Journal of the Geological Society, London, Vol. **156**, 1999, pp. 865–868. Printed in Great Britain.

SPECIAL

Small and short-lived magma batches at composite volcanoes: time windows at Tongariro volcano, New Zealand

B. J. HOBDEN[1,2], B. F. HOUGHTON[3], J. P. DAVIDSON[4] & S. D. WEAVER[1]

[1]*Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand*
[2]*Present address: Department of Earth Sciences, The University of Waikato, Private Bag 3105, Hamilton, New Zealand (e-mail: b.hobden@waikato.ac.nz)*
[3]*Institute of Geological & Nuclear Sciences, Private Bag 2000, Taupo, New Zealand*
[4]*Department of Earth & Planetary Sciences, University of California, Los Angeles, CA90095-1567, USA*

Many arc volcanoes are characterized by frequent eruptions of small (<0.1 km^3) volume. A key question is do such small events represent discrete magma batches or do these magmas share a partial common history and to what depths? The last 1000 years of eruptions at Tongariro volcano, New Zealand, offer a series of time-calibrated 'snap shots' of an arc magmatic system. Complex and abrupt changes in magma chemistry at Tongariro attest to the small size (<1 km^3) and short life span (years to decades) of many magma batches and a powerful role for shallow level assimilation, fractional crystallization and mingling in modifying magma compositions on time scales as short as a year.

Keywords: Tongariro volcano, andesite, time scales, magmas, contamination.

Many composite cone volcanoes have a complicated volcanological and magmatic history of short-lived, closely spaced and small volume eruptions, and any comprehensive understanding of the magma batch dynamics is lost if time constraints are not taken into account during petrological modelling. Assessing geochemical trends and patterns *without* secular constraints means that complex petrogenetic trends and relationships often remain undetected. Recent studies have begun to address these concerns at a few composite volcanoes such as Tatara-San Pedro, Chile (Singer *et al.* 1997), Mount Adams, Washington (Hildreth & Lanphere 1994; Hildreth & Fierstein 1997), and Crater Lake, Oregon (Bacon & Druitt 1988; Bacon *et al.* 1994). The Tongariro volcano, a frequently active composite cone in southern Taupo Volcanic Zone, New Zealand (Fig. 1), featured in this study, has the additional advantage of six recorded eruptions since 1870.

At Tongariro, we have combined detailed field mapping and geochronology with new geochemical analyses to examine magma evolution during short time windows of 100 and 1000 years. This approach has provided insights into magma batches at Tongariro: they are typically small (<0.1 km^3) and short-lived (≤1 ka), and compositionally diverse. Even on these time scales the system is multi-process (no single geochemical trend), open (mixing of variably contaminated, isotopically diverse small magma batches), and is not unidirectional (no simple evolution with time).

Tongariro volcano. Tongariro volcano is an ideal subject for this study because of the exposure of numerous chemically and isotopically diverse lava flows and pyroclastic units in well-constrained stratigraphic sequences (Hobden *et al.* 1996; Hobden 1997). The 275 ka eruptive history of the *c.* 60 km^3 volcano has been divided into 17 small (>0.3 km^3) to large (12 km^3) nested and overlapping cones (Fig. 2). There is no orderly progression in space for cone-building events; the locus of activity shifted non-systematically over the lifetime of the complex within a 13 km long and 5 km wide vent corridor, and cone-building at individual vents overlapped in time. Cone growth has varied from short-lived (<10 ka) and rapid (*c.* 1 km^3 ka^{-1}) episodes, to cones where activity lasted for periods of about 50 ka at eruptive rates of less than 0.1 km^3 ka^{-1} (Fig. 2). Andesite is by far the most common rock type, accompanied by lesser volumes of basaltic andesite and, rarely, dacite. As a result of detailed geochronology (Hobden *et al.* 1996) we have been able to evaluate petrological, geochemical and volcanological variations over several time windows varying from 100 years to the lifetime of the entire complex. This study concentrates on the implications of variations found within the shortest time windows of 100 and 1000 years.

One hundred year time window. The historical record of Tongariro volcano spans 130 years, of which eruptions from Ngauruhoe cone in 1870, 1949, 1954 and 1975 have been sampled for this study. Whereas the products of this 106 year interval are principally basaltic andesite to andesite, there are striking variations in composition that can be illustrated on simple variation diagrams such as MgO versus SiO$_2$ (Fig. 3).

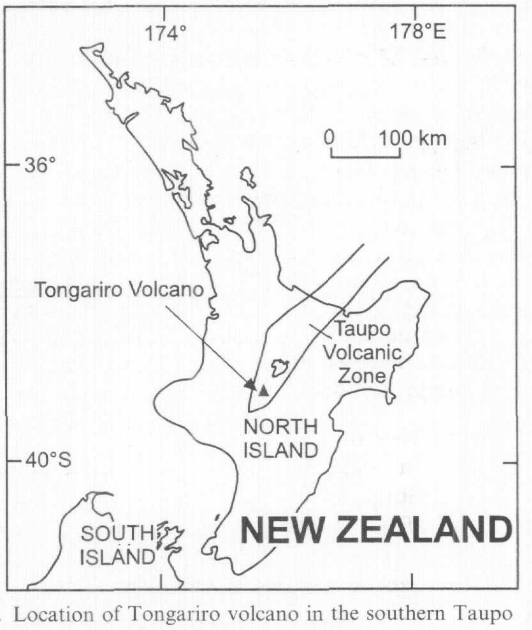

Fig. 1. Location of Tongariro volcano in the southern Taupo Volcanic Zone, North Island, New Zealand.

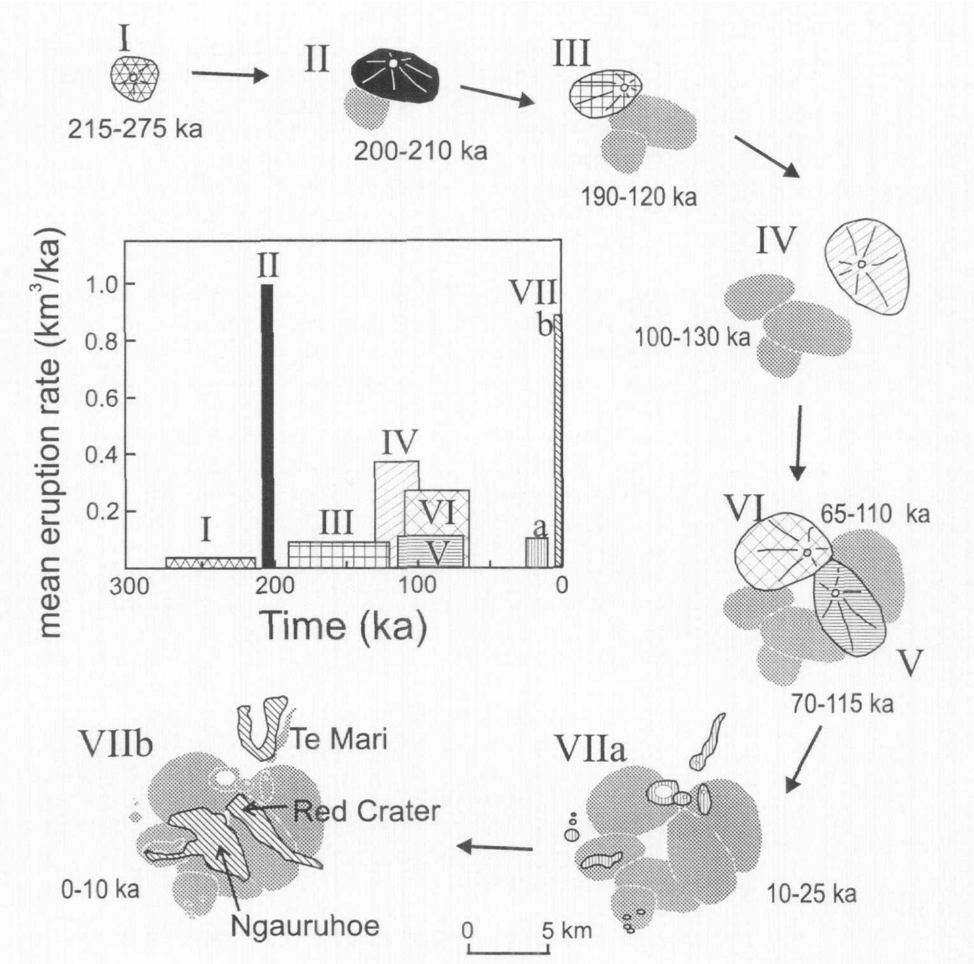

Fig. 2. Schematic representation of the growth of the Tongariro cone complex, showing main periods of cone-building (labelled I to VII), and graphical relationship between mean eruption rate and duration of cone-building.

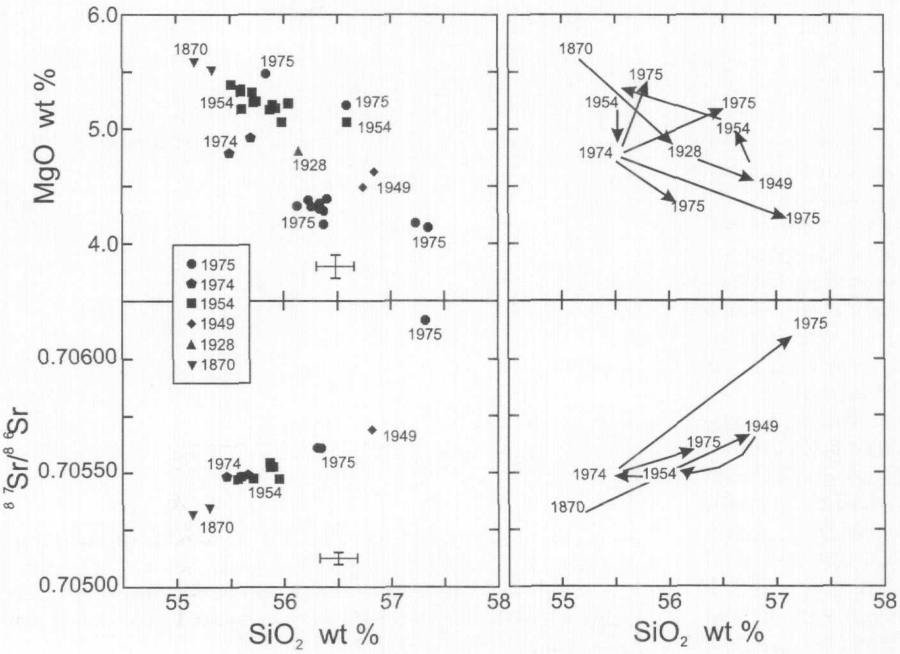

Fig. 3. MgO and $^{87}Sr/^{86}Sr$ plotted v. SiO_2 for historical Ngauruhoe lava flows and pyroclastic products representing 100 year time window. Vectors highlight the apparently random change in composition with time. Error bars for SiO_2 ($\pm$ 0.15 wt%) and MgO ($\pm$ 0.10 wt%) are for 2 standard deviations based on replicate analyses. Two sigma precision for $^{87}Sr/^{86}Sr$ is better than 0.000025.

Table 1. *SiO_2 wt%, MgO wt% and $^{87}Sr/^{86}Sr$ analyses for selected samples*

Sample	Cone/group	Eruption date	SiO_2	MgO	$^{87}Sr/^{86}Sr$
TG010	Ngauruhoe 5	19 Feb. 1975	56.93	4.11	0.706165 ± 14
P39864	Ngauruhoe 5	28 Mar. 1974	55.82	4.82	0.705482 ± 11
TG044	Ngauruhoe 5	18 Aug. 1954	55.59	5.14	0.705521 ± 9
TG042	Ngauruhoe 5	29 July 1954	55.67	5.19	0.705540 ± 10
TG038	Ngauruhoe 5	4 June 1954	55.94	5.38	0.705469 ± 11
TG019	Ngauruhoe 5	9 Feb. 1949	56.51	4.60	0.705686 ± 10
TG001	Ngauruhoe 5	7 July 1870	55.44	5.52	0.705305 ± 10
TG288	Ngauruhoe 4	Prehistorical	57.30	5.41	0.704720 ± 12
TG205	Ngauruhoe 3	Prehistorical	58.03	2.17	0.705268 ± 10
TG020	Ngauruhoe 2	Prehistorical	55.55	3.77	0.704766 ± 13
TG163	Ngauruhoe 1	Prehistorical	55.51	4.70	0.704532 ± 12
TG112	Red Crater	Prehistorical	53.38	7.71	0.704562 ± 10
TG282	Te Mari Crater	Prehistorical	59.86	3.63	Not analysed

There are no progressive changes in composition with time that could be ascribed to (or successfully modelled by) a single process acting on a single batch of magma, such as closed system fractional crystallization. A scatter of data about linear or curvilinear trends suggests that multiple processes are involved: e.g. fractional crystallization punctuated by mafic recharge and magma mixing. For example, the 1954 data signal a return to more mafic compositions (MgO 5.2–5.4%) compared with what was erupted in 1949 (MgO 4.5–4.6%), and, based on the accumulated volume of lava erupted during 1954, suggest the arrival of a small (<0.1 km^3) batch of more primitive new magma which mixed with resident 1949 magma (Fig. 3).

Strong support for the involvement of magma mixing also comes from petrographic evidence such as plagioclase phenocrysts containing zones of glass inclusions (sieve texture) and strong reverse zoning, and Fe/Mg ratios of olivines and pyroxenes which are not in equilibrium with those of their hosts. Ion microprobe studies of mineral phases from Ngauruhoe lavas have also shown complex trace element profiles consistent with a complex history of magma mixing, contamination and crystal fractionation (Rogan & Blake 1994).

Isotopic compositions can also be employed to monitor open system evolution at Ngauruhoe. New $^{87}Sr/^{86}Sr$ data (Table 1) show that there are clear cut short term variations over the one hundred year period (Fig. 3), and even within an interval of less than one year: compare the 1954 lava flows erupted on 4 June ($^{87}Sr/^{86}Sr$ 0.70547), 29 July (0.70554) and 18 August (0.70552). The radiogenic isotopic ratios of magmas do not vary with closed system processes like fractional crystallization, but are sensitive to source differences and contamination by the crust through which the magma must ascend. The occurrence of crustal xenoliths and the isotopic diversity of the historical Ngauruhoe deposits suggests that variable degrees of interaction between magmas and the crust have occurred late in the evolution of magmas at shallow crustal levels over periods as short as 20 years (the notable example being the increase in $^{87}Sr/^{86}Sr$ from 0.70547 in 1954 to as high as 0.70617 in 1975). The variations in magma compositions erupted from Ngauruhoe appear to occur more frequently and more randomly than some other documented historical eruption sequences at composite cones (e.g. Reagan *et al.* 1987).

One thousand year time window. When considering a period of 1000 years, our spatial dimension widens to include more than one cone and more than one vent. Ngauruhoe cone is estimated to have grown over the last 2500 years (Topping 1974), with most of the sampled lavas erupted in the last 1800 years. These historical and prehistorical flows from Ngauruhoe were interspersed with the eruption of young lava flows from Red Crater, and in *c.* AD 1500 (Topping 1974) from Upper Te Mari Crater (Fig. 2).

Over this longer time interval, the Ngauruhoe products may be divided into five distinct groups in age order 1–5 (which lie within period VIIb of Fig. 2) on the basis of both stratigraphy and composition (Fig. 4). The observed geochemical variability in the historical 100 year time window extends to the 1000 year window of cone activity. Compositional range

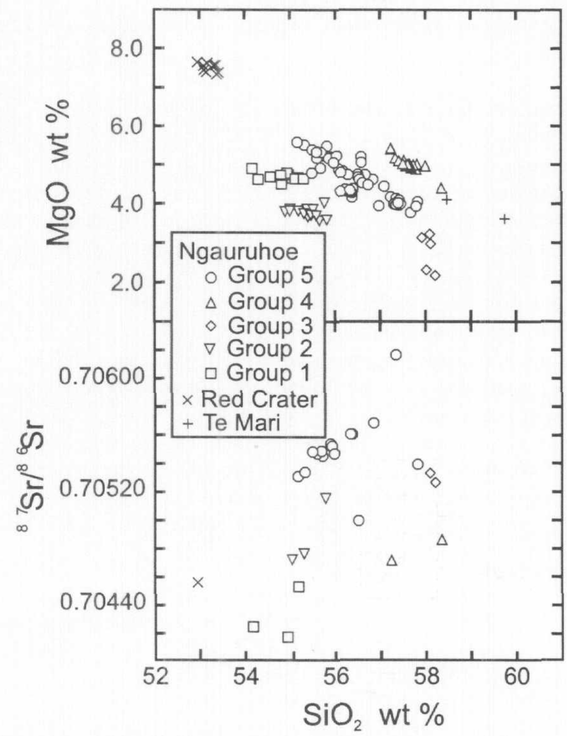

Fig. 4. MgO and $^{87}Sr/^{86}Sr$ plotted v. SiO_2 for products erupted from Upper Te Mari Crater, Red Crater and Ngauruhoe in a 1000 year time window. See Fig. 2 for location of cones. Ngauruhoe flows are divided into five groups (1=oldest, 5=youngest). Errors are less than size of symbols.

broadens with this longer time scale: on the MgO–SiO_2 plot the samples from the last 130 years (Fig. 3) plot with the youngest of the prehistorical samples (to form Group 5), which all scatter about a single broad trend, whereas the older prehistorical Ngauruhoe lavas belong to four other distinct groups or trends (Groups 1, 2, 3 and 4) which occupy different regions both on the diagram (Fig. 4) and on the cone.

When we add data from the other vents active in the last 1000 years, we also see abrupt and non-systematic changes in composition with time (which also exist within the groups): from the relatively evolved Te Mari eruptive units, back-tracking to the much more primitive cluster of Red Crater samples, then to a compositional loop which takes in the Ngauruhoe groups 1, 2, 3 and 4, then the youngest group 5 (Fig. 4). These patterns definitely cannot be attributed to closed system fractionation, but instead signal the involvement of many different small batches of magma introduced into and mixing in a complex plumbing system. The relative independence of chemical trends for products erupted from the three vents (Ngauruhoe, Red Crater and Te Mari Crater), spread over a 6 km distance (Fig. 2), suggest that magmatic pathways during this 1000 year interval of volcanism were short-lived and of limited cross-sectional area.

On Figs 3 and 4 there is not one simple (single) assimilation fractional crystallization (AFC) trend linking magma batches from different eruptions, and, knowing the time relationships of the data, we can see that there are inconsistent age relationships along the broad AFC 'trend' (e.g. Fig. 3), or, perhaps more accurately, that there are multiple AFC trends (Fig. 4). These reflect the variable degrees of crustal interaction by different magma batches (different ascent paths and residence times in a complex plumbing system) and also the composition of the heterogeneous Mesozoic metasedimentary basement they encounter at different locations within the subvolcanic domain.

Implications for size and lifespan of magma batches. Longer time windows at Tongariro, say 10 000 years, show larger scale trends not always detectable in the smaller time windows, such as extremes in volume discharge which include dacite Plinian events from multiple vents (Nairn *et al.* 1998), and the alternation of intervals of rapid cone-building with more moderate production or quiescence (Fig. 2). Inconsistent age-composition relationships (in which samples which follow each other in eruption sequences are not progressively more differentiated with time) point to open-system differentiation processes operating on the numerous magma batches whose eruption has contributed to cone growth. However this compositional variability is more difficult to characterise fully over these extended time intervals with less precise time constraints and poorer degrees of preservation and exposure.

By examining compositional variation within well-constrained narrow time windows, we have found that numerous small (<0.1 km^3) and short-lived (≤ 1 ka) magma batches are frequently erupted from a complex plumbing system beneath Tongariro. We conclude that small magma batches ascend and occasionally reside temporarily at higher levels in a complex system of narrow conduits and small holding chambers. This geometry may allow varying degrees of interaction with the heterogeneous Mesozoic basement, and the repeated injection of less-fractionated magma into the high level plumbing system which in turn initiates episodes of magma mixing on time scales as short as years.

Supported by a NZ Universities' Postgraduate Scholarship (B.J.H.), a MoRST Postgraduate Scholarship (B.J.H.), the University of Canterbury Mason Trust (B.J.H.), and the NZ Foundation for Research, Science and Technology (B.F.H.). We thank M. A. Lanphere (US Geological Survey) for providing new K Ar age determinations, and M. F. Thirlwall (Royal Holloway, University of London) in whose lab some of the Sr isotope analyses were obtained (others obtained at UCLA with thanks to J. Hora, analyst). Helpful reviews of the manuscript were provided by W. Hildreth, S. Blake and N. W. Rogers.

References

Bacon, C.R. & Druitt, T.H. 1988. Compositional evolution of the zoned calcalkaline magma chamber of Mount Mazama, Crater Lake, Oregon. *Contributions to Mineralogy and Petrology*, **98**, 224–256.

—, Gunn, S.H., Lanphere, M.A. & Wooden, J.L. 1994. Multiple isotopic components in Quaternary volcanic rocks of the Cascade arc near Crater Lake, Oregon. *Journal of Petrology*, **35**, 1521–1556.

Hildreth, W. & Fierstein, J. 1997. Recent eruptions of Mount Adams, Washington Cascades, USA. *Bulletin of Volcanology*, **58**, 472–490.

— & Lanphere, M.A. 1994. Potassium-argon geochronology of a basalt-andesite-dacite arc system: The Mount Adams volcanic field, Cascade Range of southern Washington. *Geological Society of America Bulletin*, **106**, 1413–1429.

Hobden, B.J. 1997. *Modelling magmatic trends in time and space: eruptive and magmatic history of Tongariro volcanic complex, New Zealand*. PhD thesis, University of Canterbury.

—, Houghton, B.F., Lanphere, M.A. & Nairn, I.A. 1996. Growth of the Tongariro volcanic complex: new evidence from K-Ar age determinations. *New Zealand Journal of Geology and Geophysics*, **39**, 151–154.

Nairn, I.A., Kobayashi, T. & Nakagawa, M. 1998. The ~10 ka multiple vent pyroclastic eruption sequence at Tongariro Volcanic Centre, Taupo Volcanic Zone, New Zealand: Part I. Eruptive processes during regional extension. *Journal of Volcanology and Geothermal Research*, **86**, 19–44.

Reagan, M.K., Gill, J.B., Malavassi, E., Garcia, M.O. 1987. Changes in magma composition at Arenal volcano, Costa Rica, 1968–1985: Real-time monitoring of open-system differentiation. *Bulletin of Volcanology*, **49**, 415–434.

Rogan, W. & Blake, S. 1994. Trace element zonation of phenocrysts from Ngauruhoe Volcano, New Zealand: Constraints on magmatic processes. *Mineral Magazine*, **58A**, 783–784.

Singer, B.S., Thompson, R.A., Dungan, M.A., Feeley, T.C., Nelson, S.T., Pickens, J.C., Brown, L.L., Wulff, A.W., Davidson, J.P. & Metzger, J. 1997. Volcanism and erosion during the past 930 k.y. at the Tatara-San Pedro complex, Chilean Andes. *Geological Society of America Bulletin*, **109**, 127–142.

Topping, W.W. 1974. *Some aspects of Quaternary history of Tongariro Volcanic Centre*. PhD thesis, Victoria University of Wellington.

Received 16 February 1999; revised typescript accepted 8 April 1999.
Scientific editing by Nick Rogers.