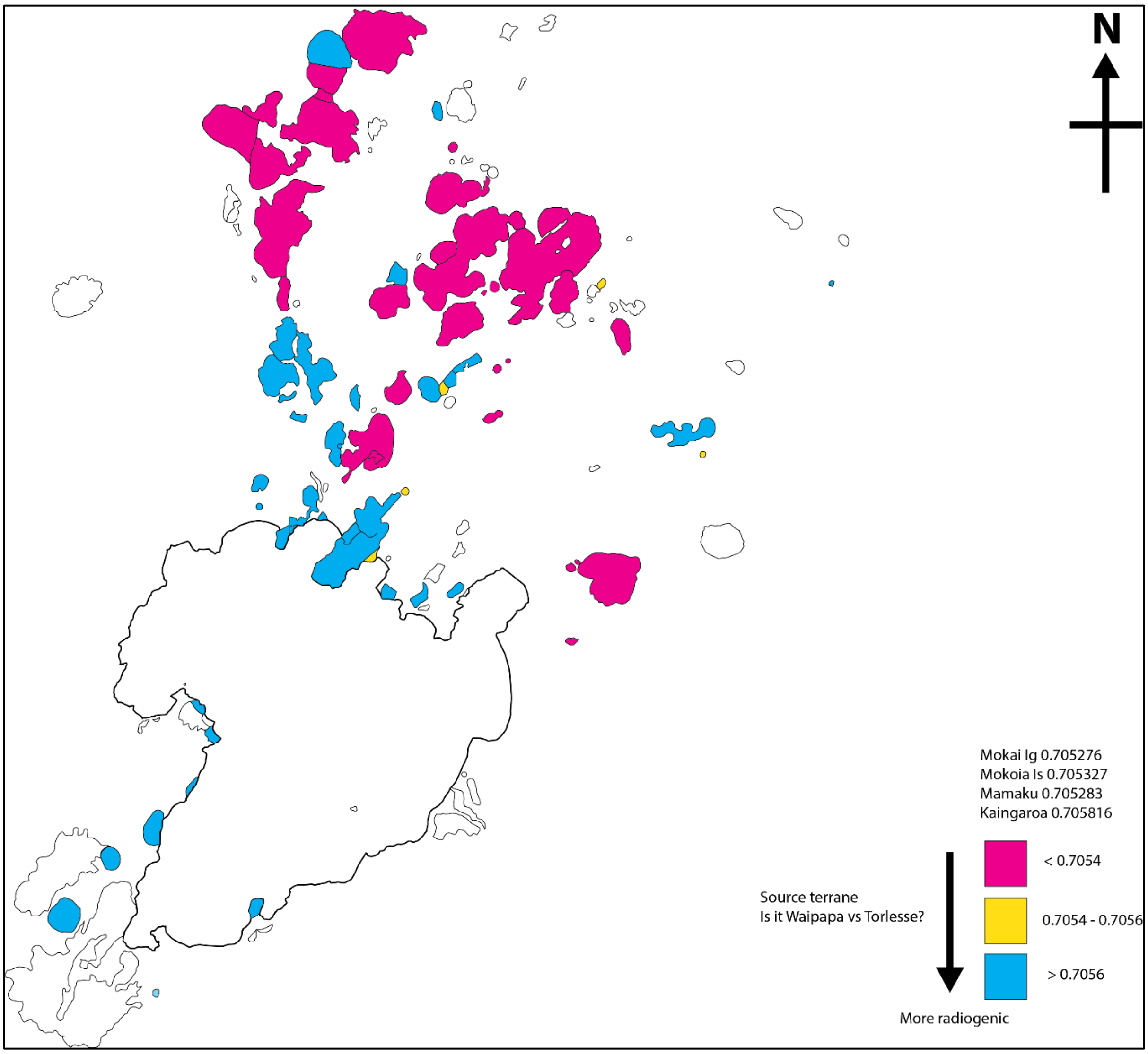

Figure 7. $^{87}Sr/^{86}Sr$ ratios, as categorised in Figure 7, plotted in map view, showing that the two broad trends at $^{87}Sr/^{86}Sr$ = 0.7052-0.7053 (magenta) and 0.7056-0.7060 (blue), plus the yellow intermediate category. Open shapes are eruptives (mostly rhyolite domes) for which no data are available.

Impacts

The impacts of this research relate to what the results mean for the two modern magma systems and potentially active magmatic systems in the Taupō area. Recognition of the migration patterns of volcanism over the last 400,000 years allows the two modern systems to be linked to this history, and implies that future activity will be from the two modern areas. Any treatment of the spatial patterns of volcanism across this area to derive probabilistic assessments of future activity (e.g. Kósik et al., 2020) needs to take into account that past systems are, indeed, in the past and should have no bearing on the probability of future outbreaks away from the two modern areas (with the exception of monogenetic basaltic events). The new insights into the dynamical behaviour of volcanic and magmatic systems in the north Taupō area, highlights the importance of assessing the state of the modern contemporaneous systems in order to be able to identify any unrest related to magmatic activity (e.g. Illsley-Kemp et al., 2021) or the movement of magma.

A second impact from this research related to recognition of the common parental crustal roots shared by eruptions in specific areas, and the controls on how these crustal roots are expressed at the surface. What we think of as defining or characteristic of a caldera volcano may not necessarily be true the longer we look back in time, and the intensity of volcanism has fluctuated greatly with time. In addition, the age data imply that magma systems like those feeding the WDB lavas may not be destroyed in a caldera collapse, as indicated by the eruption of lava domes in the WDB area both before and after collapse of the Whakamaru caldera. Coupled with new information on the geometry of the Whakamaru-aged equivalent ignimbrites at Wairakei, a re-think on the geometry of the Whakamaru caldera is required.

A third impact from this research arises from comparisons of the age patterns obtained in this work and that of Downs et al. (2014b) from surficial eruptives, versus the eruptive age and subsidence histories now constructed from U-Pb age dating of buried volcanic lithologies in the geothermal systems at Ngatamariki (Chambefort et al., 2014), Rotokawa (Milicich et al., 2020) and Wairakei-Tauhara (Rosenberg et al., 2020). These show patterns of subsidence in the Taupō-Reporoa Basin that increase towards the modern Taupō area that may have implications for associated faulting and seismic hazard. Surficial faulting is much more obvious in the area studied for this project (Leonard et al., 2010; Langridge et al., 2016), but this in large part relates to the fact that the surface rocks are much older and preserve the topographic expression of fault traces. The youth of the pyroclastic deposits and sediments in the Taupō-Reporoa Basin, in contrast, serve to conceal faults of comparable age. There is the need for further work to characterize the large-scale uplift/subsidence histories in these areas and relate them to processes that might give rise to faulting and associated seismic hazards.

Future work

The next steps involved in this project relate to characterizing magma types, characterising their mineral chemistry, and using amphibole thermobarometry to estimate magma storage depths. These data will be compared with geochemical data from regional ignimbrites and drillhole formations in nearby geothermal fields (e.g. Bégué et al., 2014; Chambefort et al., 2016, McNamara et al., 2016; Milicich et al., 2020; Rosenberg, et al., 2020). Special focus will be given to Whakamaru isotope chemistry (Brown et al., 1998) and how these data relate to the contemporaneous WDB and younger systems. This knowledge will aid understanding of the structural development in this time period regionally, and across the broader Taupō Volcanic Zone. Further consideration will also be given to how magma systems evolve at supervolcanoes in between two large eruptions and whether this is different at other silicic systems globally (e.g. Perry et al. 1990; Lipman, 2000; Hildreth 2004; Fellah, 2011). For example, I hope to consider in these global examples how multiple magma systems have developed through time in parallel with one another, how younger magma systems evolve from older magma systems and what the underlying mechanisms may be to produce such widely distributed, small volume lava eruptions.

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Various ahu whenua trusts	
Victoria University of Wellington Doctoral Scholarship	

Outputs and dissemination

Presentation: A window into magmatic time (340 - 25 ka): How magma systems reorganise between super-eruptions in north and west Taupō, IAVCEI Volcanic Geology Workshop 2019

Presentation: Wellington East Girls College class, 2020

Presentation: ESCI 414 class, SGEES, Victoria University of Wellington, 2021

Links to publications

Barker, S.J., Wilson, C.J.N., Illsley-Kemp, F., Leonard, G.S., Mestel, E.R.H., **Mauriohooho, K.**, Charlier, B.L.A. (2020). Taupō: an overview of New Zealand's youngest supervolcano. New Zealand Journal of Geology and Geophysics 64 (in press, doi: 10.1080/00288306.2020.1792515).

Other papers will be submitted after submission of the thesis.

Conference presentations:

Mauriohooho, K. & Wilson, C., 2017. Magma inception and the birth of a supervolcano. In: Baker, J., Rowe, M. (eds). Abstracts, Geosciences 2017, Auckland, Geoscience Society of New Zealand Miscellaneous Publication **147A**, p. 70.

Mauriohooho, K., Wilson, C.J.N., Leonard, G.S., Chambefort, I. (2019). A window into magmatic time (340-25 ka): how magma systems reorganised between supereruptions in the north Taupo area. Proceedings, IAVCEI 5th Volcanic Geology Workshop, Palmerston North, February 25–March 4, 2019.

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Barker, S., Wilson, C., Illsley-Kemp, F., Leonard, G., Mestel, E., **Mauriohooho, K.**, Charlier, B. (2020). Taupō: what we know (and don't know) about New Zealand's youngest supervolcano. In: Bassett K.N., Nichols A.R.L., Fenton C.H. eds. Geosciences 2020: Abstract Volume. Geoscience Society of New Zealand Miscellaneous Publication 157A, p. 32.

End Users

University and other geoscience research institutions globally and nationally, the MBIE Endeavour Fund ECLIPSE Programme, supervolcano research programs in Italy, United States, Europe, Iwi groups, future researchers, geothermal geology researchers, outreach programs.

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