

Geological Society of New Zealand



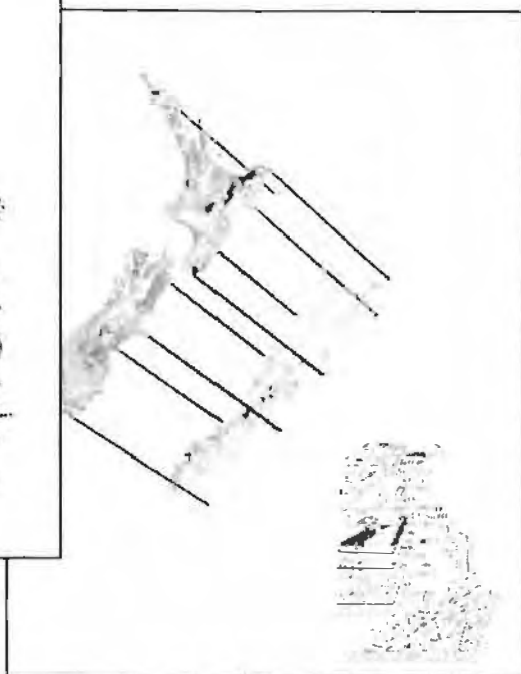
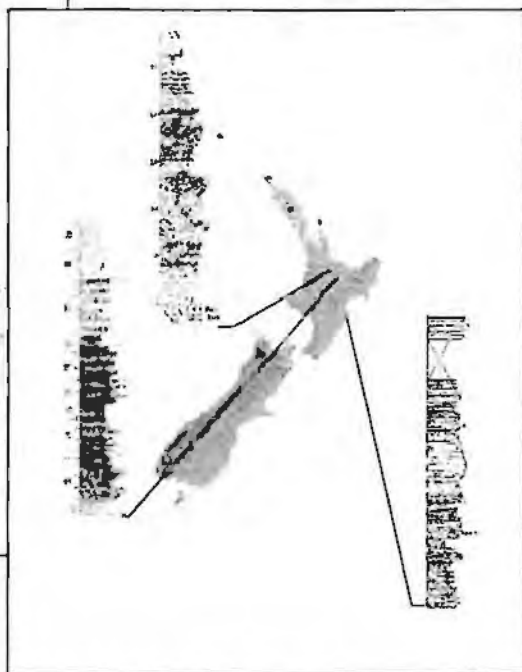
Annual Conference 2001

27th - 29th November, Hamilton

"Advances in Geosciences"



The University of Waikato
Te Whare Wānanga o Waikato



Fieldtrip Guides

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Fieldtrip Guides



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2001 CONFERENCE FIELD TRIPS

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Pre-Conference Field Trips, Monday 26 November

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Acknowledgements

The organizing committee is very grateful to all the field trip leaders for their valued contribution to the success and diversity of the 2001 GSNZ annual conference.

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Field Trip FT7

Growth and Magmatic Evolution of Tongariro and Ruapehu Volcanoes, New Zealand

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The aim of this excursion is to examine new work on the eruptive and magmatic histories of Tongariro and Ruapehu Volcanoes. By integrating geochemical and isotopic analyses within a well-constrained framework of geochronology and volcanic stratigraphy, our studies have shown that growth of these andesite cone volcanoes involves multiple small batches of magma whose compositions are strongly modified in complex, probably polybaric plumbing systems on time scales as short as a year. Rapid production and ascent of magma is a characteristic of the Quaternary history of both the silicic and andesitic portions of Taupo Volcanic Zone (TVZ). Central TVZ is dominated by two exceptionally active rhyolitic calderas, Okataina and Taupo, while the landscape of the southern TVZ is dominated by two highly active composite volcanoes, Tongariro and Ruapehu. There are strong similarities between Tongariro and Ruapehu (compare for example Hobden et al., 1999 with Gamble et al., 1999).

The itinerary for this three-day excursion is summarised below.

Thursday 29 November: Depart University of Waikato around 4.00 p.m. at close of conference (time to be confirmed). Drive south on State Highway 1 from Hamilton to Ruapehu, with stop in Taupo for evening meal. Stay at the Skotel in Whakapapa Village for next 3 nights.

Friday 30 November (Day 1): Traverse of the Tongariro volcanic complex (c.8 hour hike) to examine the complexities and variety of cone-building processes, including the most recent flows from Ngauruhoe volcano.

Saturday 1 December (Day 2): Examine lava flows in the Whakapapa skifield area and, weather permitting, visit the crater lake at the summit of Ruapehu (c.4 hour round trip hike from top of chairlifts).

Sunday 2 December (Day 3): Visit the southern flanks of Ruapehu to examine the stratigraphy of lava flow sequences and age relationships of tephra cover beds in the Turoa-Mangaturuturu valley area (c.2 hour round trip walk). Drive back to Hamilton, arriving late afternoon/early evening.

Day 1 (Friday) - Geology of the Tongariro Volcano Traverse

Introduction

Tongariro is a c.60 km³ composite structure built from the overlapping products of at least 6 early cones (erupted between 275 and 65 ka) and 11 cones/vents younger than 25 ka erupted from a "vent corridor" roughly 5 kilometres wide and 13 kilometres in length (Fig 1).

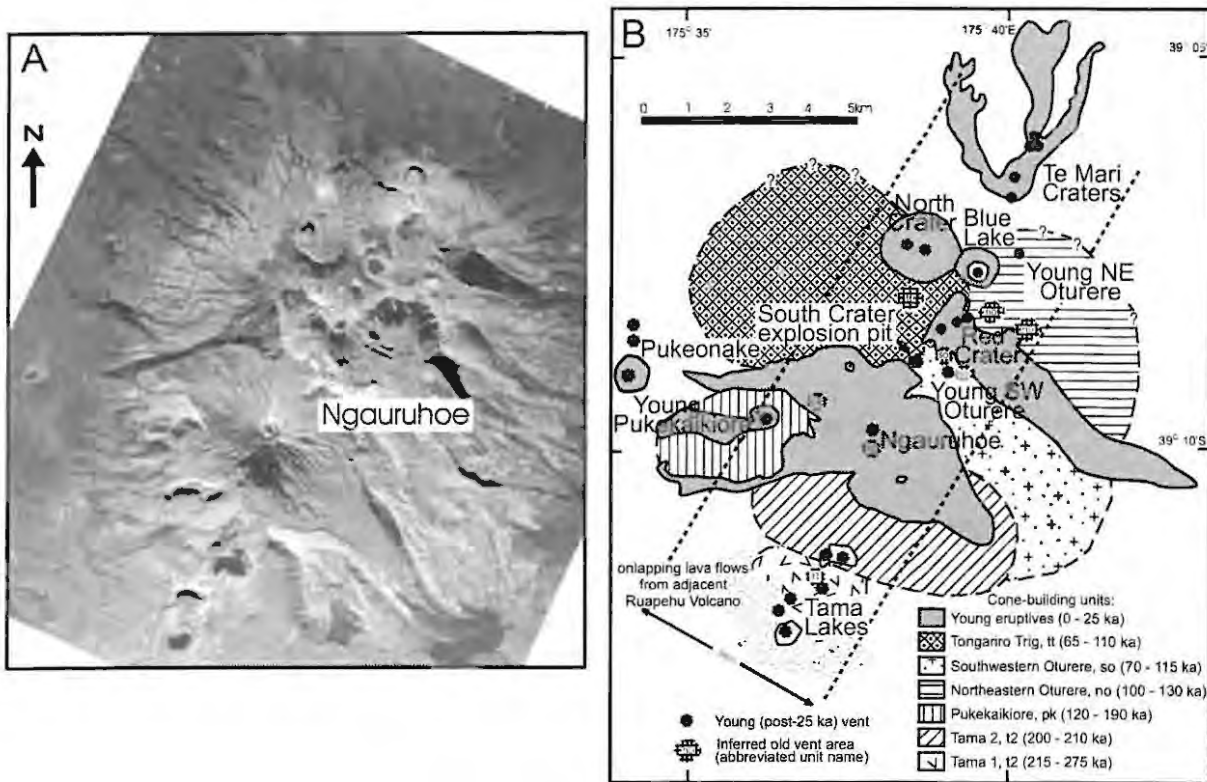


Figure 1: A Vertical aerial photograph of Tongariro (NZ Aerial Mapping Ltd). B Map of cone-building and young eruptive units of Tongariro composite volcano, New Zealand. (after Hobden et al., in press).

The symmetrical young cone of Ngauruhoe forms the highest part of the complex (2287 m above sea level) and is the best-constrained “subunit” of the cone complex. Tongariro’s geometry of clustered, coalescing, and overlapping cones is perhaps superficially more complex than Ruapehu but the two volcanoes have been inferred to have similar patterns of growth, involving multiple small magma batches, whose compositions are strongly modified by shallow level assimilation, fractional crystallisation and mingling in modifying magma compositions on time scales as short as a year.

Tongariro has been the focus of an intensive study involving numerous colleagues including Bruce Houghton, Ian Nairn, Marvin Lanphere, Steve Weaver, David Shelley, Matthew Thirlwall, Nelson Eby, Jon Davidson, and John Hora. This study has been designed to understand the dynamics of evolution, ascent and eruption of andesitic magma over “time windows” ranging in scale from less than one year (e.g. the duration of the 1954 Ngauruhoe eruption) to more than 10 000 years (life spans of the older Tongariro cones). Re-mapping of the volcano at a scale of 1:12500 was followed by an intensive programme of K-Ar and Ar-Ar age determinations at USGS, Menlo Park (Hobden et al., 1996). We have then performed major and trace element and isotopic analysis on well-constrained Tongariro lavas (Hobden, 1997, Hobden et al., 1999). These data offer a picture of a complex plumbing system in which small ($\ll 0.1 \text{ km}^3$), short-lived ($\leq 1 \text{ ky}$) and geochemically distinctive magma batches undergo polybaric fractional crystallisation at a variety of crustal levels. The small magma batches ascend and occasionally reside temporarily at higher levels in a complex system of conduits and small holding chambers. This geometry allows 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.

In the current phase of the study we are using the historical lava sequence to document the extent to which successive magma batches at Ngauruhoe share common histories in their magma reservoirs. To test our model of frequent recharge and short magma residence times we are comparing the whole rock evidence with isotopic and chemical disequilibria recorded in Ngauruhoe crystals and liquids. Analysis of crystal Sr isotopic compositions of historical lavas indicates disequilibrium between crystals and groundmass, between phenocryst phases in the same lava, between different size populations of the same phase, and between zones within a single crystal (Hobden et al., 2000b; Hora et al., 2000a, 2000b). The evidence strongly suggests that many of the ‘phenocrysts’ in Ngauruhoe lavas should be regarded as entrained ‘xenocrystic’ remnants of earlier magma batches or the crust, which mingled with variably contaminated magmas to produce the lava sampled at the surface. We are also

investigating how the degree of U-Th and Ra-Th isotope disequilibria in as near liquid compositions as possible vary with the degree of differentiation. Preliminary results indicate that U-Th isotopic disequilibria do exist between eruptions (Hobden et al., 2001). The disequilibria may be linked to the repeated injection and eruption of short-lived magma batches, a process that we expect would repeatedly reset or significantly disturb the isotopic system.

Volcanic stratigraphy and eruptive history

We divide Tongariro volcano into 17 volcano-stratigraphic units (Hobden et al., 1996), a significant refinement of the previous broad division into an older group (>20 ka) of strongly eroded lavas, and a younger group (<20 ka) of lavas which display un-eroded volcanic morphology (Mathews, 1967; Topping, 1974; Cole and Nairn, 1975; Cole, 1978). There is no orderly progression in space for cone-building events; the locus of activity has shifted non-systematically over the lifetime of the complex, and cone-building at individual vents has overlapped in time. The inferred older vent areas are roughly aligned SW-NE, very similar to the modern vent configuration, and their combined distribution defines a 13 km-long and 5 km-wide vent corridor (Fig 1). The persistent cone-building activity documented for Tongariro indicates the magmatic system has remained almost constantly activated over the volcano's known lifetime. Formation of the Tongariro complex may have been virtually continuous, but this growth did not occur at a steady rate. Cone growth has varied from short-lived (<10 ky) and rapid (c.1 km³/ky) episodes, to periods of activity lasting about 50 ky at eruptive rates of less than 0.1 km³/ky (Fig 2; Hobden et al., 1999).

The magnitudes and range of cone lifetimes and eruptive rates at Tongariro are similar to those found for the few other well-documented large composite volcanoes such as Mount Adams (Hildreth and Lanphere, 1994) and Tatará-San Pedro (Singer et al., 1997; Dungan et al., 2001). The pattern of growth seen at Mount Adams (Hildreth and Lanphere, 1994) of several intense growth spurts with high magma production rates, interspersed with much longer periods of sporadic, low-level background activity is shared by Tongariro. The periods of peak productivity add significant volumes to the cone complex over relatively short periods of time.

Characteristics of the volcano-stratigraphic units recognised on Tongariro volcano are summarised in Table 1. The earliest known history of the complex is recorded in the hornblende-bearing silicic andesite lava flow and dome remnants exposed in the Tama Lakes area (**Tama 1 cone**; c.275-215 ka), which appear to have been comparatively small in volume (c.2 km³) with a low eruptive rate of 0.03 km³/ky. Activity remained focused in the south of the complex with the rapid growth (1.00 km³/ky) of the large (c.10 km³) **Tama 2 cone** between c.210 and 200 ka. At least 55 hornblende-phyric andesite lava flows have been mapped dipping southwards away from hydrothermally altered vent breccias exposed on the flanks of Ngauruhoe.

The final phase of this concentration of hornblende-andesite production in the southern portion of the complex is represented by the eroded remnants of **Pukekaikiore cone**, situated just west of the Tama centres. This cone, of moderate proportions (c.6 km³ original volume) and low eruptive rate (0.09 km³/ky), was active between c.190 and 120 ka, producing thick, columnar-jointed silicic andesite flows from a vent now concealed beneath Ngauruhoe.

The first obvious indication of the SW-NE vent corridor which dominates the overall Tongariro vent configuration is provided by the **NE Oturere cone**, which represents a shift in vent location from the south to the northeast when an intense period of activity commenced around 130 ka (Fig 1). Between 130 and 100 ka the bulk of the c.11 km³ cone was formed (0.37 km³/ky) by eruption of more than 70 andesitic block lava flows and intercalated scoria-tuff deposits, now exposed as thick stratigraphic sequences (bounded by angular unconformities) in the glacial valley wall. Erosion of the glacial valley is believed to have removed most of the central vent facies for the NE Oturere cone, although some remnants of proximal fall deposits and hydrothermally altered vent breccias are preserved in the upper valley wall.

As activity waned in the northeast, the central portion of Tongariro grew from material erupted synchronously from two cones, **SW Oturere** and **Tongariro Trig**, between 115 and 65 ka. Thick stacks of andesitic-dacitic autobrecciated lavas, pyroclastic and epiclastic deposits are exposed along the walls of the SW Oturere and north Mangatepopo valleys and South-Central Crater. The **Tongariro Trig cone** appears to have originally been larger (12 km³) and more productive (0.27 km³/ky) than the **SW Oturere cone** (5 km³, 0.11 km³/ky), although the SW Oturere cone preserves evidence of a greater number of flows and pyroclastic units (c.65)

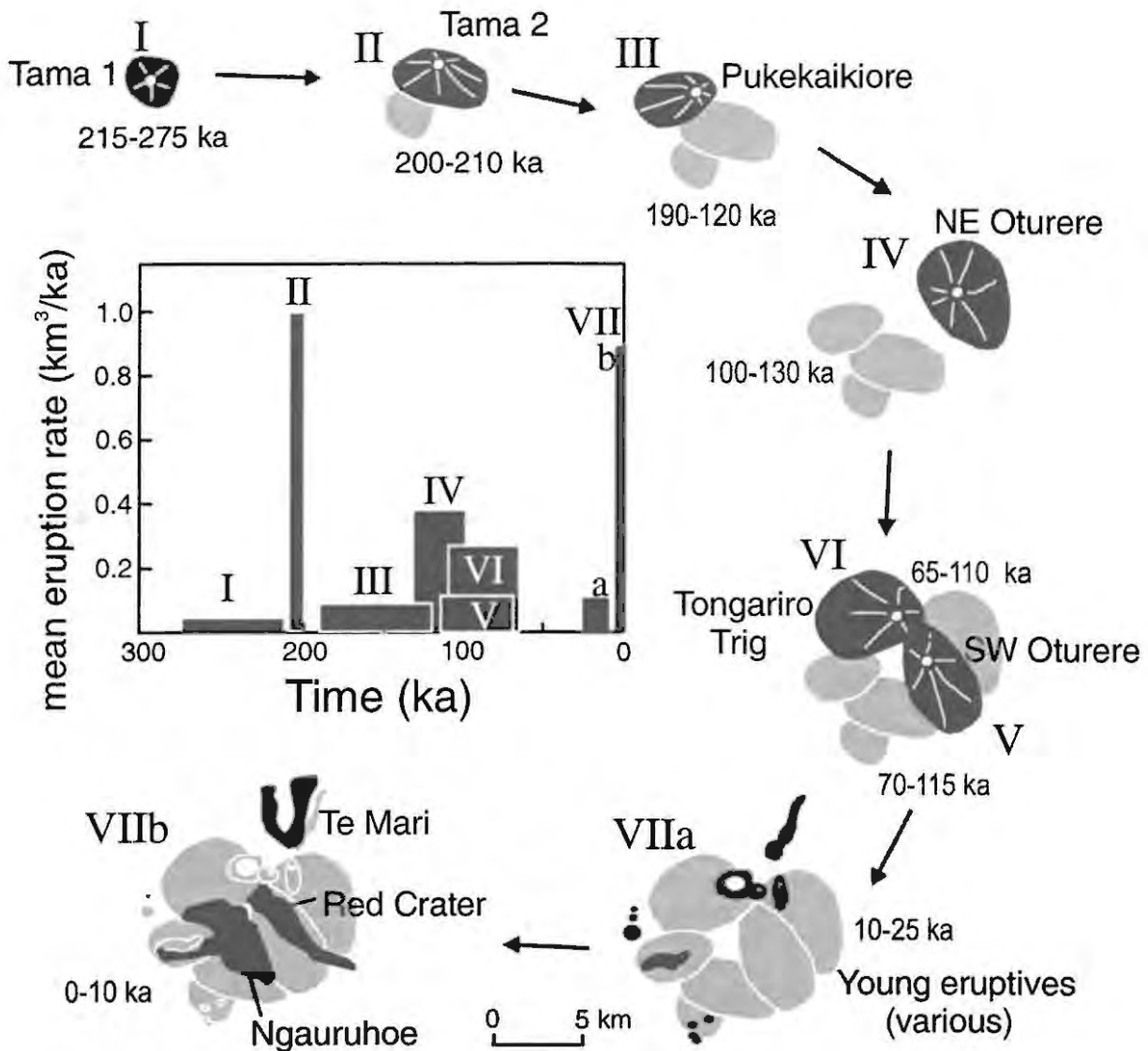


Figure 2: Schematic representation of the growth of the Tongariro cone complex, showing main periods of cone-building (labelled I to VII, see Fig 1 for detail), and graphical relationship between mean eruption rate and duration of cone-building. (after Hobden et al., 1999)

compared to the Tongariro Trig cone (c.45). Vent areas can be recognised for both cones, in the form of extensively hydrothermally-altered lavas and lapilli-tuff breccias, dike-like intrusive bodies, proximal scoria and spatter deposits, and lava flows with steep and opposing dips.

Following a possible lull in eruptive activity between c.65 and 25 ka, (or, more plausibly, after erosion of rocks of this age range during the Otiran Glaciation (c.70-10 ka; Pillans, 1994)), the complex system of vents comprising the “young eruptives”, small-volume cones and pyroclastic deposits, was established on the eroded remnants of the six older cone-forming units (Fig 1). Recognisable original morphologies of both cones and flows have been preserved for most of these units, and they dominate the broad summit landscape and skyline. These young eruptives were typically more mafic than those erupted previously, with generally higher proportions of olivine-bearing basaltic andesites. Tongariro’s postglacial history of explosive volcanism is also well established from ¹⁴C age determinations and tephrostratigraphy (Topping, 1973; Donoghue et al., 1995; Cronin and Neall, 1997, Nairn et al., 1998) and includes approximately 80 eruptions in historical times (Cole and Nairn, 1975).

The basaltic andesite **Pukeonake** scoria cone, lava flows, and associated vents formed c.23 ka and represent the only known eruptions *peripheral* to the main Tongariro complex. At this time, back on the main edifice, a

Table 1: Summary characteristics of Tongariro volcano-stratigraphic units (BA = basaltic andesite, A = andesite, D = dacite; oliv = olivine, hbl = hornblende).

Volcano-stratigraphic unit	Approx. age (ka)	Present volume (km ³)	Original volume (km ³)	Eruptive rate (km ³ /ka)	Approx. No. of flows	Proximal eruptive products	Rock type	SiO ₂ wt% range
Ngauruhoe	0-2.5	2.2	2.2	0.88	80	Aa - block lava flows, scoria cone, pyroclastic avalanches, ballistic blocks.	oliv BA - A	54.2 - 58.6
South Crater explosion pit	1.8-c.2	<<0.01	<<0.01		<<5	Scoria bomb and block deposit.	A	57.8
Red Crater	0-c.3	0.5 - 0.7	0.5 - 0.7	0.17 - 0.23	15	Transitional pahoehoe to aa and aa to block lava flows, scoria cone, dikes.	oliv BA - A	53.0 - 61.1
Tama Lakes	c.10	0.1	0.1		10	Pumice-lapilli-ash fall deposits, scoria bombs, welded scoria fall deposits.	aphyric BA - D	56.1 - 64.2
Te Mari Craters	0-14+	0.2	0.2		15	Lava flows, ballistic blocks, vent tuff breccia.	A	57.5 - 60.2
Young SW Oturere	c.10-14	<<0.01	<<0.01		<5	Welded scoria fall deposit.	aphyric BA - A	55.0 - 57.4
Young Pukekaikiore	c.15	<0.1	<0.1		<5	Scoria mound, lava flows.	oliv A	56.9 - 57.4
North Crater	c.10-15	0.5	0.5		25	Welded tuffs & agglutinates, lava spatter cone, lava lake, scoria fall and flow deposits, ballistic blocks.	oliv BA - A	56.3 - 60.1
Blue Lake	c.10-20	0.1	0.1		15	Welded tuffs & agglutinates, lava spatter cone, scoria fall deposits, ballistic blocks.	oliv A	56.8 - 59.9
Pukeonake	c.23	0.3	0.5		10	Scoria cone, lava flows.	oliv BA	56.5 - 57.0
Young NE Oturere	c.20+	<<0.01	<<0.01		<5	Welded scoria fall deposit.	A	57.6 - 58.1
Tongariro Trig	65-110	10 ± 4	12 ± 5	0.27 ± 0.11	45	Welded tuffs and agglutinates, lava flows, scoriaceous tuff breccias, lapilli tuff, vent breccias.	A - D	57.0 - 62.3
SW Oturere	70-115	3 ± 1	5 ± 2	0.11 ± 0.05	65	Lava flows (some ponded and overthickened), welded agglutinates, scoria cone, tuff breccias.	A - D	57.2 - 65.5
Pukekaikiore	120-190	2 ± 0.5	6 ± 2	0.09 ± 0.02	15	Lava flows (some ponded and overthickened).	hbl A	59.8 - 61.8
Tama 2	200-210	6 ± 1	10 ± 2	1.00 ± 0.20	55	Lava flows, pumice flow deposit, tuff breccias.	BA - hbl A	56.4 - 63.0
NE Oturere	90-250	5 ± 1	11 ± 2	0.37 ± 0.07 (main period 100-	75	Lava flows, welded agglutinates, tuffaceous scoria cone, pyrocl. surge deposits, tuff breccias, scoria fall deposits.	oliv BA - A	55.4 - 62.2
Tama 1	215-275	1 ± 0.5	2 ± 1	0.03 ± 0.02	10	Lava flows and domes.	hbl A	59.5 - 62.6

cluster of small cones was starting to form on the north flanks. The **Young NE Oturere** scoria fall deposit, **Blue Lake** spatter cone, **North Crater** spatter cone and lava lake, and **Te Mari Crater** cone were constructed c.25-10 ka. Explosive eruptions also occurred further to the south (**Young SW Oturere** scoria deposit, **Tama Lakes** explosions) and west (**Young Pukekaikiore** scoria deposit and lava flows) during the same time interval. Many of these eruptions occurred around 10 ka, during a period of intensive volcanic activity and peak productivity of magma for the Tongariro complex (Nairn et al., 1998, Nakagawa et al., 1998).

The most recent activity has taken place within the last 3 ka from new vents near the centre of the complex. Eruptions from the **Red Crater** vent have built up a small scoria cone and sent small to large lava flows in many directions, with ash and steam eruptions occurring last century. The **Upper Te Mari Crater** has also erupted historically, but has not produced a lava flow since c.1500AD. By far the most productive of all the post-glacial vents has been that of **Ngauruhoe**, which has issued numerous lava flows (c.70 exposed) and rapidly built a 2.2 km³ cone within its 2.5 ka lifetime at an average rate of 0.88 km³/ky. Ngauruhoe has been frequently active in historic times, most recently in 1975.

Products and styles of volcanism

Moderately to strongly porphyritic andesite is by far the most common rock type on Tongariro, accompanied by lesser volumes of basaltic andesite and, rarely, dacite. Tongariro comprises a wide variety of erupted products, which often occur together in vertical successions (e.g. NE Oturere Valley wall) characterised by rapid lithological changes and complex alternations of dominant lava flows with minor pyroclastic and epiclastic deposits. A lateral change or partitioning in eruptive products (related to preservation) is also evident; lava flows dominate the proximal cone whereas widespread pyroclastic fall deposits and reworked volcanoclastic material dominate the distal part of the volcanic complex. There is no obvious progression or pattern to the occurrence of different eruptive styles through time.

The styles of volcanism exhibited by Tongariro can be summarised as:

1. repeated effusion of numerous aa and block lava flows from many summit and flank vents, with some lavas extending up to 7 km down valleys towards the ring plain,
2. frequent hawaiian to strombolian fire fountaining eruptions, and the occasional formation of lava lakes ponded in craters, forming significant but localised welded spatter deposits and scoria cones,
3. small phreatic to phreatomagmatic eruptions creating explosion craters or tuff cones and pyroclastic surge deposits, often associated with scoria cone growth,
4. vulcanian style eruptions with associated pyroclastic flows and ejection of ballistic blocks, the frequency of which is difficult to determine due to low preservation potential,
5. relatively infrequent generally dacitic subplinian to plinian eruptions which deposit extensive tephra on the ring plain.

Extrusion of basaltic andesite to andesite block and aa lava flows has been the principal means of cone construction for Tongariro, and these are evident as young, channel/valley-filling flows and older cone-forming sequences everywhere around the complex. Lava domes are seldom seen, (or perhaps preserved) and exposures of dikes are likewise very rare. One solidified lava lake can be recognised in North Crater. Rheomorphic welded tuffs and agglutinates are present around North Crater, Blue Lake and Tongariro Trig, but otherwise pyroclastic fall deposits form only minor to locally significant outcrops on the volcano (welded spatter deposits, scoria cones, ballistic blocks), where their preservation chiefly depends on welding or burial by lava flows. Non-welded fall material is rare in the cone-forming sequences due to rapid erosion and re-working, but is of course an important constituent of the medial-distal tephra deposits on the ring plain. Several small volume pyroclastic flow and surge deposits are preserved on Tongariro; most notably the block-and-ash flows erupted from Ngauruhoe in 1975. Epiclastic deposits encountered on the Tongariro cones include pyroclastic material reworked or redeposited by debris avalanches, mudflows, and streamflows, although most evidence for such processes is preserved again only on the ring plain.

The styles, and therefore the products, of Tongariro volcanism are probably determined by a complex interplay of controlling factors including, but not limited to, magma composition. Magma composition will influence controls such as temperature, viscosity, yield strength, and pre-eruptive volatile content of the magma but we feel changes in eruptive style are more affected by variations in the rates of magma ascent, with their obvious implications for the extents of magma degassing, undercooling and syn-eruptive crystallization of microlites. Physical aspects of the vent and conduit (e.g. diameter, presence of blockage) and the geometry of the upper cone (e.g. slope angle, presence or absence of barriers and channels) also contribute to the diversity and

distribution of eruptive products, including flow direction, length, aspect ratio and surface morphology of lava flows.

Magma evolution in time and space

Tongariro is an excellent laboratory for studying the petrological evolution of a composite volcano - there is now a very good data base of absolute age data, well exposed products of numerous historical eruptions, and excellent exposure of the products of older portions of the complex in valleys cut during the last glaciation. Previous work on Tongariro petrology was mainly focused on chemical and isotopic analyses of historical eruptions and some of the young post-glacial eruptives (e.g. Steiner, 1958; Ewart and Stipp, 1968; Topping, 1974; Nairn et al., 1976; Cole, 1978; Cole et al., 1983). Graham and Hackett (1987) included some Tongariro lavas in their petrology-based classification scheme for Ruapehu lavas, later applied to all TVZ andesites (Graham et al., 1995). Patterson and Graham (1988) published some of the few data (prior to this study) on older portions of the Tongariro complex, and added a further magma type to Graham and Hackett's (1987) scheme. Graham et al., (1992) included several Tongariro samples in their TVZ Pb isotope study, and Gamble et al., (1993, 1996) presented data on Red Crater.

The eruptive products sampled from Tongariro range almost continuously in composition from 53.0 to 64.2 wt% SiO₂ and are dominated by andesites, accompanied by minor basaltic andesites and dacites (Fig 3). Variation diagrams such as Fig 4 are most usefully considered within the context of volcanological constraints. When we place time, space and volume restrictions on the interpretation of such diagrams, the broad trend of many data points is shown to conceal a large number of complex petrogenetic relationships on a range of scales. By examining chemical and isotopic variation within a framework of the established volcanic stratigraphy, we can view Tongariro's magma evolution as a series of time-calibrated "snap shots" of an arc magmatic system. Owing to the large number of volcano-stratigraphic units, we will limit our discussion here to a general summary of overall Tongariro relationships, followed by the case study of Ngauruhoe cone.

There are varying degrees of similarity and diversity between and within the Tongariro volcano-stratigraphic units. Selected chemical and isotopic data are presented in Table 2. Variation diagrams can highlight the differences which exist between and within units in terms of absolute major and trace element abundances for given SiO₂ contents, degree of compositional variability (length of trends), rate of compositional change with respect to SiO₂ (steepness of trends), shape of trends (curvilinear versus linear), conformity of data points to trends (scattered versus tight trends), and distribution of chemical groups within observed SiO₂ ranges.

The older (c.275-160 ka) southern andesite cones of Tama 1, Tama 2 and Pukekaikiore are distinguished by the presence of hornblende phenocrysts, relatively high silica (up to 63 wt%), higher K/Rb for a given SiO₂ content, and comparatively low K₂O, Rb, La, Ce, Y and Zr abundances relative to other Tongariro units. The c.130-90 ka olivine basaltic andesite to andesite NE Oturere cone represents a significant change to more mafic compositions (up to 7.1 wt% MgO) and strong evidence for disequilibrium and mixing of multiple magma batches, with relatively low ⁸⁷Sr/⁸⁶Sr (0.704600 - 0.704980). Another contrast is then provided by the c.110-65 ka low-MgO (down to 1.8 wt%) andesite-dacite cones of SW Oturere and Tongariro Trig, which also exhibit widely ranging ⁸⁷Sr/⁸⁶Sr (0.704876-0.706193). The close spatial and temporal proximity of the young (c.20-0 ka) northern andesite cones and eruptives of Young NE Oturere, Blue Lake, North Crater, Te Mari Craters and pre-1.8 ka Red Crater is mirrored by their similar geochemical traits, including similar K/Rb and Rb/Zr, and ⁸⁷Sr/⁸⁶Sr ranging 0.705126-0.705700. The c.14-10 ka southern basaltic andesite to dacite eruptives from Young SW Oturere and Tama Lakes share overlapping low-MgO (down to 1.1 wt%) trends spanning a wide compositional range (55.0 - 64.2 wt% SiO₂). The young (c.23-0 ka) olivine basaltic andesite to andesite eruptives from Pukeonake, young Pukekaikiore, and post-1.8 ka Red Crater represent some of the most extreme compositions erupted from Tongariro, with the highest MgO (6.9 - 9.2 wt%) and among the least radiogenic ⁸⁷Sr/⁸⁶Sr (0.704442-0.704758) values. The historically active (c.2.5-0 ka) olivine-bearing basaltic andesite to andesite Ngauruhoe cone occupies an almost unique position in the Tongariro compositional spectrum, and is characterised by considerable isotopic heterogeneity (⁸⁷Sr/⁸⁶Sr 0.704191 - 0.706133) and readily identifiable multiple magma batches.

Tongariro's magmatic history represents a complex interplay between a number of contrasting magma reservoirs and magma batches which experienced varying degrees of differentiation by a variety of processes, namely magma mixing, fractional crystallization and crustal assimilation. Evidence for disequilibrium between phenocryst phases and groundmass and the involvement of magma mixing processes is especially prevalent in

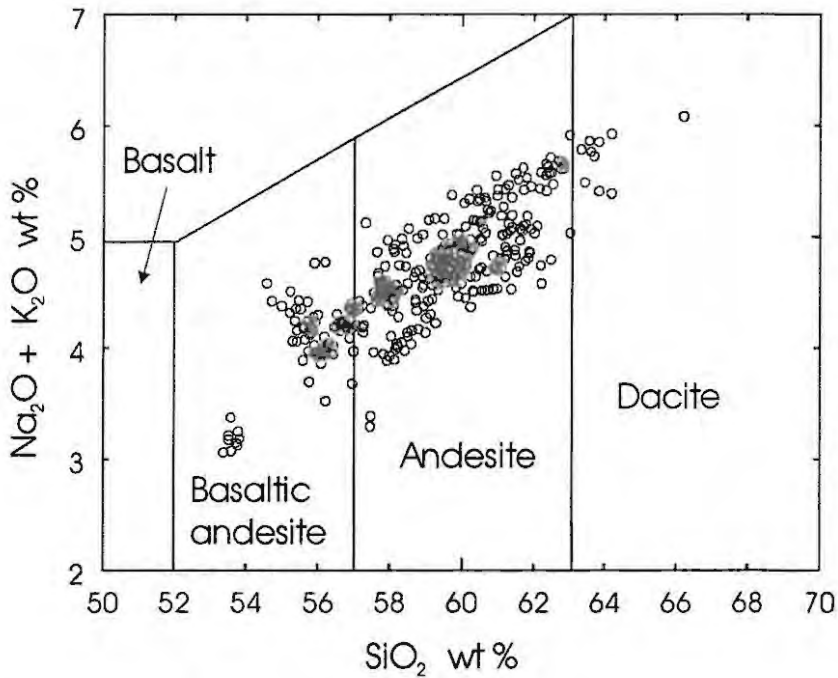


Figure 3: Tongariro analyses (n=370) plotted on a total alkali-silica (TAS) classification diagram (after Le Bas et al., 1986). Analyses recalculated anhydrous.

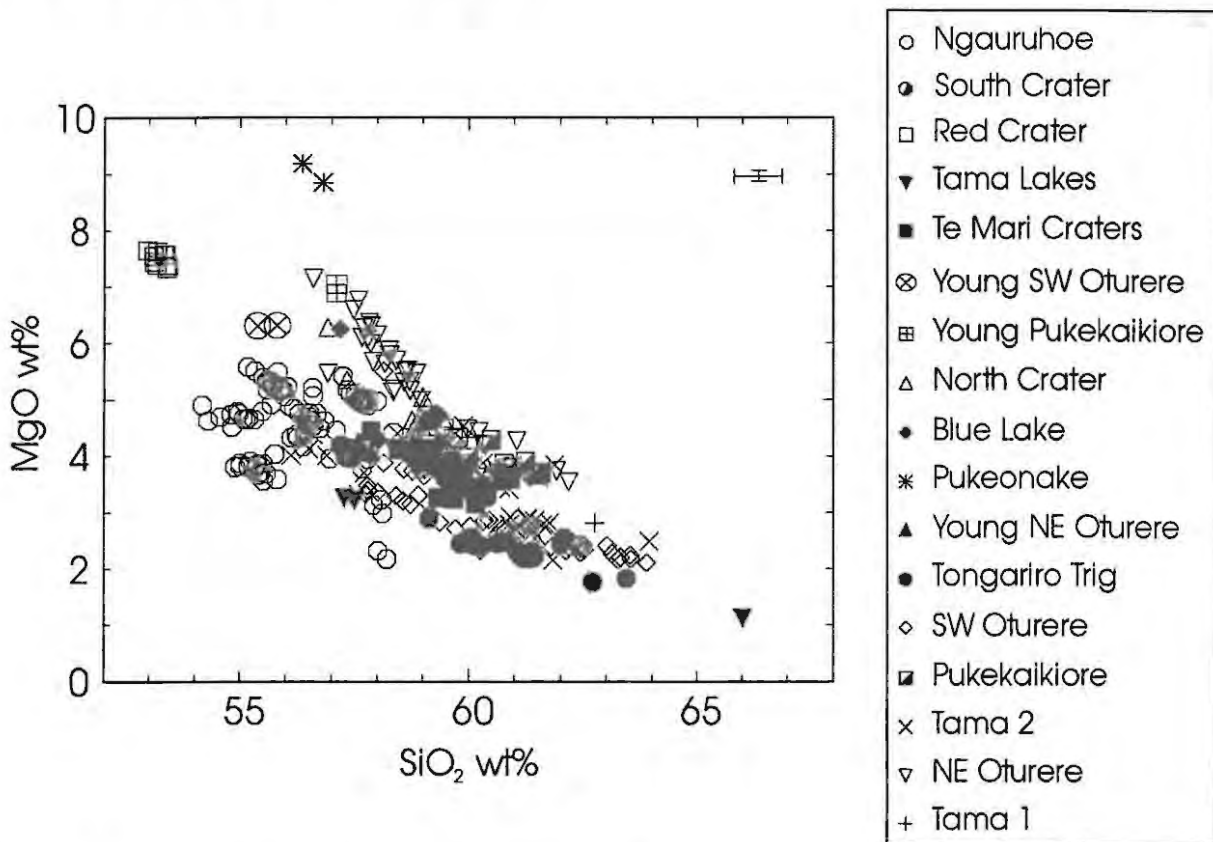


Figure 4: MgO - SiO₂ variation diagram for Tongariro eruptives (plotted according to volcano-stratigraphic unit) showing multiple trends and complex petrogenetic relationships within and between units. All data recalculated anhydrous. Error bars represent total error (2 sd from mean).

Table 2: Chemical and isotopic data for selected Tongariro volcano-stratigraphic units viewed on this field excursion. Major element compositions determined by XRF at Canterbury University. Trace element data obtained by XRF at University of Canterbury (shown in italics) and Royal Holloway & Bedford New College (shown in bold), all other trace element data obtained by INAA (University of Massachusetts). Radiogenic isotope data obtained at Royal Holloway and UCLA. na = not analysed.

Cone unit	Ngauruhoe	Ngauruhoe	Ngauruhoe	Red Crater	Red Crater	North Crater	Tong. Trig	Pukekaikiore	NE Oturere
Sample No.	TG010	TG001	TG003	TG112	TG135	TG196	TG140	TG265	TG115
Description	1975 pyrocl. avalanche. Mangatepopo Valley (Gp 5)	1870 lava flow, head of Mangatepopo Valley (Gp 5)	prehistoric lava, head of Mangatepopo Valley (Gp 2)	post-1.8ka lava flow, upper north Oturere Valley	pre-1.8ka lava flow, upper south Oturere Valley	c.14 ka lava lake section exposed in explosion pit	c.90 ka lava, north wall of Mangatepopo Valley	158 ka lava flow, base of bluffs on N Pukekaikiore	c.120 ka lava flow, base of main valley wall section
SiO ₂	56.93	55.44	55.92	53.38	60.94	59.20	61.17	60.55	56.35
TiO ₂	0.72	0.77	0.87	0.72	0.68	0.78	0.89	0.62	0.68
Al ₂ O ₃	17.09	16.48	17.57	15.45	15.98	17.11	16.96	16.45	15.01
Fe ₂ O ₃	8.49	9.12	9.33	9.70	6.73	7.23	7.26	6.55	7.76
MnO	0.15	0.16	0.16	0.16	0.11	0.12	0.12	0.11	0.14
MgO	4.11	5.52	4.04	7.71	3.82	4.08	2.18	3.76	7.12
CaO	7.27	8.60	8.18	10.49	6.49	6.93	5.71	6.73	8.72
Na ₂ O	3.03	2.83	3.07	2.43	3.31	3.25	3.68	3.28	2.65
K ₂ O	1.33	1.12	1.01	0.63	1.78	1.45	1.80	1.31	0.99
P ₂ O ₅	0.15	0.16	0.14	0.13	0.14	0.15	0.18	0.12	0.13
LOI	-0.41	-0.11	-0.79	-0.71	-0.17	-0.42	0.43	-0.20	0.83
TOTAL	98.86	100.09	99.50	100.09	99.81	99.88	100.38	99.28	100.38
Mg#	49.0	54.5	46.2	61.2	52.9	52.8	37.3	53.2	64.5
Sc	28.58	34.80	na	40.03	24.24	24.87	22.91	21.97	32.29
V	185	222	229	260	155	180	156	153	186
Cr	46	89	35	239	66	36	7	38	260
Co	37.29	53.12	na	49.03	39.09	38.95	24.21	32.11	41.17
Ni	17	29	10	60	21	11	3	13	53
Cu	35.7	47.6	na	67.4	19.9	na	na	na	52.0
Zn	83.4	85.2	87	83.2	64.7	76	74	61	74.3
Ga	19	22	18	19	21	20	23	21	21
Rb	45	34	34	18	64	53	67	41	31
Sr	238	278	200	278	269	281	284	270	326
Cs	1.99	2.02	na	1.48	3.74	2.89	1.35	1.00	1.90
Ba	263	232	187	134	373	326	391	319	220
La	14.24	13.05	8	7.63	15.94	14.67	21.51	9.75	11.04
Ce	31.35	27.13	23	16.52	33.53	31.28	39.08	20.51	25.81
Nd	17.92	15.92	10	9.40	17.76	16.31	23.74	11.98	14.86
Sm	4.02	3.77	na	2.74	3.94	3.65	4.91	2.76	3.21
Eu	1.02	1.07	na	0.85	0.99	0.95	1.15	0.78	0.92
Gd	3.81	4.30	na	3.32	4.27	3.80	5.21	2.90	3.10
Tb	0.66	0.68	na	0.52	0.68	0.57	0.80	0.49	0.46
Tm	0.38	0.33	na	0.31	0.38	0.34	0.38	0.30	0.29
Yb	2.61	2.29	na	2.20	2.60	2.37	2.57	2.00	2.04
Lu	0.39	0.33	na	0.34	0.37	0.35	0.37	0.30	0.32
Y	24.2	22.0	24	18.7	24.5	21	28	20	18.2
Zr	132	110	107	79	146	111	140	114	108
Nb	5.5	4.3	na	2.7	5.8	na	na	na	3.6
Hf	3.33	2.86	na	2.00	3.83	3.17	3.95	2.68	2.73
Ta	0.49	0.35	na	0.24	0.47	0.52	0.51	0.34	0.35
Pb	8.3	6.5	na	8.1	10.0	na	na	na	8.6
Th	5.47	4.02	5	2.10	6.45	5.86	6.59	4.03	3.68
U	1.05	1.02	na	0.51	1.44	1.39	1.60	1.18	0.75
⁸⁷ Sr/ ⁸⁶ Sr	.706133±10	.705305±10	.705171±10	.704562±10	.705126±11	.705543±10	na	.704794±10	.704861±10
¹⁴³ Nd/ ¹⁴⁴ Nd	.512643±11	.512682±11	.512711±11	na	na	.512646±8	na	.512812±7	na

lavas from Tama 2, NE Oturere, SW Oturere, Pukeonake, Red Crater, and Ngauruhoe. Characteristics include: plagioclase containing zones of intense concentrations of glass inclusions (sieve texture) coinciding with major compositional breaks/reversals and inner resorption surfaces; strongly reverse and/or patchy zoned crystals; crystals with lower $^{87}\text{Sr}/^{86}\text{Sr}$ than the surrounding groundmass; complex internal Sr isotope stratigraphy of individual crystals; co-existing high-temperature and low-temperature phases some showing evidence of disequilibrium such as resorption (corroded/embayed crystal edges) and reaction rims; olivine phenocrysts with much higher Fo contents than expected from whole-rock Mg#; and bimodal or very widely ranging crystallization temperature estimates for some samples.

Variations in isotopic and incompatible trace element ratios point strongly towards contamination of magma with the underlying Mesozoic Torlesse metasedimentary basement (average $^{87}\text{Sr}/^{86}\text{Sr} = 0.71459$; Graham et al., 1992). The Torlesse terrane basement outcrops <10 km to the east of Tongariro, and occurs at depths of approximately 2-15 km beneath the volcano. Torlesse lithologies vary from 2 m to >100 m thick massive greywacke and massive argillite units, to cm- to m-scale greywacke-argillite alternations, and melange of argillite, sandstone, chert, siltstone and limestone (Beetham and Watters, 1985). This lithological variability supplies a wide chemical and isotopic range to potential contaminants of Tongariro magmas (Graham, 1985). If, as seems likely, contamination of Tongariro magmas occurs in relatively thin dykes rather than large magma chambers, the compositional banding of the Torlesse contaminant will have a significant effect on the compositional diversity of Tongariro magmas. Ngauruhoe lavas contain crustal xenoliths that represent fragments of the Mesozoic metasediments, providing petrographic support for crustal assimilation. Isotopic data for Tongariro indicate there is not one simple (single) AFC trend linking magma batches from different eruptions and different cones, and there are inconsistent age relationships along these multiple AFC trends (e.g. Figs 5 and 6). 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 basement they encounter at different locations within the subvolcanic domain.

Magma storage areas existed at a variety of levels beneath the volcano, and some operated independently whereas others shared some degree of connection. The major compositional differences reflected in the broad groupings of Tongariro volcano-stratigraphic units described above represent periods in Tongariro's development when a break in magmatic evolution occurred, probably resulting from a structural change in the complex subvolcanic plumbing system via the influx of a new batch of 'parental' magma, establishment of new configurations of magma reservoirs, and the ensuing modification of the magmatic intensive parameters controlling differentiation.

Ngauruhoe: example of rapid growth and non-systematic evolution of an active andesite cone

The 2.2 km³ Ngauruhoe cone has grown rapidly and in staccato fashion over the last 2500 years, with abrupt changes in magma composition. Beech leaves found near the base of the Ngauruhoe-sourced Mangatawai Tephra are radiocarbon dated at 2,500 ± 200 years B.P. (Fergusson and Rafter, 1959). Activity was most intense during the first ~700 years (Topping, 1974) with Ngauruhoe-sourced tephra declining in volume from 1.85 ka to the present (Ngauruhoe Formation). Ngauruhoe lavas are basaltic andesite to andesite (54.2 – 58.6 wt% SiO₂), with the strongly porphyritic lavas containing phenocrysts of plagioclase, orthopyroxene, augite, Fe-Ti oxide and olivine. Ngauruhoe forms a young, 900 m high, steep-sided (~30°) cone with a symmetrical profile. The active vent is the 150 m wide crater of a scoria cone that grew on Ngauruhoe summit between 1954 and 1976, and is nested within a 400 m wide, older crater.

Ngauruhoe has displayed dramatic variations in eruptive style both during and between eruptions observed over the past 120 years (Fig 7), and thus there is no single unique style of Ngauruhoe volcanism (Hobden et al., in press). Historical discharge rates averaged over individual eruption pulses of relatively uniform style and intensity have varied by almost two orders of magnitude (from 3 to 280 m³ s⁻¹), reflecting variations in high level magma ascent rates and processes such as degassing. Discharge rates averaged over an entire eruption (typically lasting days to months) involving shifts of style/intensity and including lulls have lower discharge rates (e.g. 0.6 - 2 m³ s⁻¹) that represent an averaged growth rate over that period and may relate to the size of individual magma batches. The rate of long term growth over the entire lifespan of Ngauruhoe cone is 0.9 km³ ky⁻¹ reflecting the long term deep supply rate of magma to the volcanic plumbing system. Compared with most other cones of the Tongariro composite volcano (typically 0.1 – 0.4 km³ ky⁻¹; Hobden et al., 1999), Ngauruhoe has a very high overall growth rate. Ngauruhoe thus represents one extreme in terms of cone growth and

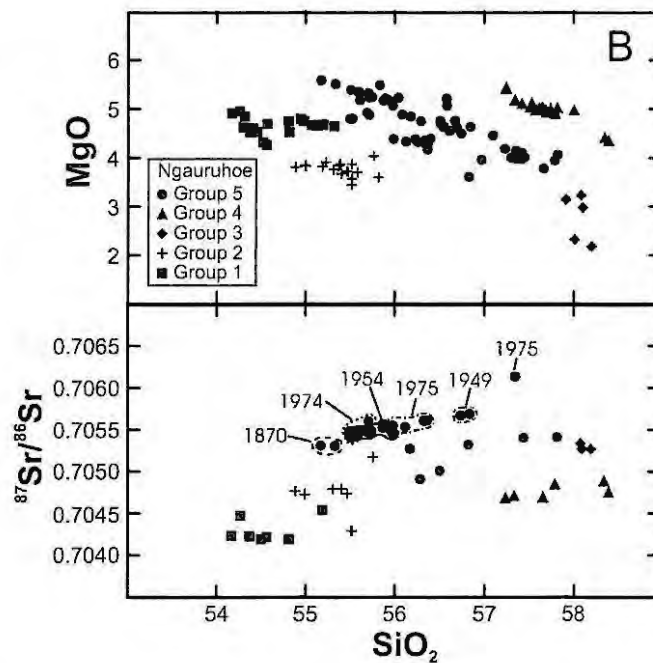
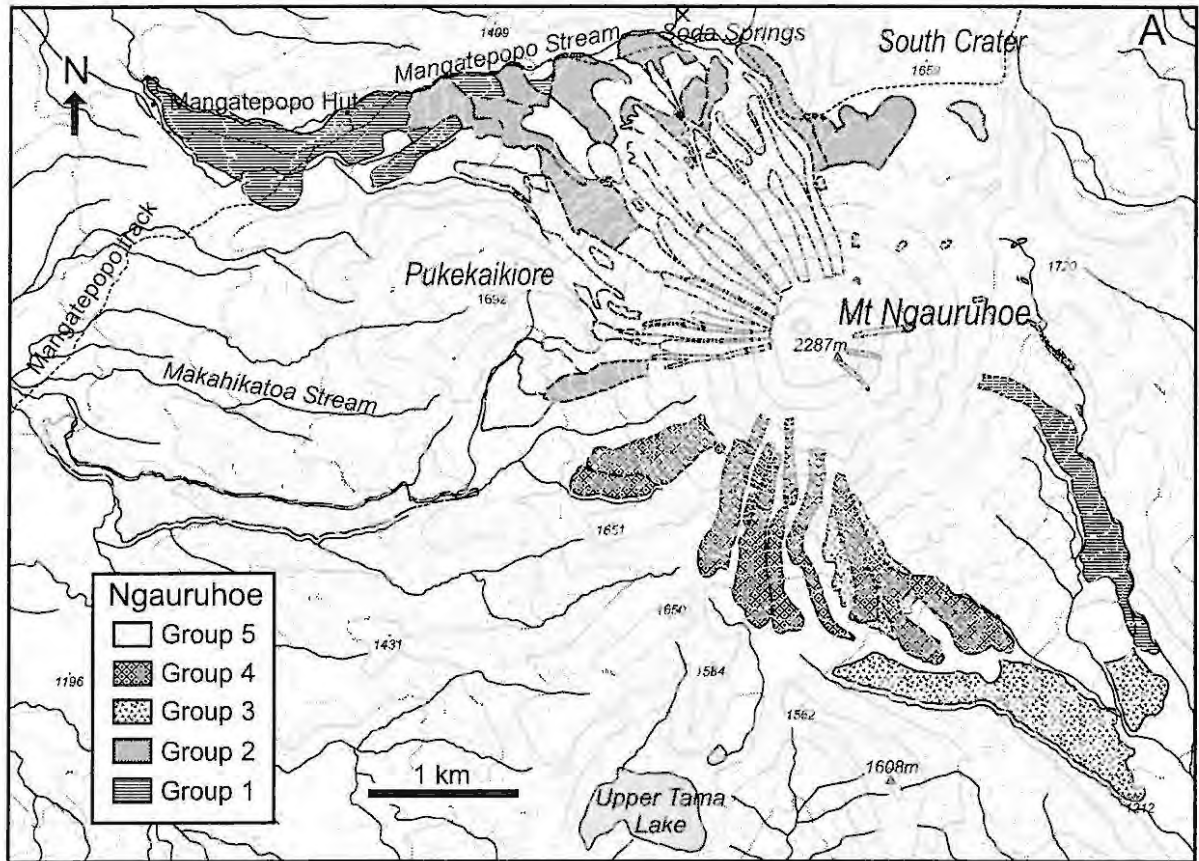


Figure 5: A Ngauruhoe cone showing more than 60 separate lava flows and block-and-ash flows mapped as five distinct groups. Non-patterned areas on cone are unconsolidated scoria/scree. B MgO and ⁸⁷Sr/⁸⁶Sr plotted v SiO₂ showing chemical and isotopic variation between and within Ngauruhoe groups. This heterogeneity is thought to reflect numerous small and short-lived magma batches mixing with each other and the crust within a complex plumbing system. Errors are the same or less than size of symbols. Two sigma precision for ⁸⁷Sr/⁸⁶Sr is better than 0.000025. After Hobden et al. (in press).

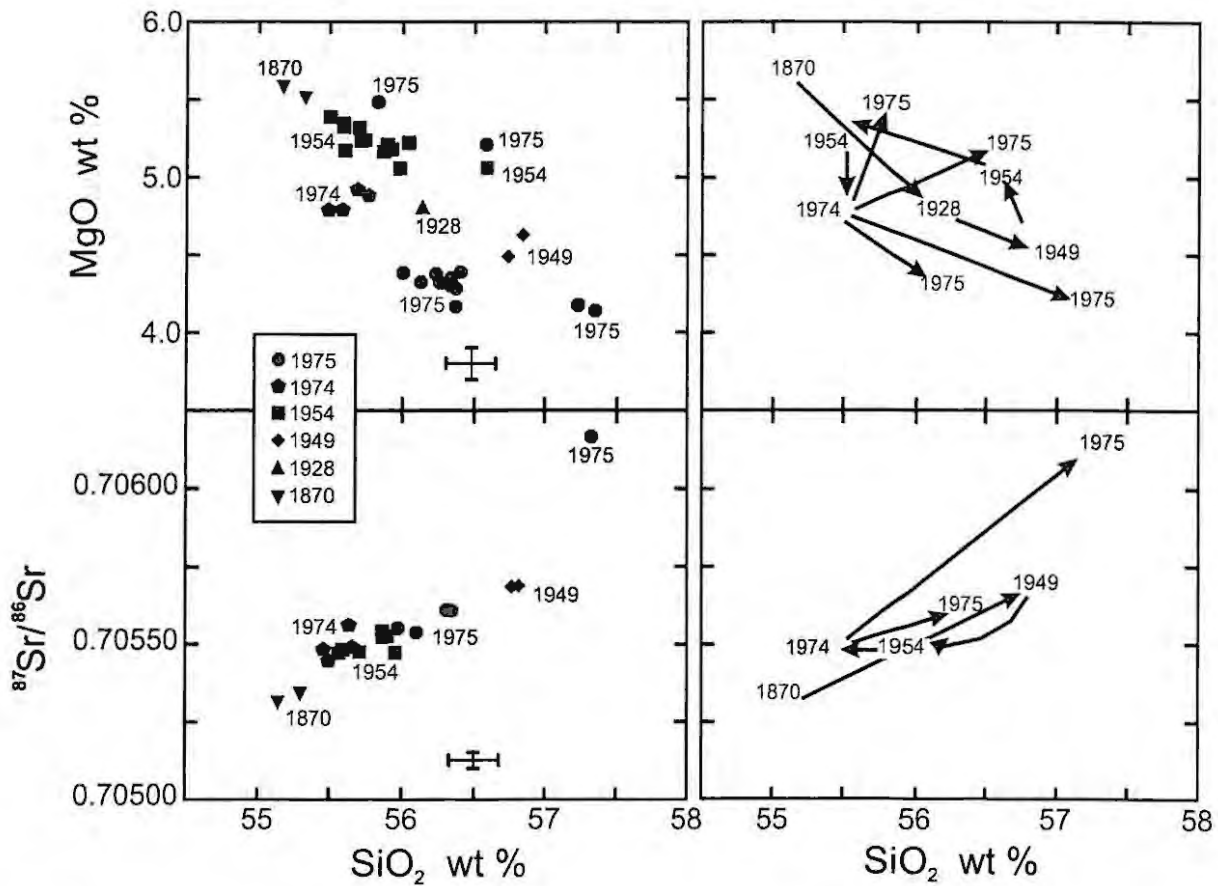


Figure 6: MgO and $^{87}\text{Sr}/^{86}\text{Sr}$ plotted vs. SiO_2 for historical Ngauruhoe lava flows and pyroclastic products representing a 100-year time window. Vectors highlight the apparently random change in composition with time. Error bars for SiO_2 (± 0.15 wt%) and MgO (± 0.10 wt%) are for 2 standard deviations based on replicate analyses. Two sigma precision for $^{87}\text{Sr}/^{86}\text{Sr}$ is better than 0.000025. (after Hobden et al., 1999)

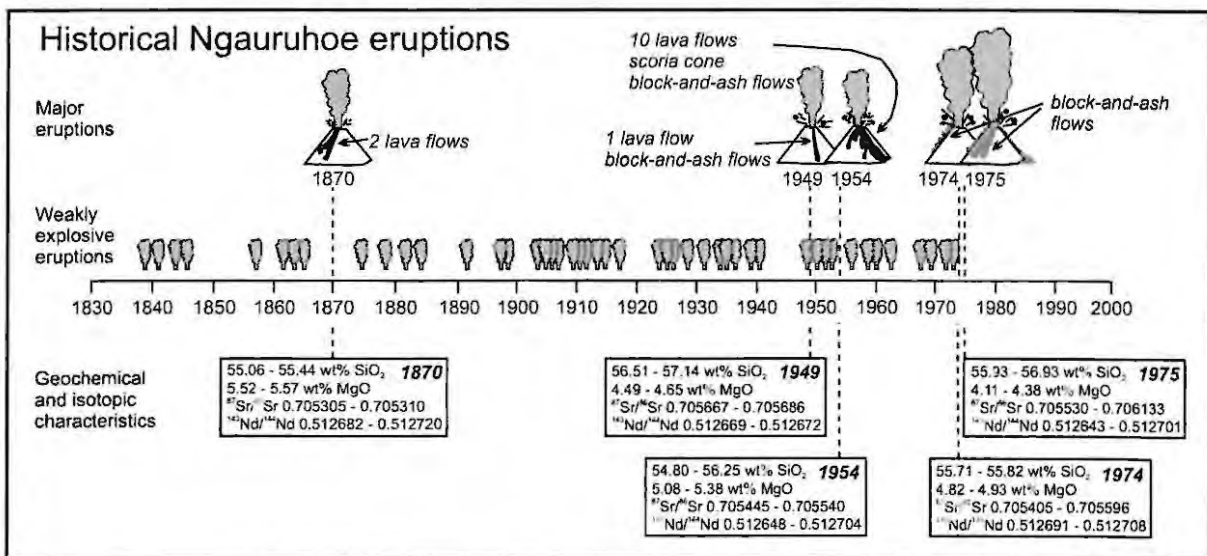


Figure 7: Sequence of observed eruptions from Ngauruhoe since beginning of European records. Historical eruptions summarised in Gregg (1960) and Cole and Nairn (1975), with recent eruptions described in detail by Allen (1949), Gregg (1956), Nairn et al. (1976), and Nairn and Self (1978). After Hobden et al. (in press).

eruptive style at Tongariro (Hobden et al., 2000a, in press), characterised by small size, short lifetime, rapid rate of cone-building, mafic composition, and a large number (over 70) of small lava flows.

We have identified five major time intervals, related to progressive growth on different sectors of the cone (Fig 5). Complex, often abrupt, non-systematic chemical and isotopic variations between and within these groups indicate that they do not represent simple evolutionary 'trends' either internally or for the cone overall. Isotopic diversity of the historical eruptives (e.g. 0.00067 differences in $^{87}\text{Sr}/^{86}\text{Sr}$ over periods as short as 20 years, Fig 6) suggest that varying degrees of interaction between magmas and the heterogeneous metasedimentary basement have occurred at shallow crustal levels within a complex plumbing system. Trends for the historical flows (Fig 6) do not represent a simple, single trend chemical and isotopic progression through time of a single evolving magma batch. Instead we see many instances of mafic recharge and mixing to such an extent that it appears that a new magma batch is 'defined' for every new eruption episode. Similar short-term geochemical variability has been documented for historical Ruapehu eruptives (Gamble et al., 1999). Even within an eruption episode, such as those of 1954 or 1975, there are significant isotopic variations between flows (Hobden et al., 1999, 2000a) and within the crystal population of single flows (Hora et al., 2000a; Hobden et al., 2001).

Ngauruhoe magma dynamics indicate an open, multi-process, multi-directional system of numerous small (<0.1 km³) and short-lived (years to decades) magma batches, with no simple time-space-composition relationships (Hobden et al., 1999). We envisage frequent injection, ascent and temporary residence of many small, short-lived, variably contaminated magma batches within a complex plumbing system of narrow conduits and small holding chambers. We see petrological and geochemical evidence for the powerful role played by shallow level assimilation, fractional crystallization and magma mingling in modifying magma compositions on time scales as short as a year. Young, small, mafic composite cones like Ngauruhoe grow rapidly compared to more silicic cones, yet their magma plumbing systems and histories of magma evolution may be no less complex.

Route Guide

Overview: The 8-hour-long Tongariro traverse allows us to view and examine many key aspects of the volcanic complex. Ideally, several days are the minimum time required to visit a wider area (including the eastern and southern sectors) in order to gain a full appreciation of the complexities and variety of cone-building. However today we will have the opportunity to view four of the six older cone remnants (the Tama 1 and Tama 2 cones to the south cannot be viewed along this route), and nearly all of the young eruptive cones and craters which have begun to partly obscure the older cone structure of the complex. Our route begins in a major Holocene glacial valley where the glacier grew and eroded the suture between the older Pukekaikioire and Tongariro trig cones. The young Ngauruhoe cone then grew to partially 'heal' the glacial scar with its lavas overlying the older flows with complex angular unconformity. At Ngauruhoe, we can discuss sectorial cone growth patterns and examine young lava flows and the 1975 block-and-ash flow deposits. We then climb up onto the high central part of the complex, viewing exposures of old lava flows, agglutinate, scoria-tuff sequences, and vent complexes of the old cone remnants of Tongariro Trig, SW Oturere and NE Oturere. Our route then follows the northeastern vent corridor past many of the young vents, including Red Crater, Emerald Lakes, Blue Lake, North Crater, Te Mari Craters and the Ketatahi Springs geothermal area before descending the northern flank of the complex.

Logistics: From the carpark at the Mangatepopo Road end (6 km off State Highway 47) we will begin the walk across Tongariro, mostly following the poled and signposted route of the 'Tongariro Crossing'. The ~15 km traverse will involve a moderately strenuous 8 hour hike as we climb ~700 m to an altitude of just over 1800 m, then descend to the Ketatahi Road end (1 km off State Highway 47A) where we will be met by the vehicles. We will be walking mainly in exposed alpine conditions, and it is essential to be prepared for changeable weather, so have alpine clothing (including warm hat and gloves), strong shoes or boots, rain gear, suncream, sunhat, personal first aid kit, food, and at least 2 litres of drinking water (water in the park is not suitable for drinking). Please note that collection of samples or use of geological hammers is not permitted in Tongariro National Park. Figure 8 provides a route map for the traverse of Tongariro, including location of likely stops. The approximate elevation of each stop locality is also noted below.

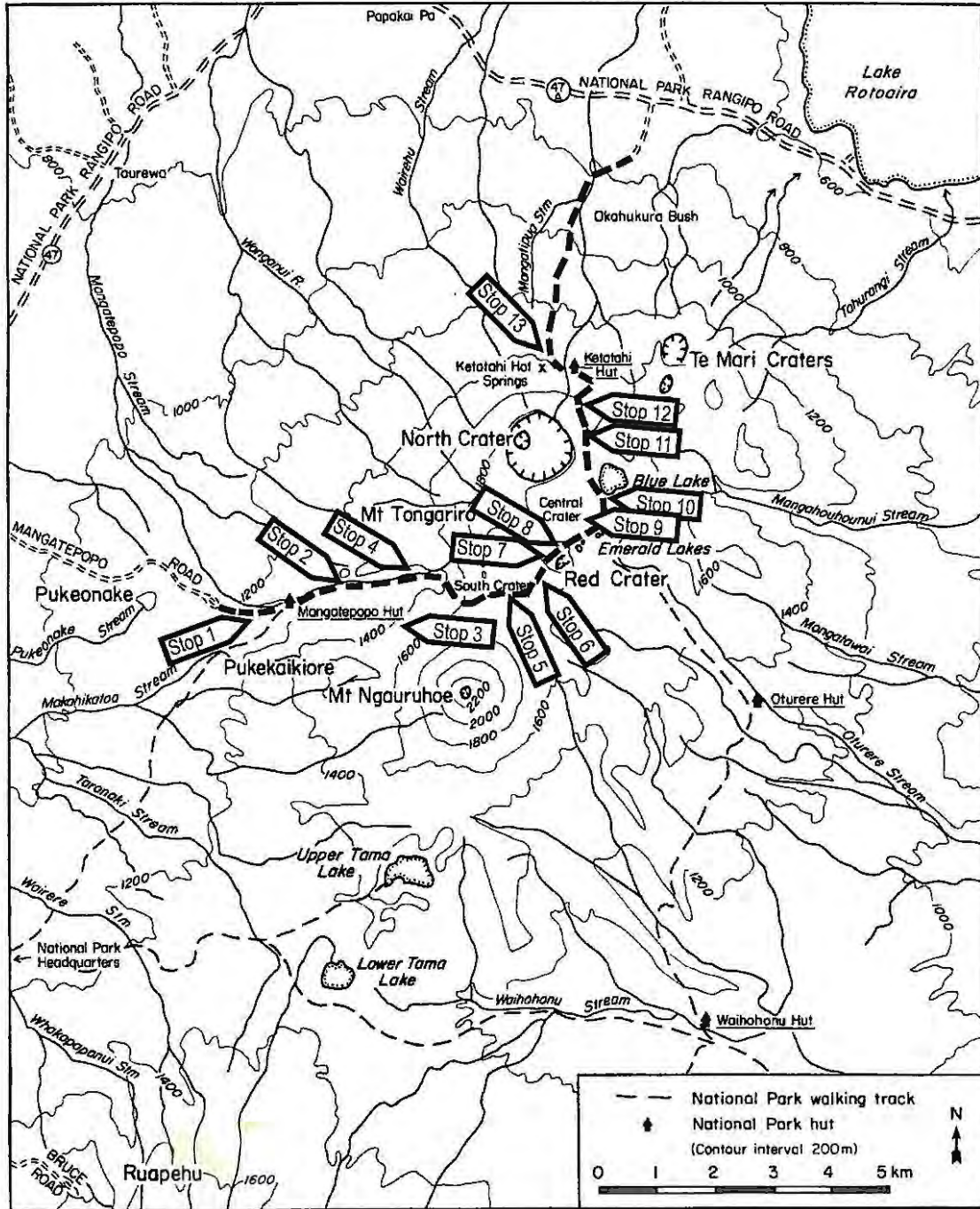


Figure 8: Location map for Tongariro volcano, showing route of traverse (highlighted) and stops.

Stop 1: Mangatepopo Valley, Ngauruhoe and Pukekaikiore viewpoint (1180 m)

The Mangatepopo Valley is a broad glacial valley flanked by paired moraine ridges. The interval 13 – 23 ka is regarded as the Last Glacial Maximum in the central North Island (Pillans et al., 1993). Such glaciated features occur elsewhere on Tongariro, and glacial erosion of deep valleys reveals the internal stratigraphy of the six older cone centres. Erosion of the pre-glacial cones has been softened to a certain extent by post-glacial cone building and infilling of valleys with young lava flows. For example, the cone of Ngauruhoe has from c.2.5 ka grown to bury the intersecting remnants of several glacially eroded older Tongariro cones (Fig 1) including Pukekaikiore, (190-120 ka), Tongariro Trig cone (110-65 ka), and Tama 2 (210-200 ka) and SW Oturere (115-65 ka) cones to the south and east. From the track we can observe thick (<100 m) lavas outcropping on

Pukekaikiore, ranging from regular sub-columnar-jointed flows (north margin, Table 2) to coulee-like ponded lava flows with massive, distorted columnar-slabby radiating jointing (east margin).

Stop 2: Ngauruhoe sectorial cone growth & historical eruption chronology (1300 m)

Ngauruhoe sectorial cone growth. The 2.2 km³, 900 m high, symmetrical cone of Ngauruhoe has grown rapidly in a piecemeal sectorial fashion reflecting constant modification of the summit of the cone. Numerous youthful andesitic aa to block lava flows are preserved around all sectors of the cone (Fig 5a). The best-constrained sequence of flows occurs here in the Mangatepopo Valley (Fig 9). This sequence is taken to be broadly representative of the evolution of the cone, showing the sectorial growth pattern, and the relationships between successive flows as they follow depressions that flank their predecessors, or reoccupy old channels (Fig 10). Lava flow paths were constrained by the cliffs of the eroded older cone of Pukekaikiore, adjacent to which they stopped and banked up in thick piles, or were diverted along the base of the cliffs in either direction. Other 1954 Ngauruhoe flows (eg. the large 30 June flow) contain small elongate windows into the underlying surface caused by temporary branching out of flow lobes around higher relief of older lava flows.

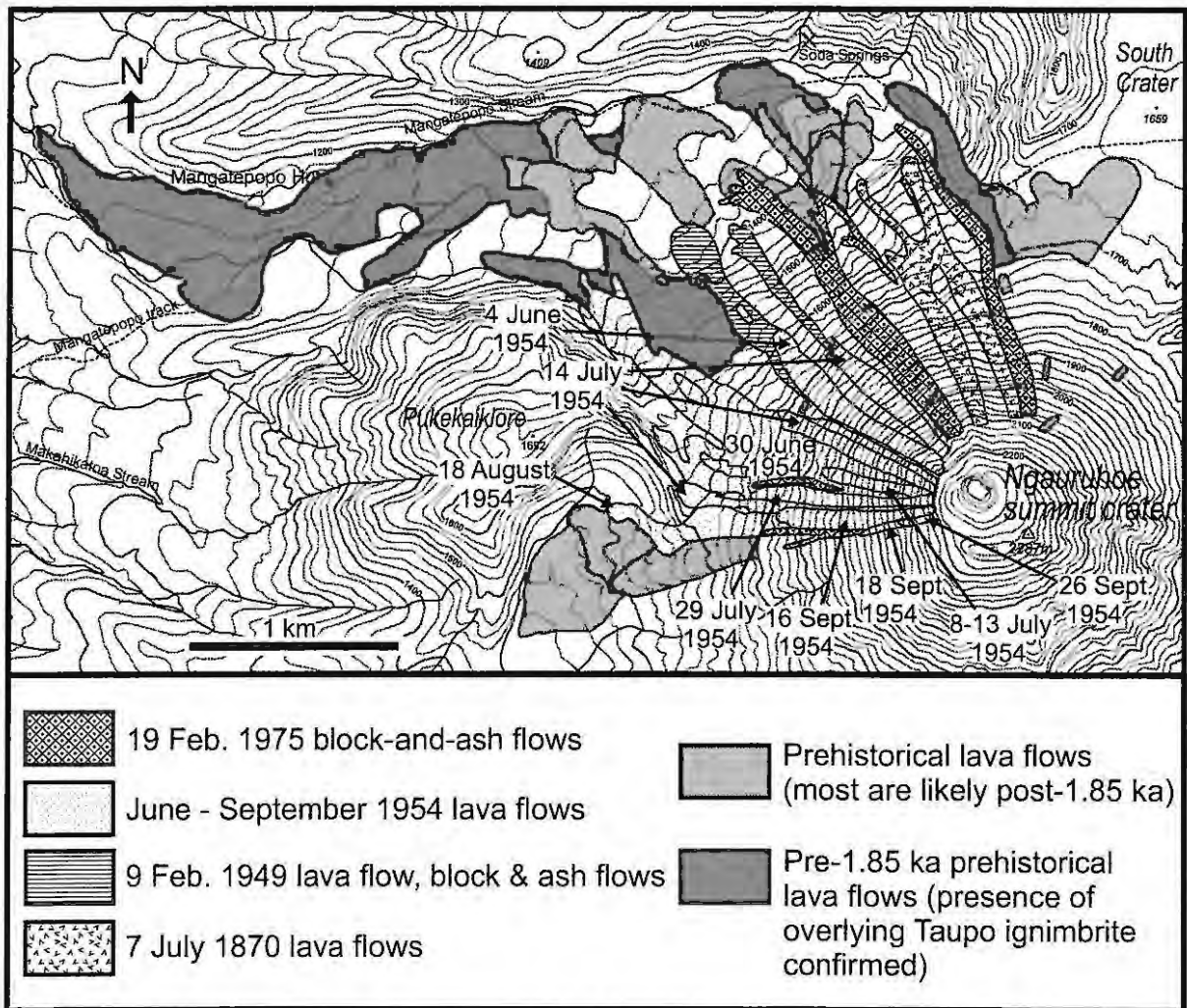


Figure 9: Detailed map of Mangatepopo Valley lava flows and pyroclastic flow deposits showing age relationships, sectorial growth pattern, and effects of topography on flow behaviour (after Hobden et al., in press). Historical flows and pyroclastic deposits were originally mapped by Battey (1949), Gregg (1956), and Nairn and Self (1978).

Lava flow distribution in Mangatepopo Valley. At least 16 prehistorical aa-block lava flows and one block-and-ash flow are preserved on the lowermost flanks of the cone and on the valley floor. Overlapping relationships, tephra marker beds and variable degrees of vegetation allow the stratigraphy to be established (Fig 9); the only

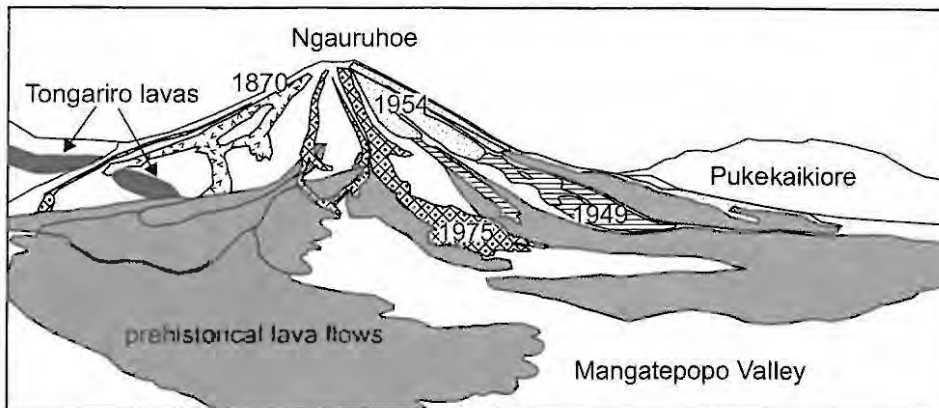


Figure 10: Ngauruhoe cone and Mangatepopo Valley viewed towards the south showing medium grey to brown, variably vegetated, prehistorical block lava flows extending into valley in foreground, and dark grey historical flows on steeper flanks of cone. Accompanying sketch map identifies key units. Hiking trail for the ‘Tongariro Crossing’ is visible at bottom of photo.

previous attempt was by Battey (1949). The presence of Taupo Ignimbrite deposits overlying the prehistoric lava flows has been confirmed in pits dug into the soil and tephra layers overlying at least eight of these flows. However, without dateable charcoal we lack constraints on the precise ages and time intervals between these prehistorical flows. Three of the five Ngauruhoe lava groups (Fig 5) are present in Mangatepopo Valley. The oldest exposed flows of Group 1 underlie the 1.85 ka Taupo ignimbrite, and outcrop near the start of the valley walk (Fig 9). These olivine-bearing basaltic andesites have the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.704191 – 0.704604) measured from Ngauruhoe (and from the entire Tongariro composite volcano). Most of the prehistorical flows on the valley floor belong to Group 2 (Fig 9), and have lower MgO and slightly more radiogenic Sr isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$ up to 0.705171) compared with Group 1. The focus of cone growth then switched to the south and SW sectors of the cone where the compositionally distinct Group 3 and Group 4 lava flows have been mapped (Fig 5). (We do not have enough time to visit this sector of the cone today.) The remainder of the flows visible in Mangatepopo Valley belong to the young Group 5, and all but three of these flows were erupted in historical times. These flows encompass the widest SiO_2 (55.1 – 58.2 wt%) and MgO (3.8 - 5.6 wt%) ranges of all the Ngauruhoe groups. They contain crustal xenoliths and have relatively high (up to 0.706133 $^{87}\text{Sr}/^{86}\text{Sr}$) and variable radiogenic isotope compositions, demonstrating an important role for crustal assimilation.

Ngauruhoe historical eruptions. Ngauruhoe has been nearly continuously active in historical times (Gregg, 1960; Cole and Nairn, 1975; Fig 7), with eruptions every two or three years on average. The more than 60 significant eruptive episodes recorded from Ngauruhoe since 1839 represent a diverse range of styles including effusion of aa and block lava flows (e.g. 1870, 1949, 1954), strombolian fire-fountaining to form scoria cones (e.g. 1954), and vulcanian-style explosions generating block-and-ash flows and pyroclastic falls (e.g. 1974-75). Figure 9 shows the historical flows preserved in Mangatepopo Valley, which comprise two lava flows from 1870 (viewed at Stop 3), one lava flow and two block-and-ash flows from 1949, at least ten lava flows from 1954, and at least 5 block-and-ash flows from 1975 (main deposit examined at Stop 3). The darkest gray lava flows were erupted over a four-month period during 1954. Each lava flow formed relatively quickly, reaching its maximum length in 1-2 days, with observed flows advancing at rates of up to ~300 metres per hour (Gregg, 1956).

Several block-and-ash flows variably accompanied, preceded or succeeded the extrusion of three of the lava flows. Spectacular and prolonged fire-fountaining between June and September 1954 resulted in the growth of a 60m high scoria cone within the summit crater. Ash explosions occurred spasmodically throughout the nine month eruptive period, with dark eruption columns (over 1 km high) observed which deposited ash and lapilli on the cone and carried ash as far away as Taupo, 65 km to the northeast (Gregg, 1956). Some particularly sharp explosions were accompanied by visible shock waves immediately preceding ash emission. Just five years earlier, in 1949, a lava flow and two block-and-ash flows were erupted (the dark gray flow is visible to left of main concentration of 1954 flows). These violent vulcanian-style eruptions were also closely observed (Allen, 1949; Battey, 1949; Cloud, 1951).

Stop 3: 1975 Ngauruhoe block-and-ash flows (1380 m)

Vulcanian eruptions. We will briefly detour from the track to examine the lobate flow front of the main block-and-ash flow deposit erupted on 19 February 1975. The most recent eruptions from Ngauruhoe occurred in 1974-75 when violent Vulcanian-style explosions and ash eruptions generated several block-and-ash flows down the northwest slopes of the cone and a thin widespread fall deposit. The eruption of 19 February 1975 was observed closely and began with voluminous gas-streaming, followed by violent cannon-like explosions which ejected ballistic blocks up to 2.8 km from the vent, accompanied by atmospheric shock waves and condensation clouds (Nairn, 1976; Nairn and Self, 1978). Dense eruption columns up to 10 km high underwent partial collapse to form block-and-ash flows (of both fresh magmatic and older lithic blocks) down the flanks of the cone (Nairn and Self, 1978). Near to Ngauruhoe the fall deposit comprised 3-4 cm of scoria-ash, and thinned to 1 mm of ash at 21 km along the dispersal axis (Nairn and Self, 1978).

Volcano monitoring. Surveillance of Tongariro, particularly Ngauruhoe, is carried out by scientists from the Institute of Geological and Nuclear Sciences at the Wairakei Research Centre. Volcanic seismicity is constantly recorded by a network of six permanent seismometers in the region, including one immediately SW of Ngauruhoe (installed in 1976) and one near Ketatahi on the north slopes of the complex. Volcano-seismicity activity at Ngauruhoe has remained low since its last eruption in 1974-75, reflecting the continuing lack of volcanic activity at the cone. Other techniques used at Tongariro include regular sampling of volcanic gases at fumaroles in Ngauruhoe crater, monitoring lake temperatures and chemistry, geothermal springs, and volcanic deformation monitoring.

Block-and-ash flow deposits. The deposits comprise a sequence of overlapping, digitate tongues of dark grey basaltic andesite, with thin (1-1.5 m) lobate fronts. The surface of the deposit features conspicuous flow channels and marginal levées, indicating high yield strength during the flow. The deposit is coarse-grained and very poorly sorted; fine ash and dense blocks and bombs are concentrated in the channels, whereas scoriaceous blocks up to 1 m in diameter dominate the levées and flow fronts. Bombs may have smooth, ropy surfaces or be vesiculated, breadcrusted or cauliflower-shaped. Dense, massive blocks lack any signs of plastic deformation, indicating that they were rigid when ejected. Some blocks have prismatic joints caused by stress release during cooling, showing that they were hot when ejected (temperatures of blocks in the deposit varied from >900°C to cold, Nairn and Self, 1978). Altered orange-white lithic blocks are also a component of the block-and-ash flow deposit. Quartzite xenoliths present in the lava contain a thin, irregular, closely-spaced layering of calc-silicates between the quartz grains which is interpreted to represent the original structure of calcite/dolomite-quartz veins within the Mesozoic Torlesse metasedimentary crustal basement. Glass along the grain boundaries is evidence for partial melting of these quartzite xenoliths, suggestive of their involvement in crustal contamination of Tongariro magmas. Chemical and isotopic data for this deposit are presented in Table 2.

Stop 4: 1870 Ngauruhoe lava flows and 'window' into the older Tongariro cone structure (1380 m)

1870 lava flows. The first lava flow eruption since recorded observations began in 1839 occurred on 7 July 1870 (Hector, 1870), when two lava flows travelled down the north side of the cone, diverging to flow either side around a prominent bluff of older Tongariro lava (Fig 11). At the bluff's break in slope, the lava flows lost coherence and broke up into loose blocks and scree, cascading down to the valley floor. Emplacement of the lava flows was accompanied by explosive eruptions of incandescent blocks and short-lived ash plumes, associated with loud detonations heard 200 km away. Chemical and isotopic data for one of these flows are presented in Table 2.



Figure 11: The effect of pre-existing topography on lava flow morphology is illustrated by the 1870 Ngauruhoe lava flow that encountered an old bluff of Tongariro lavas.

Old cone remnants. The lava bluffs, comprising four autobrecciated lava flows dated at 79 ka, are part of the Tongariro Trig cone, which is mainly exposed in the headwalls of the Mangatepopo Valley and the South Crater/Tongariro Trig ridge. These bluffs provide one of just a few 'windows' into the earlier cone structure existing prior to growth of the Ngauruhoe cone. Chemical data for one of these old Tongariro Trig flows are presented in Table 2.

We will now climb steeply up one of the older (pre-1.85 ka) prehistorical Ngauruhoe lava flows to the saddle between Ngauruhoe and South Crater. Note the minor 1975 block-and-ash flow deposit exposed between the track and the 1870 lava flow. As we walk up the track, the older lavas and agglutinates from the Tongariro Trig cone can be seen dipping beneath the Ngauruhoe lavas, correlating with the isolated bluff between the 1870 flows.

Stop 5: South Crater (1660 m)

After the climb up to the saddle, this is a strategic point to stop and recover whilst observing several features. South Crater was mis-named by early European explorers; there is no evidence of an explosive origin and it is more likely to be a glacial cirque basin. In the west wall of the basin we can observe the continuation of the 110-65 ka Tongariro Trig cone lava flows and agglutinates observed on the walk up out of Mangatepopo Valley. In the north and NE walls of the basin, a >30 m thick scoria-tuff cone deposit and hydrothermally altered lapilli-tuff vent breccias are exposed. A pyramidal outcrop of welded agglutinates and lava, topped by a small scoria cone, occurs on the saddle between Ngauruhoe, South Crater and the head of Oturere Valley.

A c.7 m thick sequence of hydrothermally altered tuff breccia overlain by juvenile andesitic scoria is exposed within a small explosion pit at the southern end of the South Crater basin. Intercalated tephra marker beds constrain the age of this small eruption to c.2-1.85 ka.

From Red Crater (to the east), a small, post-1.85 ka, basaltic andesite lava (53.6 wt% SiO₂, 7.4 wt% MgO) has flowed down the steep wall of South Crater but failed to reach the floor of the basin. A relatively low effusion rate may have limited the extent of this flow, which is of a very similar composition to the broad and very thin Red Crater flow that we will observe at Stop 9.

We now take the poled route across the flat South Crater, then begin the short but steep climb up the ridge leading to Red Crater.

Stop 6: Oturere Valley viewpoint (1800 m)

Old cone sequences. Thick sequences of lavas and pyroclastics are exposed on the glaciated walls of Oturere valley, erupted between 130 and 70 ka. This is one of the periods in Tongariro's history during which a noticeable upsurge in magma production occurred, encompassing the main growth phases of NE Oturere, SW Oturere and Tongariro Trig cones. Around 50% of the lavas and pyroclastics making up the Tongariro complex were erupted during this period of accelerated activity. The NE Oturere cone remnant is now represented by the thick (>200 m) sequence of at least 75 andesitic lava flows and intercalated scoria-tuff cones, agglutinates and vent breccias preserved in the NE wall of the valley (see Table 2 for chemical and isotopic data). Note the angular unconformities separating discrete packages of lava and scoria. Breaks and reversals in magma chemistry up section indicate at least five episodes of magma recharge and mixing. Erosion of the glacial valley is believed to have removed most of the central vent facies for the NE Oturere cone. In the SW Oturere valley wall, we have mapped at least 65 andesitic to dacitic lava flows and pyroclastic units, including an area of intense hydrothermal alteration, breccias, rare dikes and steeply dipping lava flows marking the location of the old SW Oturere cone vent.

10 ka multiple vent pyroclastic eruption sequence. Mantling part of the upper SW Oturere valley wall is a young, variably welded, basaltic andesite scoria fall deposit (<15 m thick) marking one of at least 10 NNE-trending vents from which a sequence of six major (each c.1 km³) and several minor pyroclastic eruption episodes occurred during a period of intense activity at ~ 10 ka (Nairn et al., 1998). This Pahoka-Mangamate sequence had an apparent duration of c.200 - 400 years, and multiple vents between Ruapehu and Te Mari Craters were active during each of the plinian eruption episodes. Juvenile ejecta from each eruption are chemically and petrographically diverse, indicating that a number of separate small magma bodies were tapped during the c.10 ka eruption sequence (Nakagawa et al., 1998).

Red Crater lava flows. From the Red Crater vent visible to our left, at least 5 aa to block andesite flows were directed into Oturere Valley before 1.85 ka, when the Taupo pumice and ignimbrite were deposited on the flows (Fig 12). The lower age limit for Red Crater activity is uncertain, but Topping (1974) noted that some of the older flows underlie the 1.8-2.5 ka Mangatawai Tephra, providing at least a minimum age for the unit. The flows contain marked transverse pressure ridges and spinose surfaces. The largest pre-1.85 ka flow is unusually long (6.5 km) and thick (< c.150 m), filling the floor of the Oturere Valley (Fig 12). The flow has an estimated volume of 0.3-0.5 km³ (Stevens, in press) which is several orders of magnitude greater than any other of the Red Crater flows (c.0.003 - 0.0003 km³). Since this is the oldest preserved flow from Red Crater, it could represent an initial near-emptying of the magma reservoir after which time no significant replenishment occurred and only relatively small remnants of magma were erupted to produce the subsequent (and much smaller volume) andesite flows. Injection of more basic magma after 1.85 ka is implied by the younger, thin, pahoehoe transitional to aa, basaltic andesite flows (Stops 5 and 9) which have SiO₂ contents of 53.0-53.7 wt%, quite distinct from the andesite flows which range from 59.1 to 61.1 wt% (Table 2).

Stop 7: Red Crater (1860 m)

The track takes us up and along the north rim of Red Crater, the highest point on our traverse today. The Red Crater cone is composed of dark red and black, variably welded basaltic andesite scoria which drapes older light grey columnar-jointed lava flows. Several basaltic andesite feeder dikes are exposed within the c.60-80 m deep crater, one of which is preserved as a drained hollow lava tube. Inner and outer wall vent facies can be observed in the crater. A transition from red-black true magmatic scoria to orange-grey phreatomagmatic material is visible on the western inner crater wall. Ash and steam eruptions were observed from Red Crater from 1855 to probably 1890, and since then sulphurous steaming ground and fumaroles have remained active.

Stop 8: Emerald Lakes (1700 m)

Phreatic eruptions during the last 1.85 ka (Topping, 1974) have created a line of explosion pits NE of Red Crater, three filled by the Emerald Lakes, which mirror the overall NE vent lineation of the Tongariro complex. The lakes are up to 4.5 m deep with a pH of 3 - 5. The green colour is due to the entry of fumarolic sulphur into the lake and the ensuing formation of polysulphide ions

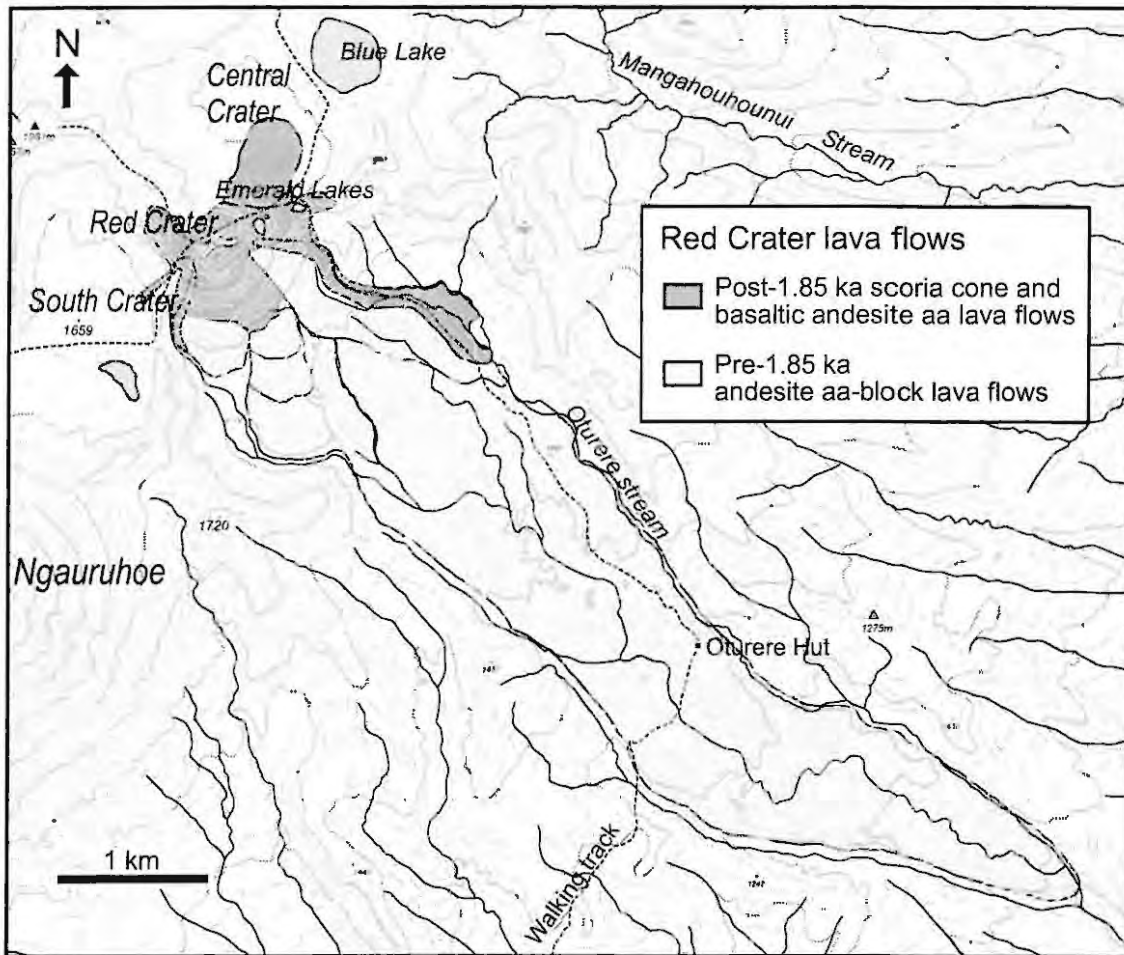


Figure 12: Map of Red Crater lava flows showing distribution of the two different lava types.

Stop 9: Red Crater lava flow, Central Crater (1700 m)

As is the case for South Crater, and despite its name, the depression called Central Crater does not have an explosive origin. It occurs at the intersection of several older cone remnants (Tongariro Trig, NE Oturere, and SW Oturere) and the post-glacial cones of Red Crater, North Crater and Blue Crater. As we cross Central Crater we can examine the margin of a post-1.85 ka Red Crater lava flow. This is an unusually thin (1-5 m) but widespread (400 m wide) aa lava flow with some surface relief and small pressure ridges evident. This olivine-bearing basaltic andesite lava is one of the most primitive compositions on Tongariro (53.7 wt% SiO₂, 7.4 wt% MgO) and illustrates the influence of chemical composition on lava viscosity when compared to the high aspect ratio pre-1.85 ka Red Crater andesitic lava (60.0 wt% SiO₂, 4.3 wt% MgO) filling Oturere Valley.

Stop 10: Blue Lake crater and agglutinate (1740 m)

A short climb up from Central Crater takes us onto the south rim of Blue Lake crater, from where we can observe the inner wall, andesitic, agglutinate-lava facies exposed on the north rim. These thin (2-3 m thick), draping, welded agglutinates were deposited during fire-fountaining eruptions. Based largely on distal ring plain tephrostratigraphy, Topping (1973) and Donoghue et al. (1995) suggested a Blue Lake source for the c.9.7 ka subplinian Poutu Lapilli eruption. However, Nairn et al.'s (1998) near-source mapping indicates that the main vent was not at Blue Lake crater, and the thick welded scoria fall deposits associated with the formation of Blue Lake crater are >10 ka in age. Platey-jointed 3-5 m thick lava flows are intercalated between the intensely welded agglutinate units and rheomorphic flows. Scoria bomb beds display rapid lateral transitions from proximal, oxidised, moderately- to intensely-welded agglomerate, to medial/distal, non-oxidised, non-welded scoria fall material. Up to metre-sized, breadcrusted-scoriaceus ballistic blocks are scattered around the crater rim and the northern slopes of the Blue Lake cone. Blue Lake has a diameter of 400 m and is 16.5 m deep, with a pH of 5.

Stop 11: North Crater welded agglutinate viewpoint (1700 m)

The track takes us between the Blue Lake and North Crater cones, and as we sidle around the flanks of North Crater we can observe andesitic welded tuffs and agglutinates with vertical cooling joints. The flat-topped North Crater spatter cone was probably built up at about the same time as the one at Blue Lake, although it is possibly not quite as old. Nairn et al. (1998) used overlying tephra to constrain the age of the youngest North Crater lava flows to the c.14 ka Rotoaira eruption sequence. Topping (1973, 1974) and Donoghue et al. (1995) suggested that the c.9.8-10 ka subplinian Pahoka Tephra and Te Rato Lapilli were erupted from a vent at or near North Crater, but recent mapping of proximal-medial tephra sections enabled Nairn et al. (1998) to show that the source vents are further to the south. The 1 km wide, level surface of North Crater is a solidified lava lake, a section through which is exposed in a c.40 m deep and 300 m wide explosion pit present on the northwest side (Table 2). Remnants of the encircling crater rim are composed of 1-10 m thick welded agglutinates, and rheomorphic tuffs, formed during hawaiian-strombolian style fire-fountaining eruptions. Proximal scoria flow and fall deposits are preserved on the outer slopes of the cone.

Stop 12: Te Mari Crater lava flow viewpoint (1600 m)

From the track we can look eastwards and observe the distinctive morphology of a c.4 km long andesitic lava flow from Upper Te Mari Crater. This is one of the youngest flows to have come from the Upper Te Mari Crater, most of them directed in multiple, overlapping lobes down the NW slopes and one into the lower crater. These flows are younger than the Taupo pumice (ie. <1.85 ka) and have been tree-ring dated by Topping (1974) at c.1500AD. Activity in the Te Mari area probably began about 13.8 ka with the subplinian eruption of the NE- and SE-dispersed Rotoaira Lapilli from the Lower Te Mari Crater (Topping, 1973). A large levéed flow directly north of Lower Te Mari Crater is overlain by Papakai Formation, leading Topping (1974) to suggest an age of c.6-9.7 ka. Historic phreatic and phreatomagmatic eruptions were observed from Lower Te Mari Crater by the Maori and early Europeans (in 1839 and 1867; Gregg, 1960), and from Upper Te Mari Crater between 1868 and 1897 (e.g. Hill, 1894). With a duration of activity spanning at least 14 ka, the Te Mari Craters represent the most long-lived of the young eruptives.

Stop 13: Ketatahi Springs viewpoint (1340 m)

The Tongariro complex contains several small geothermal areas at Ketatahi Hot Springs, Te Mari Craters, Red Crater and Ngauruhoe. Most of these surface manifestations are believed to be fed by the same underlying vapour-dominated system (with an area of 15-20 km²), formed from a combination of magmatic steam mixed with circulating meteoric water (Wilson, 1960; Moore and Brock, 1981; Hochstein, 1985). Equilibrium temperatures of 230-290 C have been inferred for the Tongariro geothermal system (Hochstein, 1985).

Ketatahi Springs, the major area of thermal activity on the Tongariro complex, are located on the northern slopes of North Crater, and the mineral-laden waters have long been respected for their medicinal powers by the local Maori people, who retained ownership of this small area when the rest of Tongariro (and Ruapehu) was gifted as a national park to the people of New Zealand in 1887. We can obtain a view of the springs from the track, but please respect that access is prohibited on this private land. Present at Ketatahi are fumaroles (some superheated up to 138 °C), hot springs, mud pools and thermally altered ground with sulphur deposition covering an area of c.16 000 m² (Wilson, 1960; Moore and Brock, 1981). The hot springs discharge acid-sulphate waters (characterised by high concentrations of SO₄, B, Mg, NH₄, Ca; very low concentrations of Cl and F), and a maximum heat output has been estimated at 100-130 MW (Moore and Brock, 1981). Gregg (1960) found no evidence for major eruptions from Ketatahi, although a lahar was generated down the Mangatipua Stream in about 1895. We will see exposures through this lahar alongside the track just past the springs. We now descend the tussock slopes of the volcano to the forest bushline, then on through the podocarp-hardwood forest to the end of the Tongariro traverse at the Ketatahi road end.

Days 2 - 3 (Saturday - Sunday): Geology of the Whakapapa skifield and Turoa - upper Mangaturuturu areas, Ruapehu volcano

Introduction

Ruapehu volcano is the largest of the andesite volcanic edifices in the Tongariro National Park with a volume of around 110 km³ (Hackett and Houghton, 1988). The summit (Tahurangi, 2797m) is permanently snow-capped and supports a number of near permanent snow and ice fields. A crater lake partially fills the present day active crater in the plateau-like summit area and phreatic and phreatomagmatic explosions through this lake have been responsible for a number of minor eruptions and lahars over the last 50 years, the last event being the eruptions of September 1995 - July 1996. This event ejected phreatomagmatic tephra through the vent, produced lahars down a number of catchments, and when the lake water ($9 \times 10^6 \text{ m}^3$) was finally emptied (12 October 1995) strombolian eruptions deposited vesicular tephra. When activity resumed in July 1996 spectacular incandescent strombolian fire fountaining accompanied eruptions between 18 - 19 July.

A lahar, resulting from failure of the natural dam wall of the crater lake, was directly responsible for the Tangiwai Disaster on Christmas Eve 1953, when the Wellington - Auckland express train plunged into the swollen waters of the Whangaehu River after bridge supports had been swept away by a lahar. More than 150 lives were lost in New Zealand's greatest natural disaster.

Topping (1973), Donoghue et al (1995) and Donoghue and Neall (1996) have reported the detailed tephrostratigraphy of andesitic tephra from the Tongariro Volcanoes and Hackett (1985) and Hackett and Houghton (1988) described the proximal stratigraphy of Ruapehu volcano in detail, recognising four main stratigraphic formations. Recent mapping and new geochronologic data (Price et al., 2000) have enabled some refinement of this stratigraphy (Table 3). The distribution of the major flow formations is shown in Figure 13.

Table 3: Volcanic stratigraphy – lava sequences on Ruapehu Volcano

Formation	Age	Method
Whakapapa Formation	<10 ka	Overlying tephra sequences
Mangawhero Formation - Eastern segment	20-29 ka	Ar/Ar
Mangawhero Formation -Southwestern segment	37-53 ka	Ar/Ar
Wahianoa Formation	130-147 ka	Ar/Ar
Te Herenga Formation	183-205 Ka	Ar/Ar

Data from Stipp (1968); Tanaka et al, (1997); Gamble et al, (1998), and W. McIntosh et al. (unpublished data).

Andesites are the dominant lava type throughout Ruapehu but overall the lavas range between basalt and dacite. Graham and Hackett (1987) identified six lava types on Ruapehu, based upon a combination of petrographic and geochemical parameters.

- *Type 1:* Plagioclase-pyroxene phyric lavas, which are the dominant lava type in all Tongariro Volcanic Centre volcanoes, occurring in all the Ruapehu formations. Phenocrysts range from 15 - 40% comprising plagioclase > pyroxene > olivine. The latter only occurs in the most basic lavas and orthopyroxene exceeds clinopyroxene in the more acidic lavas.
- *Type 2:* Plagioclase phyric lavas, which are probably accumulative with respect to plagioclase.
- *Type 3:* Pyroxene -(olivine)- phyric lavas which represent accumulative lavas transitional from Type 1 but richer in pyroxene ± olivine.
- *Type 4:* Pyroxene phyric lavas, which are similar, petrographically, to Type 3 yet chemically distinctive.
- *Type 5:* Olivine - pyroxene phyric lavas with plagioclase restricted to groundmass.

- *Type 6*: Hybrid lavas with phenocrysts showing marked disequilibrium textures and abrupt chemical zonation.

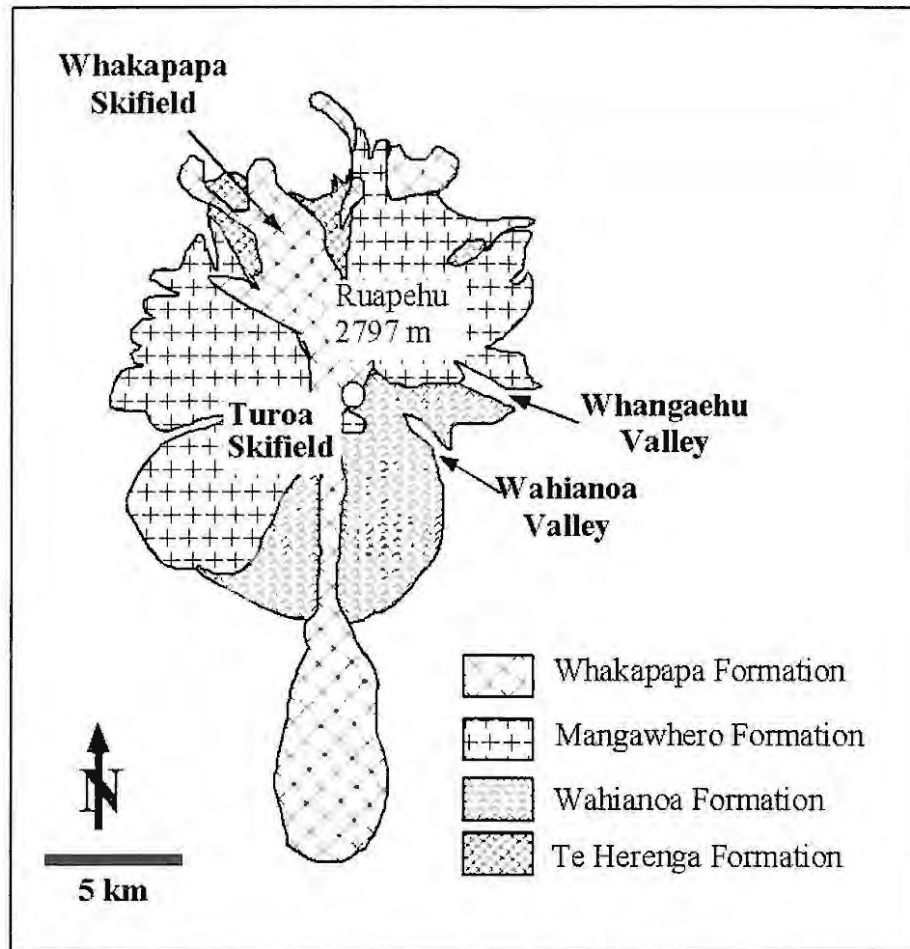


Figure 13: Distribution of major flow formations on Ruapehu (after Hackett, 1985).

The six types reflect the complexity of magmatic processes beneath an established andesite volcano. Processes that operate include: source heterogeneity, mixing, hybridisation, fractional crystallisation and assimilation (AFC). Some or several of these can be demonstrated to have operated simultaneously. Graham and Hackett (1987) reported an overall positive correlation between Sr - isotope ratios and SiO₂ content and noted that both appeared to increase with time, consistent with their model of combined AFC.

Recent and more detailed studies of the chemical stratigraphy of Ruapehu andesites (Price et al. 1997; Gamble et al., 1999) have indicated that trends identified by Graham and Hackett (1987) are true only in a general sense. Closer inspection of the geochemical relations between successive flow units in carefully measured sections reveals marked breaks and reversals in cycles consistent with mixing, mingling and recharge, probably at relatively shallow depths in the edifice. Furthermore, the products of the 1995 - 1996 eruptions encompass the entire field of compositions erupted during the previous 50 years and indeed, span a considerable proportion of the compositional range defined by prehistoric lavas (Figure 14 - Gamble et al., 1999).

Graham and Hackett (1987) argued that Types 1-3 Ruapehu andesites were produced when fractionating mafic magmas assimilated partially melted basement greywacke. Type 5 andesites were considered to have been generated by crystal fractionation without crustal assimilation, and the geochemical characteristics of Type 6 andesites were interpreted to arise in part from magma mixing. In contrast, Gamble et al. (1999) concluded that, although the broad patterns of geochemical variation are consistent with control by assimilation and crystal fractionation, relatively rapid and unsystematic variations in magma composition over relatively short time intervals appear to reflect complex magma mixing and mingling in small, high level reservoirs such as dykes and sills. This model appears to be consistent with the variations in geochemical composition observed throughout the eruptive history of Ruapehu.

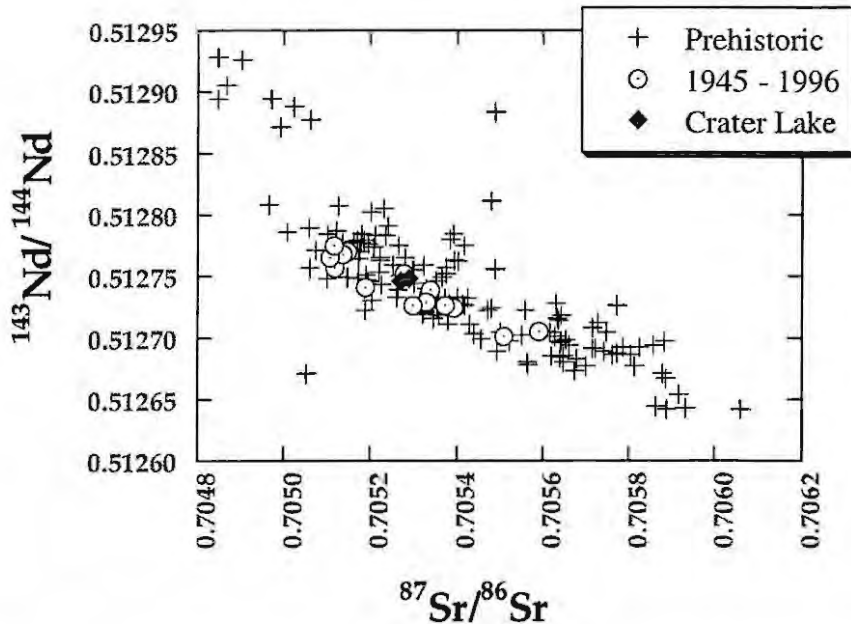


Figure 14: Sr and Nd isotopic compositions for modern (1945-1996) eruptives and comparison with prehistoric lavas from Ruapehu (from Gamble et al., 1999).

Day 2 - The Whakapapa skifield area

Within the Whakapapa skifield area, three of the major lava flow formations of Ruapehu are exposed (Map 1 – page 28). The principal outcrops of Te Herenga Formation occur along Pinnacle Ridge, between the Whakapapaiti and Whakapapanui river valleys. Outcrops of this unit also occur in the Whakapapaiti valley. Lavas of the Mangawhero Formation are exposed along the southern side of the Whakapapaiti valley, and flows of the Whakapapa Formation outcrop extensively between the Whakapapaiti valley and Pinnacle Ridge (Map 1). The purpose of this excursion is to examine the flows of the Whakapapa and Te Herenga Formations and relationships between these two formations and younger tephra units.

Whole rock geochemical analysis of the Te Herenga Formation (Valente, 1995) has demonstrated a limited range in compositional variation within the flows of this unit. SiO₂ abundance ranges from 56-57.4 wt% and MgO content from 4.53-5.15 wt%. In contrast, Mangawhero and Whakapapa Formation flows are much more variable. For example, Whakapapa Formation flows show SiO₂ contents ranging from 57-60 wt% and MgO abundances range from 4.6-5.3 wt% and for the Mangawhero Formation SiO₂ content ranges from 57 wt% to 64.5 wt% and MgO abundance is in the range 3-7.4 wt%.

The oldest and youngest formations exposed in the Whakapapaiti catchment show distinctly different geochemical characteristics. Lavas of the Te Herenga formation are relatively low in K₂O (mean=0.73%) and SiO₂ (mean = 56.63%), and have lower ⁸⁷Sr/⁸⁶Sr ratios (mean = 0.70495) than younger flows. The Te Herenga lavas also show relatively limited variability (eg. K₂O range = 0.55-0.92% - see Figure 15). In contrast, successively younger lavas show higher K₂O and progressively more variability with relatively evolved (higher SiO₂) lavas becoming more common.

Lavas of the Whakapapa Formation (<15 ka) have a mean K₂O abundance of 1.52% and the range in SiO₂ content is 55.5 - 61.2% (mean = 58.38%). Younger lava sequences also tend to have more radiogenic Sr isotopic compositions; Whakapapa lavas show a mean ⁸⁷Sr/⁸⁶Sr ratio of 0.7053.

Mapping by Schneider (1995), along the southern side of the Whakapapaiti valley and new geochemical data have been used to separate a younger group of flows from those of the Mangawhero Formation (Figure 13). These have been informally termed Whakapapaiti flows and they predate the flows of Hackett's (1985) Whakapapa Formation (Map 1).

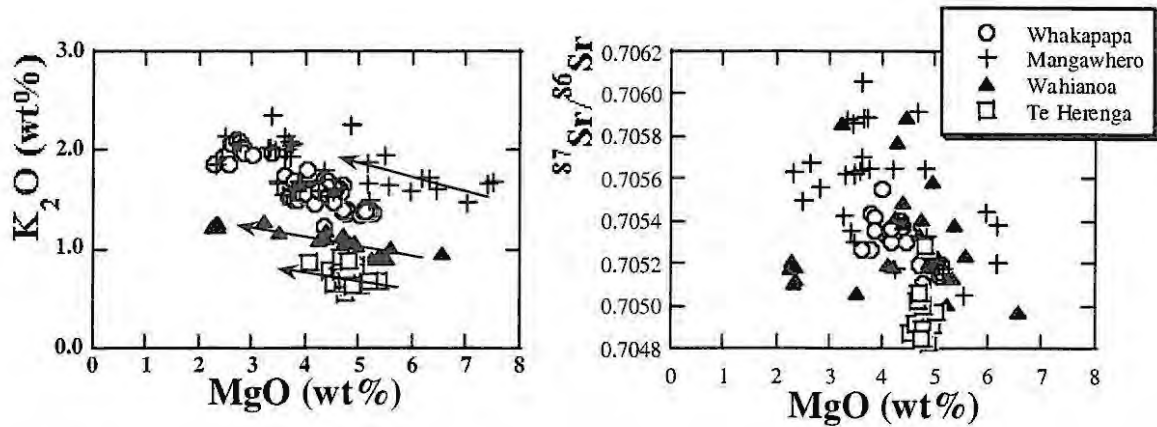


Figure 15: K_2O content and $^{87}Sr/^{86}Sr$ versus MgO abundance for Ruapehu lavas. Formation names are explained in Table 1. Arrows show broad trends within each formation.

Detailed mapping and geochemistry within the Whakapapa Formation provide the basis for subdividing the Formation into several sub-units. From oldest to youngest, these have been termed: Amphitheatre, Lower Bruce Road, Happy Valley, Staircase, Lower Te Heuheu, Upper Te Heuheu, Knoll Ridge, National Downhill, and Delta Corner flows (Map 1). Except for the Delta Corner flows, all of these sub-units show similar major, trace element, and Sr/Nd isotopic characteristics. All are strongly porphyritic andesites (SiO_2 content 57-60 wt%) with phenocryst abundances (plagioclase > orthopyroxene > clinopyroxene > magnetite) being typically between 45-50% of the rock. Most rocks are vesicular (up to 15% vesicles) and many contain an abundance of small (1-5 cm) quartzofeldspathic and granulitic xenoliths.

Delta Corner flows are relatively less evolved and have relatively less radiogenic Sr isotopic compositions than is the case for the rest of the Whakapapa Formation (Figure 16).

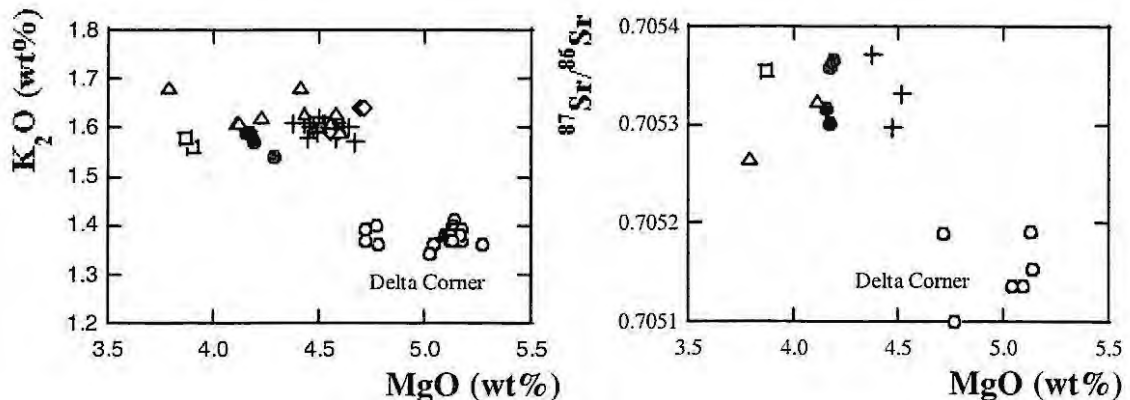


Figure 16: K_2O content versus and $^{87}Sr/^{86}Sr$, Filled circles = Knoll Ridge, Squares = Upper Te Heuheu, Crosses = Happy Valley, Triangles versus MgO abundance for Whakapapa Formation lavas (open circles = Delta Corner, Diamonds = National Downhill = Amphitheatre).

Collectively, the samples from the Whakapapa Formation define scattered trends on variation diagrams that are broadly consistent with control by assimilation and crystal fractionation. Within specific groups of flows, however, the patterns are more complex and are best explained in terms of open system magma mixing or mingling processes taking place in a system of dykes and sill within the sub-volcanic feeder system (Price et al., 1997; Gamble et al., 1999).

Table 4: Representative analyses - Whakapapa skifield area. TH = Te Herenga Formation (numbers in parenthesis are flow units of Valente (1995). For Whakapapa Formation- Amph= Amphitheatre, HV=Happy Valley, UTH=Upper Te Heuheu, KR=Knoll Ridge, DC= Delta Corner flows. PC (W) and PC (T/M) are chocolate pumice clasts from Whakapapa and Turoa areas respectively.

	T6/9 TH (9)	T6/16 TH (4)	T6/19 TH (2)	97/78 Amph	97/76 HV	97/82 HV	97/100 UTH	97/96 KR	97/90 DC	95/30 PC (W)	97/4 PC(T/M)
SiO ₂	57.21	56.04	56.02	58.67	58.80	58.81	61.17	59.26	57.70	57.93	57.64
TiO ₂	0.65	0.67	0.66	0.67	0.68	0.67	0.61	0.67	0.68	0.66	0.77
Al ₂ O ₃	16.74	17.37	17.50	17.04	16.92	16.72	16.47	16.79	16.74	16.64	16.86
Fe ₂ O ₃	2.72	2.79	3.42	1.16	1.63	1.25	1.49	1.31	1.30	6.78	1.96
FeO	5.23	5.30	4.47	5.21	4.89	5.11	4.40	5.16	5.68		5.34
MnO	0.14	0.15	0.14	0.14	0.11	0.14	0.13	0.14	0.15	0.11	0.15
MgO	4.62	4.78	4.72	4.11	4.53	4.16	3.63	4.18	4.72	4.52	4.11
CaO	7.48	7.99	7.57	6.99	6.98	6.98	6.33	6.90	7.56	7.16	7.46
Na ₂ O	3.32	3.30	3.36	3.44	3.37	3.45	3.49	3.37	3.39	3.28	3.19
K ₂ O	0.73	0.71	0.78	1.61	1.61	1.59	1.74	1.59	1.39	1.46	1.47
P ₂ O ₅	0.08	0.09	0.09	0.15	0.14	0.14	0.14	0.15	0.14	0.11	0.15
H ₂ O+	0.22	0.17	0.51	0.41	0.50	0.43	0.46	0.47	0.33	0.26	0.29
H ₂ O-	0.09	0.48	0.40	0.14	0.22	0.13	0.14	0.11	0.22	0.2	0.1
CO ₂	0.16	0.03	0.02	0.05	0.10	0.06	0.06	0.06	0.04	0.04	0.05
	99.39	99.87	99.66	99.79	100.48	99.64	100.26	100.16	100.04	99.15	99.54
Cs	0.5	0.2	0.6	4.4		5.2	8.5	10.8	4.4		3.9
Ba	220	209	273	387	387	400	390	495	380	365	341
Rb	16	14	17	58	59	61	67	61	49	49	57
Sr	217	226	235	269	272	273	244	271	288	264	248
Pb	3.2	2.3	5.2	9.3	9	10.1	12.9	16.1	9.7	9	11.3
Th	1.4	1.1	1.7	4.9	11	4.9	5.7	6.6	4.3	5	4.6
U	0.5	0.4	0.6	1.6	2	1.6	1.8	2	1.3	2	1.2
Zr	56	52	53	122	124	124	118	123	107	121	117
Hf	2.2	1.9	2	3.5		4.1	3.3	4.2	3.5		3.1
Nb	2.2	2.1	2.1	5.1	5	5.1	4.8	6.3	4.3	2	4.7
Y	18	18	18	20	20	20	19	19	18	19	21
La	5.5	5.7	7.0	14.2		14.3	13.3	16.3	10.9		12.6
Ce	12.9	12.7	15.0	31.6		31.2	29.0	35.6	24.6		27.6
Pr	1.9	1.9	2.1	4.1		4.0	3.7	4.5	3.1		3.6
Nd	8.4	8.4	9.3	16.2		15.9	13.6	17.8	12.7		14.3
Sm	2.4	2.3	2.5	3.7		3.4	3.2	4.0	3.0		3.3
Eu	0.87	0.80	0.82	0.98		0.96	0.78	1.15	0.92		0.96
Gd	2.76	2.62	2.65	3.68		3.57	3.21	4.08	3.12		3.69
Tb	0.48	0.44	0.44	0.58		0.55	0.51	0.67	0.52		0.55
Dy	2.88	2.75	2.71	3.34		3.36	3.06	3.90	3.12		3.27
Er	1.83	1.72	1.67	1.94		1.93	1.79	2.37	1.86		0.21
Yb	1.86	1.82	1.70	2.01		2.07	1.87	2.57	1.95		1.98
Lu	0.30	0.28	0.26	0.31		0.32	0.31	0.40	0.32		0.32
Sc	30.3	26.8	25.3	24.6	24	25.8	21.4	30.7	29.1	31	26
V	201	180	175	166	216	159	141	161	185	208	199
Cr	150	228	147	72	80	74	63	73	72	88	58
Ni	24	24	24	33	34	33	25	33	38	38	14
Cu	31	52	80	38	47	52	40	43	43	53	37
Zn	68	63	65	59	61	63	57	64	66	69	71
Ga	16	17	17	23	23	23	23	24	23	16	22
⁸⁷ Sr/ ⁸⁶ Sr	0.70491	0.70485	0.70506	0.70533		0.70532	0.70526	0.70536	0.70519		0.70538
¹⁴³ Nd/ ¹⁴⁴ Nd	0.51289	0.51289	0.51288	0.51276		0.51273	0.51273	0.51273	0.51275		0.51278

Major element analyses by XRF. Trace elements by XRF and ICPMS (italics). Data from Valente (1995) and R.C.Price (unpublished data).

Route Guide (Day 2)

Stop 1: Whakapapa Formation Andesite and Taupo Pumice

At this locality lava flows of the Whakapapa Formation (Happy Valley unit) appear to overlie rhyolitic Taupo Pumice. The latter has been dated at 1850 years B.P. (Froggatt and Lowe, 1990) and this locality therefore provides evidence to suggest that Happy Valley Flows are very young (V.E. Neall, *Pers. Comm.* 1998). Since the Happy Valley Flows are some of the oldest flows of the Whakapapa Formation, relationships at this locality would imply that most of the Whakapapa Formation was erupted post Taupo Pumice. Elsewhere on the Whakapapa Skifield, however, tephra sequences containing Taupo Pumice have been found overlying flows that appear to be younger than the Happy Valley Flows. The interpretation of this particular locality therefore remains problematic.

The lavas of this locality are petrographically typical of Whakapapa Formation. They are strongly porphyritic with plagioclase + clinopyroxene + orthopyroxene + Fe-Ti oxides ± rare olivine as the principal phenocrysts. Xenoliths of basement derived quartzite, meta-sediments and meta-igneous rocks are common. An analysis of a sample from this flow (sample 97/76) is shown in Table 4.

Stop 2: Meads Wall, Happy Valley

Meads Wall is formed by a dyke of andesite that cuts hydrothermally altered pyroclastic deposits of the Te Herenga Formation. From this vantage point an excellent view of the angular discordance between the younger (post-glacial), valley filling, Whakapapa Formation lava flows and the older Te Herenga Formation (pre-glacial) lavas can be appreciated. Whakapapa lavas have ramped up onto glaciated outcrops of the older formation. The lava flows of the Whakapapa Formation show complex internal structures. Folds on various scales are defined by variations in glass preservation and many flows show internal shear zones. Note the porphyritic nature of the Whakapapa flows and the abundance of quartzofeldspathic and granulitic xenoliths.

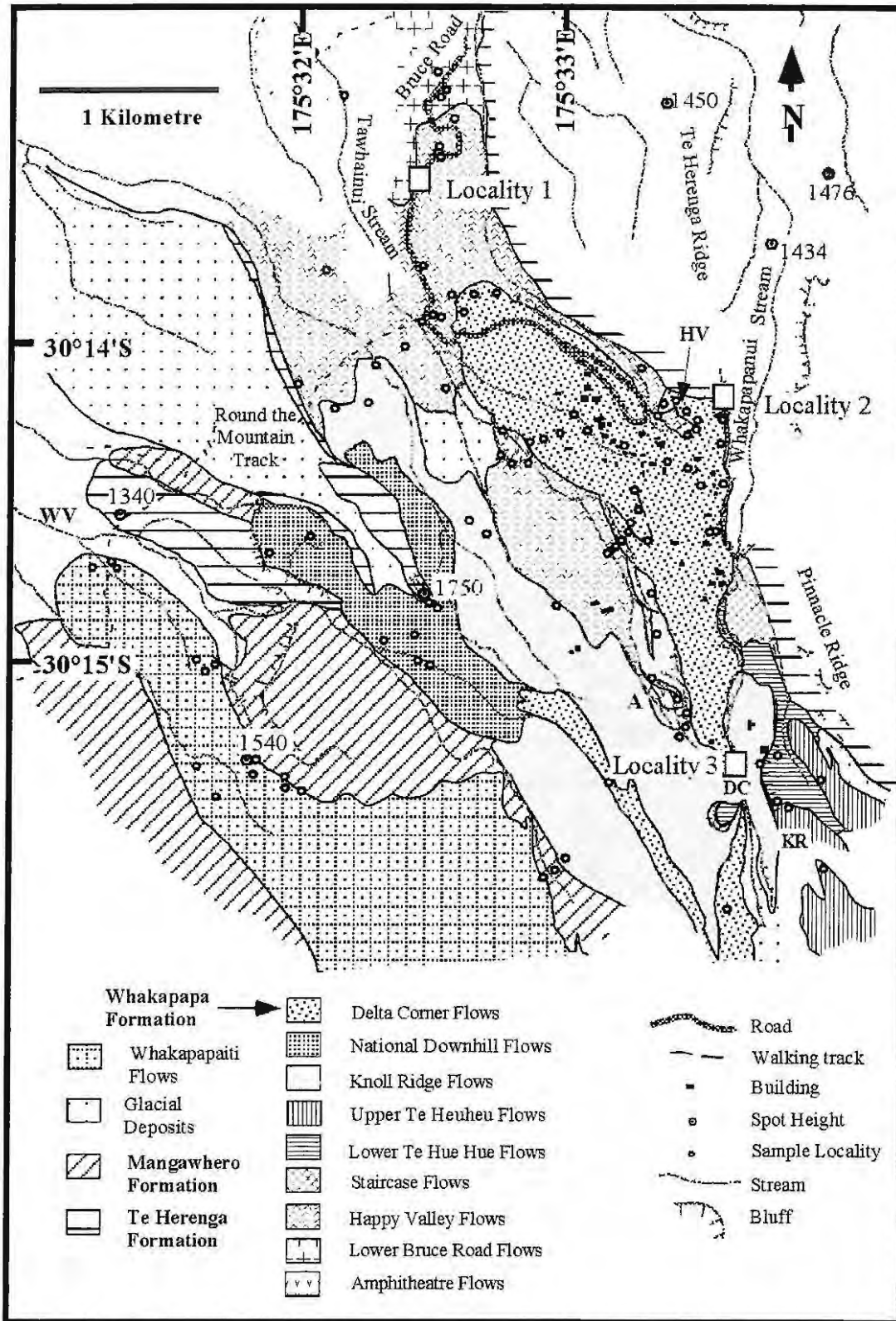
Te Herenga lavas are much less glassy than Whakapapa flows but are still distinctly porphyritic (30-40% plagioclase phenocrysts, 10-18% pyroxene phenocrysts, 2-5% magnetite, and 34-52% groundmass). Representative analyses of flows from the Te Herenga Ridge to the west of Meads Wall are shown in Table 4.

The Te Herenga lavas are in places hydrothermally altered and cut by shallow tonalitic intrusions. They form the jagged peaks of Pinnacle Ridge. Looking northeast from this vantage point in the direction of Ngauruhoe composite cone, the northern flanks of Pinnacle Ridge are draped with a distinctive welded air-fall andesite deposit whose source Hackett (1985) inferred to be in the summit area near Pinnacle Ridge.

Clasts of chocolate brown pumice are scattered across the surface of flows in the Happy Valley area. This material occurs in a number of localities on the mountain and is believed to represent fall from a significant plinian event that post-dates most Whakapapa Formation flows. Some representative analyses of this material are shown in Table 4.

Stop 3: Delta Corner, Whakapapa Flows

Whakapapa Formation flows are well exposed at Delta Corner to the south of the top of the Waterfall Express Quad Chairlift. Here, the Delta Corner flows directly overlie flows belonging to the Knoll Ridge group. Representative analyses of each unit are presented in Table 4. To the southwest, flows of the Whakapapaiti group can be seen near the edge of the summit crater. These flows are older than the Whakapapa flows and form bluffs marking the edge of a basin that may have formed in response to a sector collapse event that produced the Morumoto lahar deposits (dated at ~9500 years) on the ring plain below the Chateau (Palmer and Neall, 1989).



Map 1: Whakapapa Skifield

Stop 4: Crater rim

Note – a visit to this locality will depend on weather and circumstances on the day.

From Delta corner the route to the crater rim and Dome Shelter is along the surface of flows of the Knoll Ridge group, younger, overlying flows sourced from the summit, pyroclastic debris from summit eruptions, and extensive snow fields. The polished surfaces on many of the lava flows in this sequence show excellent examples of striations, which have traditionally been interpreted to be of glacial origin. We note, however, that pyroclastic deposits and lahars may also leave striated surfaces. The Dome Shelter is located on pyroclastic flows forming the north wall of the crater rim.



1988

1998



Figure 17: Crater Lake Contrast – pre and post 1995/1996 eruptions

From the shelter, the view south takes in Ruapehu summit and, to the east, the outlet to the Whangaehu gorge. The upper part of the Whangaehu section through Wahianoa Formation (130-147 ka) flows is visible above the outlet and Mitre Peak is also composed of flows of this formation and possibly also deposits of the younger Mangawhero Formation (37-57 ka). Flows of the Mangawhero Formation form the bluffs to the southwest on the southern side of the Whakapapa Glacier. The unconformity between the Mangawhero and Waihianoa Formations is well exposed on Girdlestone Peak (Hackett, 1985). Tephra deposits, which plastered the cliffs on Tahurangi and the Pyramid immediately following the 1995/96 eruptions have now been removed by erosion and repeated freeze-thaw events (Figure 17).

Day 3 - The Turoa- upper Mangaturuturu valley area

The purpose of this part of the excursion is to examine relationships between flow units and tephra sequences exposed on the southern side of Ruapehu Volcano near the Turoa skifield in the upper Mangaturuturu valley. The excursion begins on the Ohakune Mountain Road and follows the Round the Mountain Track into the Mangaturuturu valley.

The Ohakune Mountain Road passes upwards through Rimu and Kamahi forest into beech forest and finally into sub-alpine scrub (manuka and totara) and tussock shrubland. Above bushline, there are excellent exposures of lava flows belonging to Hackett's (1985) Mangawhero and Whakapapa Formations.

Table 5: Stratigraphy and chronology of andesitic and rhyolitic tephras – Ruapehu (from Donoghue et al., 1995 and Nairn et al., 1998 and references therein).

Rhyolitic Tephra*	Andesite Tephra	Member	Source	Age (years) 14C
<i>Kaharoa</i>	Tufa Trig Formation	Tf18-Tf8	Ru	<i>770±20</i>
	Ngauruhoe Formation		TgVC	
<i>Taupo</i>	Tufa Trig Formation	Tf7-Tf1	Ru	<i>1850±10</i>
	Ngauruhoe Formation		TgVC	
<i>Mapara</i>	Mangatawai Tephra		Ng	<i>2160±25</i>
			<i>Taupo</i>	
<i>Waimahia</i>	Mangatawai Tephra		Ng	<i>2500±200</i>
	Papakai Formation		TgVC	
<i>Hinemaiaia</i>	Papakai Formation	Black Ash - 2	Ru	<i>3280±20</i>
			<i>Taupo</i>	
<i>Whakatane</i>	Papakai Formation	Black Ash - 1	Ru	<i>4510±20</i>
	"	Orange Lapilli - 2	"	
	"	Orange Lapilli - 1	"	
			<i>Ok</i>	
<i>Poronui</i>	Papakai Formation		TgVC	<i>4830±20</i>
	Mangamate Formation		Tong	
	"	Poutu Lapilli	"	
	"	Wharepu Tephra	"	
<i>Karapiti</i>	Mangamate Formation		<i>Ok</i>	<i>9780±170</i>
	"	Ohinepanga Tephra	"	
	"	Waihohonu Tephra	"	
	"	Unnamed tephra	"	
	"	Oturere Tephra	"	
		Te Rato Lapilli	"	
<i>Karapiti</i>		Unnamed tephra	<i>Taupo</i>	<i>9820±80</i>
	Pahoka Tephra		Tong	
	(Upper) Bullot Formation		Ru	

TgVC – Tongariro Volcanic Centre, Tong. – Mt. Tongariro, Ru – Mt. Ruapehu, Ng – Mt. Ngauruhoe, Ok- Okataina Volcanic Centre.

*Key rhyolitic tephra, sourced from Taupo or Okataina (Ok) centres and dated by the radiocarbon method, are shown in italics. These tephra provide distinctive markers to which the andesitic tephra of Tongariro Volcanic Centre (TgVC) and Ruapehu (Ru) can be related.

Recent mapping by Waight et al. (2000) has established a more refined stratigraphy (Map 2 – page 36) and detailed examination of tephra sequences (R.B. Stewart and S.L. Donoghue, *Pers. Comms.* 1999) on these flows has enabled better definition of age relationships.

The tephra stratigraphy applicable to the Turoa/ Mangaturuturu area has been established by work carried out by Donoghue et al. (1995) on the ring plain to the south and east of Ruapehu. The upper part of this stratigraphy,

covering the past 10,000 years of eruptive activity from the Tongariro Volcanic Centre and Ruapehu, is summarised in Table 5.

Using the tephra stratigraphy and mapping, we have defined a number of flow units in the Turoa area and these are summarised in Table 6. Two samples from the Mangaturuturu group of flows have recently been dated by the $^{40}\text{Ar}/^{39}\text{Ar}$ method (W. McIntosh et al., unpublished data). One sample gives an age (26 ± 9 ka) consistent with those obtained for Mangawhero Formation material from elsewhere on the mountain. The other gives a much older age (147 ± 10 ka) that could be used to suggest that some of the Mangaturuturu flows belong to the Wahianoa Formation. Representative analyses of flow units are provided in Table 7.

In a recent paper, Nairn et al. (1998) suggested that Pahoka-Mangamate tephra and pyroclastic deposits, dated by the ^{14}C method at around 10,000 years B.P., were erupted from multiple vents along a northeast to southwest line extending from Lake Taupo in the north to southern Ruapehu. The Rangataua flows, to the east of the Turoa skifield appear to be associated with most southerly of these vents and the tephra stratigraphy on these flows (R.B. Stewart and R.C. Price, unpublished data) is consistent with a 10,000 year age for these flows (see Table 6).

Turoa lavas show a wide range in textural variation. Phenocryst (plagioclase, pyroxene, and magnetite) abundances range from 7-51% and plagioclase (An₄₀₋₅₅) is generally the dominant phenocryst phase. Plagioclase phenocrysts show complex oscillatory zoning and many show complex textures indicative of resorption and regrowth. Some examples show sieve textured cores containing abundant inclusions of brown glass others show narrow reversely zoned rims.

The ratio of clinopyroxene to orthopyroxene phenocrysts varies significantly [$\text{cpx}/(\text{cpx}+\text{opx}) = 0-100\%$ but mostly in range 20-65%]. Most lavas are Type 1-4 andesites according to the classification of Graham and Hackett (1987) with Types 1 and 2 dominating. The groundmass varies in terms of glass content with most of the younger flows having groundmasses dominated by brown glass and some of the older flows having more crystalline groundmasses containing microlites of plagioclase, pyroxene and opaques.

Geochemically, the lavas of the Mangaturuturu valley and Turoa skifield are dominantly medium K-andesites and SiO_2 contents range between 57 and 62% (Figure 18) although one or two basaltic andesites are represented among Mangaturuturu A flows. Both older (pre 10,000 years) and younger flows show considerable variability in composition, but for the younger flows, the groupings identified in the field appear to be more coherent.

In terms of strontium isotopic composition (Figure 18), the older flow groups show considerable variation and this may simply reflect poorer resolution in the field of specific stratigraphic relationships so that unrelated flow units have been inadvertently associated; lateral relationships between older flows are commonly obscured by younger material making correlations between even adjacent river valleys problematic. The younger flow units generally form coherent groupings in terms of overall composition and isotopic composition. The youngest lavas of Sunset Ridge group (Sunset B) show chemical compositions similar to those observed in the younger Whakapapa flows (Figure 19 and see above).

Table 6: Stratigraphy and chronology of andesitic flows in the Turoa – Mangaturuturu area (see Map 2)

Flow Unit	Probable age	Method
Tahurangi		
Sunset Ridge A		
Sunset Ridge B	>5,000 years	Tephra stratigraphy
Turoa		
Rangataua	9,700 - 11,250 years	Tephra stratigraphy
Mangaehuehu B		
Mangaehuehu A		
Mangaturuturu D		
Mangaturuturu B/C	26,000 years	Ar/Ar
Mangaturuturu A	147,000 years	Ar/Ar

Table 7: Representative analyses from the Mangaturuturu-Turoa area. M/A = Mangaturuturu A, M/B = Mangaturuturu B, M/D = Mangaturuturu D, R = Rangataua, S/A = Sunset Ridge group A, S/B = Sunset Ridge group B flows.

	97/50	97/112	97/58	95/15	97/4	97/23
	M/A	M/B	M/D	R	S/A	S/B
SiO ₂	56.50	59.94	58.82	58.95	57.64	61.71
TiO ₂	0.70	0.66	0.72	0.73	0.77	0.83
Al ₂ O ₃	17.14	14.78	15.28	17.03	16.86	16.85
Fe ₂ O ₃	1.92	0.82	1.51	7.03	1.96	0.86
FeO	5.64	5.16	5.02		5.34	4.69
MnO	0.16	0.13	0.14	0.12	0.15	0.11
MgO	4.76	5.53	5.98	3.37	4.11	2.58
CaO	7.88	6.94	7.15	6.46	7.46	5.80
Na ₂ O	3.15	3.14	2.99	3.34	3.19	3.72
K ₂ O	0.88	1.64	1.58	1.71	1.47	2.07
P ₂ O ₅	0.11	0.14	0.16	0.13	0.15	0.20
H ₂ O+	0.45	0.42	0.55	0.32	0.29	0.53
H ₂ O-	0.20	0.12	0.23	0.27	0.10	0.04
CO ₂	0.09	0.07	0.10	0.40	0.05	0.08
	99.58	99.49	100.23	99.86	99.54	100.07
Cs	<i>1.4</i>	<i>5.1</i>	<i>3.9</i>	<i>5.8</i>	<i>3.9</i>	<i>4.9</i>
Ba	<i>234</i>	<i>380</i>	<i>373</i>	<i>400</i>	<i>341</i>	<i>438</i>
Rb	<i>29</i>	<i>63</i>	<i>61</i>	<i>64</i>	<i>57</i>	<i>71</i>
Sr	<i>235</i>	<i>339</i>	<i>230</i>	<i>239</i>	<i>248</i>	<i>298</i>
Pb	<i>13.3</i>	<i>9.9</i>	<i>9.3</i>	<i>7.4</i>	<i>11.3</i>	<i>15.1</i>
Th	<i>2.4</i>	<i>5.2</i>	<i>5.3</i>	<i>5.8</i>	<i>4.6</i>	<i>5.8</i>
U	<i>0.7</i>	<i>1.7</i>	<i>1.5</i>	<i>1.8</i>	<i>1.2</i>	<i>1.5</i>
Zr	<i>80</i>	<i>137</i>	<i>124</i>	<i>146</i>	<i>117</i>	<i>144</i>
Hf	<i>2.1</i>	<i>3.7</i>	<i>3.5</i>	<i>4.4</i>	<i>3.1</i>	<i>3.9</i>
Nb	<i>6.8</i>	<i>5.7</i>	<i>5.0</i>	<i>6.0</i>	<i>4.7</i>	<i>5.7</i>
Y	<i>17</i>	<i>19</i>	<i>20</i>	<i>23</i>	<i>21</i>	<i>20</i>
La	<i>7.7</i>	<i>15.6</i>	<i>13.7</i>	<i>15.4</i>	<i>12.6</i>	<i>15.4</i>
Ce	<i>17.0</i>	<i>33.2</i>	<i>30.1</i>	<i>33.9</i>	<i>27.6</i>	<i>33.4</i>
Pr	<i>2.3</i>	<i>4.3</i>	<i>4.0</i>	<i>4.2</i>	<i>3.6</i>	<i>4.2</i>
Nd	<i>9.6</i>	<i>16.7</i>	<i>14.7</i>	<i>16.4</i>	<i>14.3</i>	<i>16.9</i>
Sm	<i>2.3</i>	<i>3.5</i>	<i>3.4</i>	<i>3.6</i>	<i>3.3</i>	<i>3.7</i>
Eu	<i>0.78</i>	<i>0.92</i>	<i>0.83</i>	<i>1.04</i>	<i>0.95</i>	<i>1.06</i>
Gd	<i>2.70</i>	<i>3.57</i>	<i>3.41</i>	<i>3.68</i>	<i>3.61</i>	<i>3.91</i>
Tb	<i>0.45</i>	<i>0.56</i>	<i>0.56</i>	<i>0.61</i>	<i>0.54</i>	<i>0.57</i>
Dy	<i>2.83</i>	<i>3.25</i>	<i>3.19</i>	<i>3.62</i>	<i>3.25</i>	<i>3.23</i>
Er	<i>1.66</i>	<i>1.87</i>	<i>1.85</i>	<i>2.19</i>	<i>2.01</i>	<i>2.00</i>
Yb	<i>1.76</i>	<i>1.91</i>	<i>1.88</i>	<i>2.33</i>	<i>2.00</i>	<i>1.99</i>
Lu	<i>0.28</i>	<i>0.28</i>	<i>0.30</i>	<i>0.38</i>	<i>0.31</i>	<i>0.31</i>
Sc	<i>30.5</i>	<i>26</i>	<i>25.9</i>	<i>22.8</i>	<i>25.5</i>	<i>17.3</i>
V	<i>215</i>	<i>151</i>	<i>172</i>	<i>183</i>	<i>199</i>	<i>167</i>
Cr	<i>60</i>	<i>223</i>	<i>272</i>	<i>29</i>	<i>58</i>	<i>12</i>
Ni	<i>23</i>	<i>64</i>	<i>86</i>	<i>9</i>	<i>14</i>	<i>6</i>
Cu	<i>51</i>	<i>65</i>	<i>49</i>	<i>24</i>	<i>37</i>	<i>34</i>
Zn	<i>68</i>	<i>58</i>	<i>60</i>	<i>74</i>	<i>71</i>	<i>62</i>
Ga	<i>22</i>	<i>22</i>	<i>22</i>	<i>16</i>	<i>22</i>	<i>24</i>
⁸⁷ Sr/ ⁸⁶ Sr	0.70515	0.70505	0.70544	0.70574	0.70538	0.70535
¹⁴³ Nd/ ¹⁴⁴ Nd	0.51275	0.51267	0.51270	0.51269	0.51273	0.51272

Major element analyses by XRF. Trace elements by XRF and ICPMS (italics). Data from Waight et al. (2000) and R.C.Price (unpublished data).

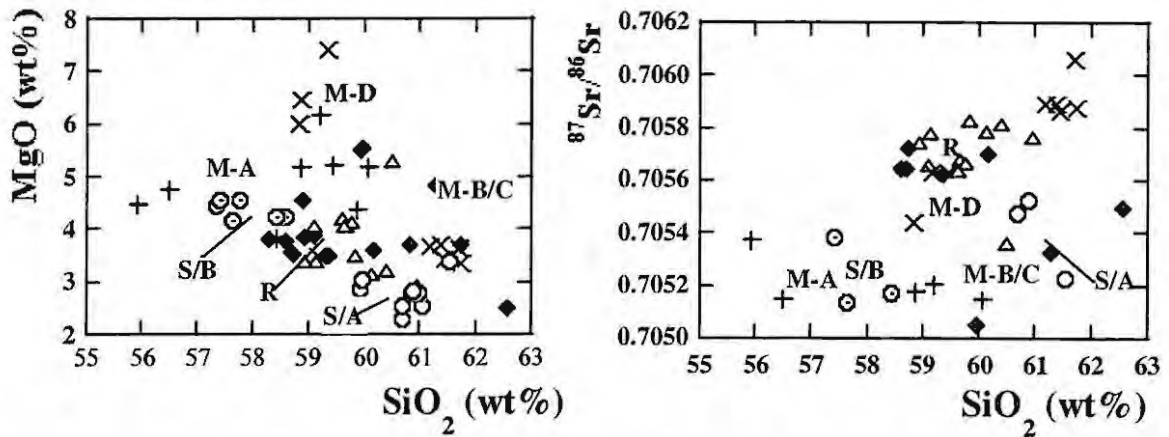


Figure 18: MgO versus SiO₂ and ⁸⁷Sr/⁸⁶Sr versus SiO₂ for flows from Turoa and the Mangaturuturu valley. In order of decreasing age the units are: M-A Mangaturuturu A, M-B/C Mangaturuturu B and C, M-D Mangaturuturu D, R Rangataua, S/A Sunset Ridge A, S/B Sunset Ridge B.

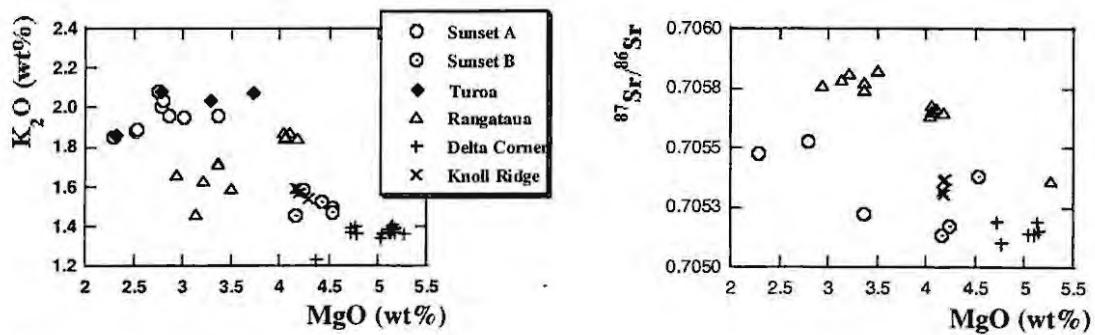


Figure 19: K₂O versus MgO and ⁸⁷Sr/⁸⁶Sr versus MgO for young (<15,000 years) flows from Turoa and the Mangaturuturu valley and comparisons with Whakapapa lavas (Delta Corner and Knoll Ridge). The Delta Corner and Knoll Ridge flows are two of the younger units of the Whakapapa Formation (see Day 2) and have been added for comparison.

Waight et al. (2000) noted that the range of compositional variation observed in the Mangaturuturu/Turoa area is almost as broad as that for the whole volcano. They were able to apply broad assimilation crystal fractionation models to explain the total variation observed within sample suite from the Mangaturuturu/Turoa areas. They attempted to examine sequential geochemical variation in two particular flow packages in an effort to understand the specific factors controlling the composition of flows erupted from the volcano at a particular time. A sequence of older flows was sampled in a waterfall in the upper part of an eastern branch of the Mangaturuturu River and a younger sequence of Sunset Ridge flows was sampled above the Turoa skifield carparks. In each case, it was not possible to demonstrate systematic changes in chemical composition with time. The sequences show wide and unpredictable variation in composition leading Waight et al. (2000) to conclude that the composition of each lava flow is a reflection of a complex interplay between crystal fractionation and crustal assimilation and mixing or mingling occurring within a complex plumbing system extending deep below the volcano.

Route guide (Day 3)

Stop 1: On the Round the Mountain Track, approximately 1 km NNW of the junction with the Ohakune Mountain Road.

A tephra sequence overlying Sunset Ridge lava flows is well exposed on both sides of the track at this locality (Figure 20). The top of the section (Ngauruhoe Formation) includes fine-grained, reworked, black ashes of the Tufa Trig Formation (Table 5) that form low amplitude dunes on the landscape (Makahikatoa Sands). Some of the Tufa Trig Fm tephras are also preserved, the most prominent of which is Tf 8. Beneath the Ngauruhoe Fm a 1-3 cm thick horizon of reworked Taupo Pumice (1.85 ka B.P.) is preserved. Traces of Mangatawai Tephra (c. 2.5 ka B.P.) can occasionally be found underneath the Taupo Pumice.

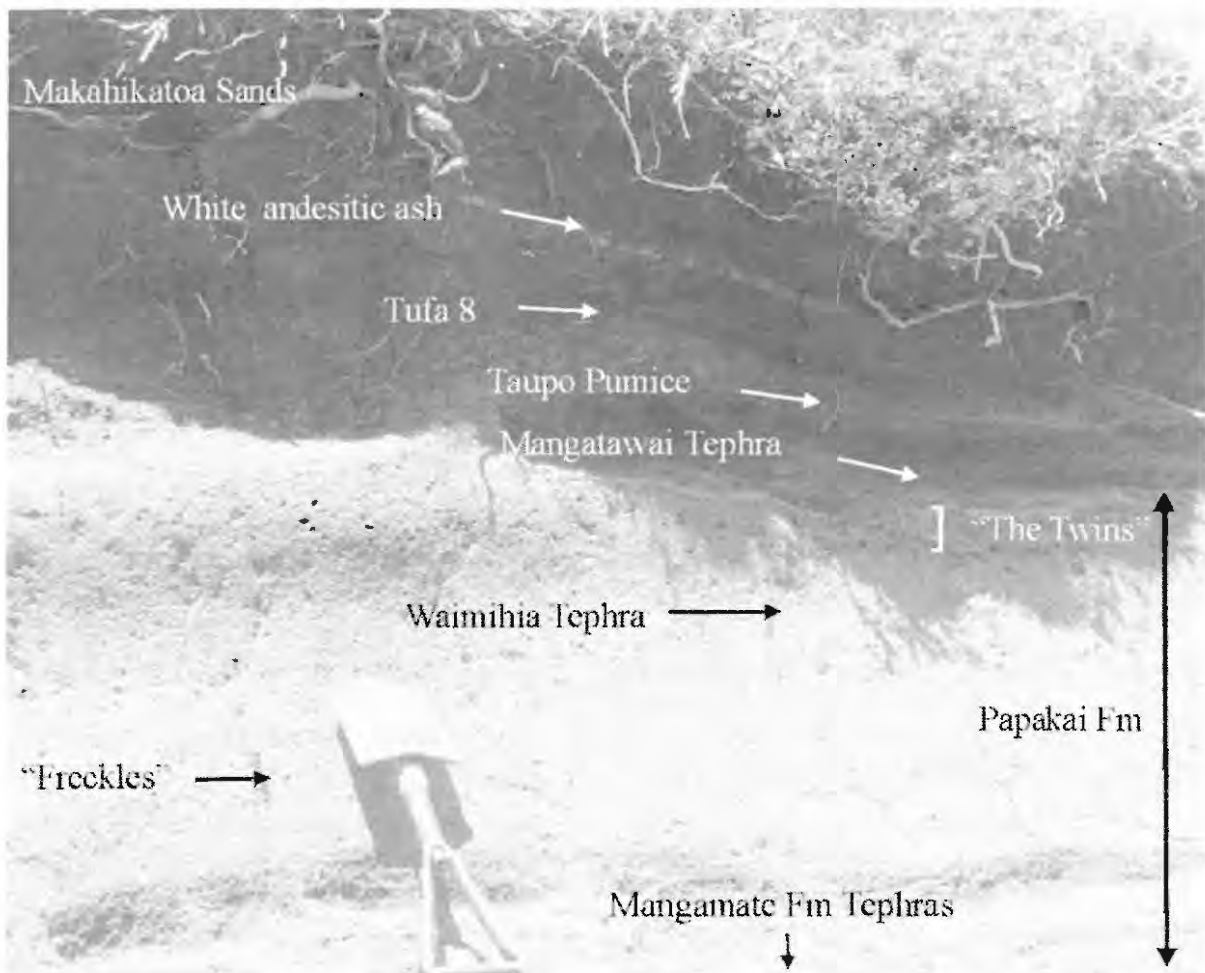


Figure 20: Stop 1: Turoa – Mangaturuturu excursion. Upper part of a section beside the Round-the Mountain Track. See Table 5 for the general stratigraphy of the area.

Papakai Fm andesitic ash forms the bulk of the section below the Mangatawai tephra. Near the top it contains a prominent, 3 cm thick orange-brown andesitic ash layer that is present throughout the sequences exposed on both sides of the track. It overlies a second, thinner lithic and pumice andesitic lapilli and the two units have been informally named “The Twins”, as they form an easily identified marker in cover bed sequences on this part of Ruapehu. In exposures to the south of the track, this horizon overlies a rhyolitic ash identified as the Waimahia

tephra (3.28 ka B.P.). Another distinctive marker in the Papakai formation beneath the Waimahia is “Freckles”, a crystal-lithic andesitic tephra that is a probable correlative of Black Ash-2 (ba-2, Donoghue and Neall, 1995).

The base of the Papakai Fm rests on Mangamate Fm pumiceous and lithic lapilli. Mangamate Fm is dated at between c. 9.7 ka B.P. for the youngest member (Poutu Lapilli) from peat accumulation rates (Topping, 1973) and 9820 ± 80 yr B.P., the radiocarbon age [NZ 1372] of the immediately underlying rhyolitic Karapiti tephra. The presence of Mangamate Fm therefore constrains the age of the Sunset Ridge lavas to be older than c. 10 ka.

Sunset Ridge lavas exposed here are moderately weathered. They resemble Whakapapa lavas and are strongly porphyritic (35% phenocrysts). Quartzofeldspathic and granulitic xenoliths are common. Phenocrysts are plagioclase (20% of the rock), clinopyroxene (5%), orthopyroxene (7%) and magnetite (1%). An analysis of the flow at this locality is provided in Table 7 (sample R97/4).

To the northeast, Sunset Ridge Flows can be seen overlying flows of the Mangaturuturu group.

Stop 2: 200 metres to the north east of Stop 1 and 150m north of the Round the Mountain Track

This stop provides access to another tephra sequence overlying Sunset Ridge lava flows. The tephra sequence is very similar, except that two other rhyolite tephras are exposed in this sequence (Figure 21). The top of the section includes reworked black ashes of the Tufa Trig Formation. The Taupo Pumice and the orange/grey ash noted at Stop 1 are also present at this locality. In addition, the Hinemaiaia tephra (c. 4.51 ka) is present towards the base of the section as discontinuous pockets of fine, rhyolitic ash. The uppermost tephra unit has, in the past, been assumed to be the Kaharoa tephra (dated at 770 years) but it has been suggested that this is more likely to be tephra from Taranaki Volcano (Dr. Ian Nairn *pers. comm.* 2000).

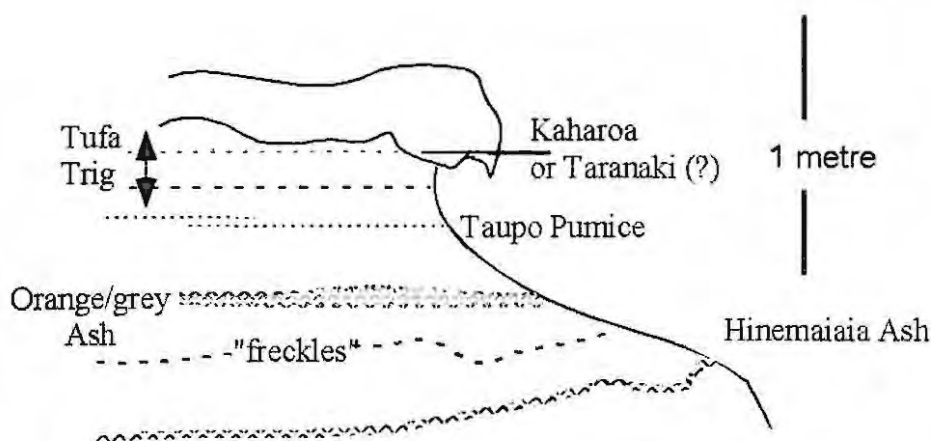


Figure 21: Stop 2: Turoa - Mangaturuturu excursion. Tephra section on Sunset Ridge lava flows. Note “freckles” is a 3-10 cm thick coarse lithic ash, most probably of Ruapehu origin.

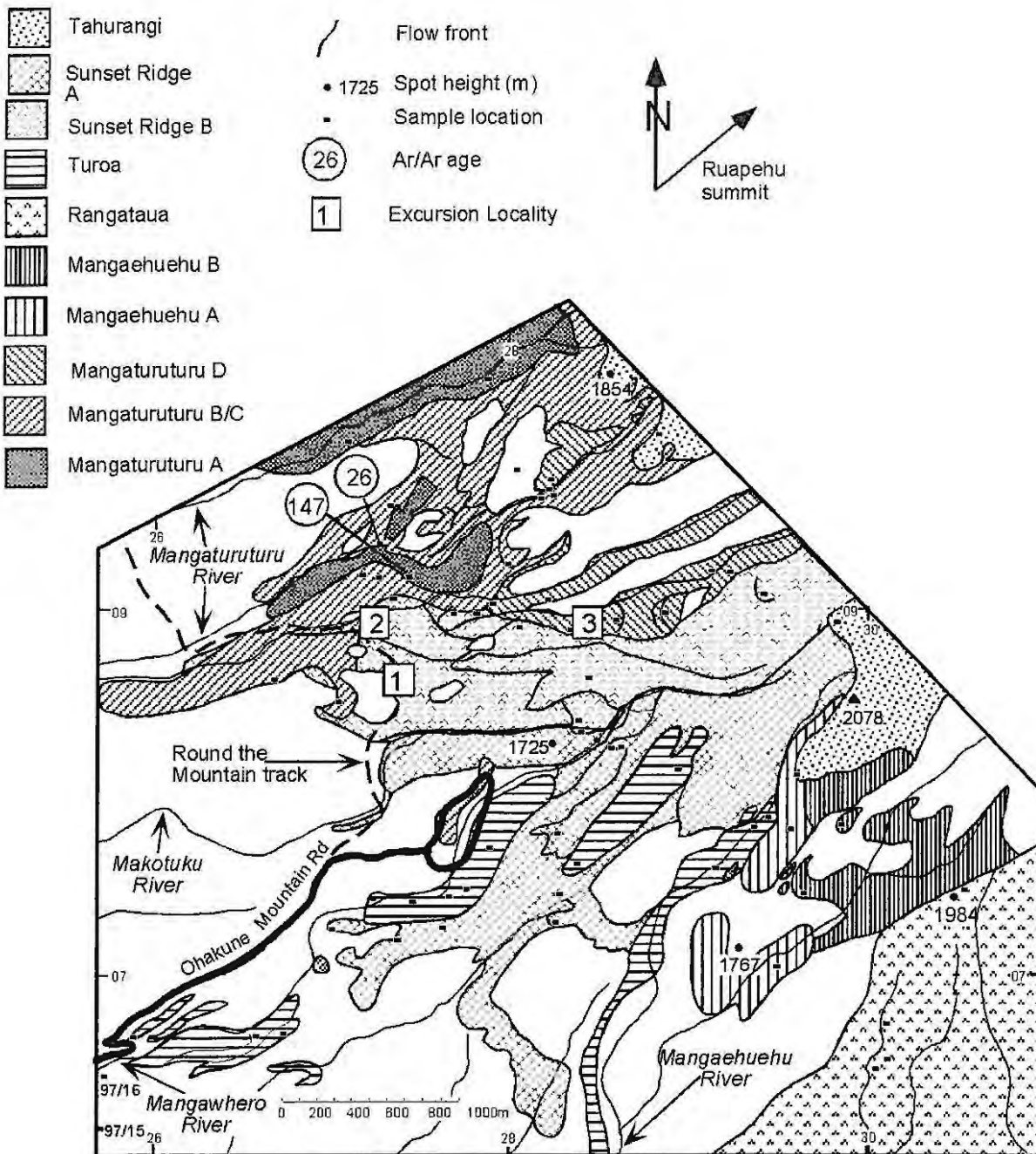
Stop 3: One kilometre north of Stop 2.

Warning - Care must be taken at this site because of loose slabs of flow material.

At this locality, Sunset Ridge flows overlie bluff-forming flows of the Mangaturuturu flow group. The bluff forming flows are members of the Mangaturuturu D unit (Waight et al., in press). Samples of Mangaturuturu B/C have been dated by the $^{40}\text{Ar}/^{39}\text{Ar}$ method at $26,000 \pm 9$ years (W. MacIntosh et al., unpublished data) so the Mangaturuturu D flows must be younger than this. A representative analysis of the bluff forming flows at this locality can be found in Table 7 (97/58). Note folded flow layering.

Clasts of chocolate coloured pumice cover the surface of flows below this locality. This material is believed to be similar to and of the same age as the plinian fall material observed at Whakapapa (see above).

The view to the south takes in the Mangaturuturu valley. Bluffs in the river valley belong to the older Mangaturuturu flow groups and an older age of $147,000 \pm 10$ years (W. MacIntosh et al., unpublished $^{40}\text{Ar}/^{39}\text{Ar}$ data – see above) suggests that at least some of this material could be correlative with the Wahianoa Formation of eastern Ruapehu. The bush-covered slopes extending outward from the lower bluffs are part of the ring plain and are largely of laharic origin.



Map 2: Turoa Skifield and Mangaturuturu

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