

Chapter 2

The Southern End of the Pacific Ring of Fire: Quaternary Volcanism in New Zealand

Phil Shane

Abstract Quaternary volcanism has played a major role in landscape formation and sedimentation in New Zealand. Every part of New Zealand's North Island, much of the South Island, and the surrounding oceans, have been impacted by volcanic eruptions to some degree. Determining the eruption history of volcanoes is critical for assessing future hazards and risk to society. From a Quaternary studies perspective, volcanic deposits provide some of the best materials for establishing the numeric chronology of sediment archives in which they are intercalated. In addition, explosive eruptions are capable of producing widespread tephra layers that are effectively instantaneous events allowing correlation between the terrestrial, ice, lacustrine and marine realms. Such markers facilitate the construction of stratigraphic frameworks, thus temporally constraining tectonic and climatic events. In the terms of magma productivity and eruption frequency, the locus of Quaternary volcanism in New Zealand is the central North Island, referred to as the Taupo Volcanic Zone. It represents the continuation of the Tonga-Kermadec oceanic subduction system into continental lithosphere of New Zealand. The volcanism has produced large rhyolite calderas and ignimbrite sheets, and andesitic-dacitic stratovolcanoes. Some Quaternary volcanism has no genetic link to subduction. Long-lived intra-plate basalt fields occur far from plate boundaries over northern New Zealand, and in a few other isolated locations. Their occurrence is poorly understood because there is no relationship to rifting or evidence for plume-like phenomena beneath New Zealand.

2.1 Introduction

Quaternary volcanism has played a major role in landscape formation and sedimentation in New Zealand. Every part of New Zealand's North Island, much of the South Island, and the surrounding oceans, have been impacted by volcanic eruptions.

P. Shane (✉)

School of Environment, University of Auckland, Auckland 1142, New Zealand
e-mail: pa.shane@auckland.ac.nz

© Atlantis Press and the author(s) 2017

J. Shulmeister (ed.), *Landscape and Quaternary Environmental Change in New Zealand*, Atlantis Advances in Quaternary Science 3,
DOI 10.2991/978-94-6239-237-3_2

35

tions to some degree. In the central North Island, the tallest mountains are andesite stratovolcanoes, and the largest lakes are rhyolite calderas, and others result from volcanic-induced damming of drainage systems. Much of the high plateau-like topography of the area is the result of extensive ignimbrite sheets. Beyond the obvious volcanic landscapes, pyroclastic flow deposits and epiclastic material fill basins and have influenced sediment transport paths. Thousands of kilometers from source, fallout ash has reached much of the New Zealand terrestrial and maritime region producing macroscopic or microscopic tephra layers. Volcanism continues today with volcanoes periodically erupting and subterranean magmatic intrusion driving extensive geothermal systems.

Studies of volcanic rocks and deposits provide insight to why volcanoes erupt, and the frequency-magnitude and spatial-temporal relationships of activity. Such information is critical for assessing future hazards and risk to society. Much of New Zealand's population and a significant portion of its infrastructure is at risk from future eruptions. From a Quaternary studies perspective, volcanic deposits provide some of the best materials for establishing the numeric chronology of sediment archives in which they are intercalated. In addition, explosive eruptions are capable of producing widespread tephra layers that are effectively instantaneous events allowing correlation between the terrestrial, ice, lacustrine and marine realms. Such markers facilitate the construction of stratigraphic frameworks, thus temporally constraining tectonic and climatic events.

The literature pertaining to volcanism in New Zealand is too extensive to comprehensively review all the facets which range from petrology and volcanology to sedimentology and geochronology. Instead, this review is an introduction to the location and tempo of volcanism in New Zealand during the Quaternary.

2.2 Volcanic Setting

In the terms of magma productivity and eruption frequency, the locus of Quaternary volcanism in New Zealand is the central North Island, referred to as the Taupo Volcanic Zone (TVZ) (Fig. 2.1). It represents the continuation of the Tonga-Kermadec oceanic subduction system into continental lithosphere of New Zealand (e.g., Cole 1990) (Fig. 2.1). The arc system is part of the 'Pacific ring of fire', an informal phrase for volcanism that surrounds the Pacific Ocean basin. Arc-style volcanism has been occurring in the North Island since the Miocene. East of North Island, near the Hikurangi Trench, the oceanic Pacific Plate is obliquely subducted westward beneath the continental Australian Plate (e.g., Stern et al. 2006) (Fig. 2.1a). The down-going slab dips at $\sim 15^\circ$ near the Hikurangi Trench and steepens westward to 50° beneath North Island. The obliquity of subduction increases southward into northern South Island. As a result, subduction ceases beneath the South Island, and a transform boundary has developed, as exemplified by the Alpine Fault. Further to the south, the polarity of subduction flips and the Australian Plate is subducting to the East along the Puysegur Trench, giving the

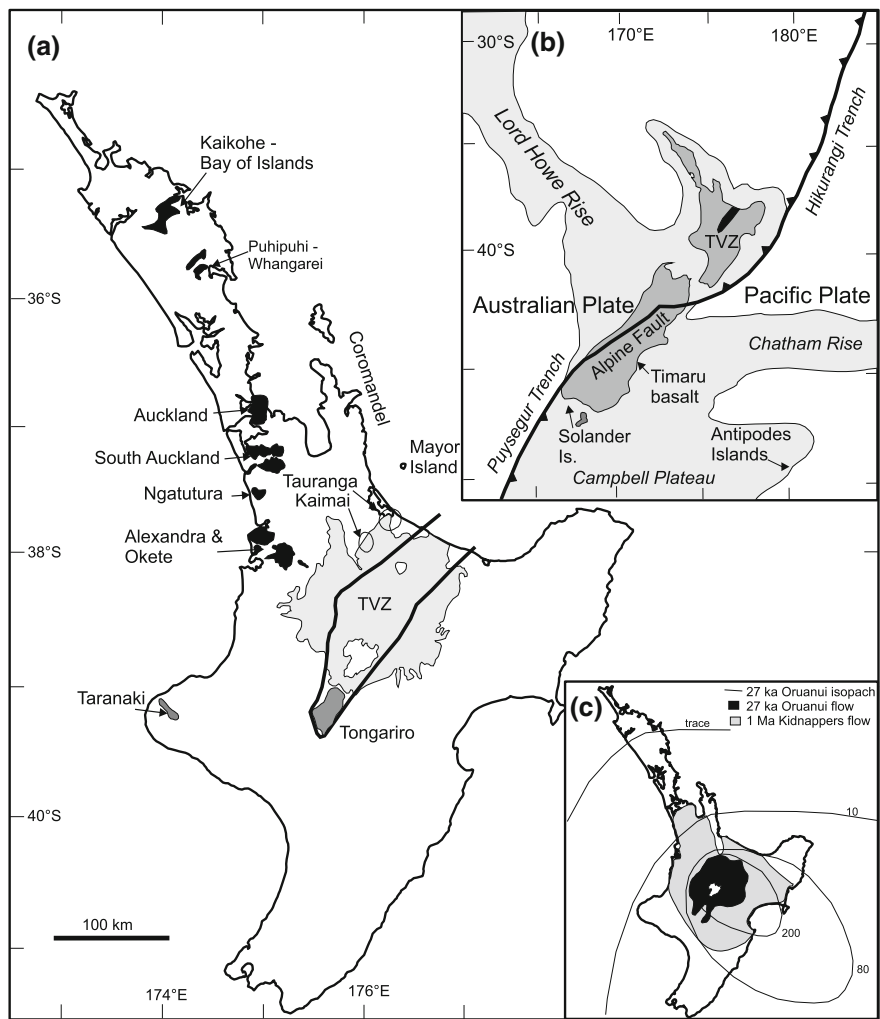


Fig. 2.1 **a** Map showing the tectonic setting of New Zealand. Adapted from Cole (1990). **b** Location of quaternary volcanic centres in North Island. Partly adapted from Briggs et al. (2005). **c** Distribution of volcanic deposits from the Kidnappers and Oruanui eruptions (based on Wilson et al. 1995c)

young volcano of Solander Island (Fig. 2.1a). Miocene to Quaternary fore-arc basins have developed in North Island's east coast region. The western margin of these basins is marked by the narrow Axial Ranges composed of uplifted Mesozoic greywacke-argillite rocks. The active volcanic arc (TVZ) occurs immediately west of the ranges. The TVZ has been variously described as a back-arc basin (e.g., Stern et al. 2006) or a rifting arc (Wilson et al. 1995a). The extension or rifting is thought to be caused by the east coast region being partitioned into major blocks or tectonic

domains that have undergone clockwise rotations relative to the Australian plate (Stern et al. 2006; Wallace et al. 2004).

Late Cenozoic tectonic reconstructions of the subduction system in the New Zealand region are numerous and varied. In the absence of obvious and unequivocal relict trenches and fore-arc basins, most reconstructions rely heavily on the location and dating of calc-alkaline rocks. This assumes they are associated with arc volcanoes that formed in a predictable geometry relative to the subducted slab. Most reconstructions for the North Island region involve a transform or subduction margin east of North Island that migrated southward from the Coromandel region to the present location of the Hikurangi Trench during the Quaternary (e.g., Seebeck et al. 2014; Stern et al. 2006).

Some Quaternary volcanism has no genetic link to subduction. Long-lived intra-plate basalt fields occur far from plate boundaries over northern New Zealand, and in a few other isolated locations, e.g. Antipodes Island (Fig. 2.1). Their occurrence is poorly understood because there is no relationship to rifting or evidence for plume-like phenomena beneath New Zealand.

2.3 Taupo Volcanic Zone

2.3.1 *Lithosphere Structure*

The Taupo Volcanic Zone (TVZ) is a 300 km-long and up to 60 km wide region in the central North Island, characterized by extensive rhyolite ignimbrite sheets and lava domes, active geothermal areas, and caldera structures, some of which are buried (Fig. 2.2a). The southern termination is marked by the Tongariro Volcanic Centre, a region of more typical andesite arc volcanoes (discussed separately below). To the north, the TVZ is contiguous with mostly submarine andesite arc volcanoes, but this offshore region remains poorly understood (see Gamble et al. 1993). Mesozoic greywackes outcrop east and west of the TVZ and probably underlie volcanic fill within the zone, either as tectonically stretched crust, or as rifted blocks separated by intrusive rocks (Stern et al. 2006). The depth and nature of the crust–mantle boundary in central TVZ is uncertain. Based on seismic reflection data, Harrison and White (2004) suggested a quartzo-feldspathic upper crust of ~16 km thickness (Fig. 2.2b). The depth interval ~16–35 km has been interpreted as either mantle with extraordinarily low P-wave velocity (6.9–7.3 km/s) containing significant melt bodies (Stratford and Stern 2004), or highly intruded mafic crust with 2 % melt (Harrison and White 2004). Stern and Benson (2011) proposed a partially molten “rift-pillow” of mafic rocks occurs between 15 and 25 km depth with P-wave velocities are in the range 6.8–7.3 km/s. They also suggest an upper mantle body of partial melt (~12 %) occurs at about 35 km (Fig. 2.2b).

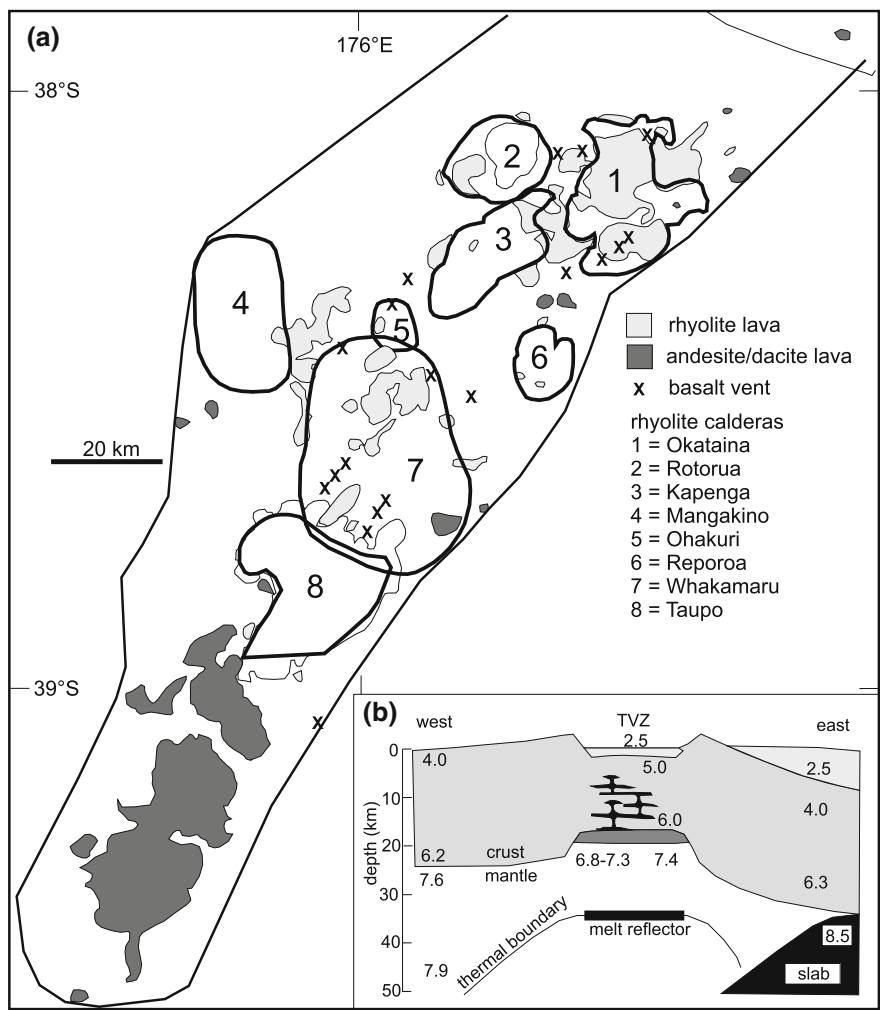


Fig. 2.2 **a** Simplified map of the TVZ showing the location of major rhyolite calderas and distribution of volcanic rocks. **b** Schematic crustal cross section of the TVZ based on seismic velocity data (redrawn from Stern et al. 2006)

The unusually active and productive TVZ rhyolite magmatic system has been attributed to a combination of thin crust, high heat flow, and an extensional tectonic regime; and has been described as a rifting arc (Wilson et al. 1995a, 2009). Current extension rates range from ~ 15 mm/year in the north to ~ 5 mm/year in the south (Wallace et al. 2004). Oblique subduction of the Pacific plate contributes to clock-wise rotation of the east coast region and thus extension within the TVZ. The heat flux is exceptionally high at ~ 4300 MW, or 26 MW/km along strike (Stern et al. 2006), similar to that of mantle-upwelling “hot spots” such as Iceland and

Yellowstone. This heat flux causes the brittle-to-ductile transition to occur at a shallow depth (typically 6–7 km) (Bryan et al. 1999). Petrological data from rhyolites indicate that rising magmas in dike-like structures have stalled at the brittle–ductile transition and formed sill-like bodies (Shane et al. 2008a, b). This is consistent with regions of low S-wave velocity that are ~10–20 km wide at depths of ~6–11 km that could represent zones of partial melt (Bannister et al. 2004). Magnetotelluric data reveal high conductivity zones representing connected melts that form a plume-like structure rising from depths >35 km beneath the axis of extension along the TVZ (Heise et al. 2010). The locations of the highest conductivities extend upwards to depths of ~10 km and pond beneath the Maroa and Okataina calderas. The lowest resistivity in these conductive zones is ~0.3 Wm, interpreted as an interconnected melt fraction of ~50 % (Heise et al. 2010). Such melt fractions approach the levels considered to be eruptible in silicic systems.

2.3.2 *Rhyolite Magma Genesis*

Mafic magmas in subduction systems such as the TVZ are ultimately derived from partial melting of the mantle wedge and/or re-melting of mafic intrusive bodies in the lower crust. However, elevated ^{87}Sr – ^{86}Sr isotope ratios in TVZ silicic magmas argue against derivation from basaltic melts via fractional crystallisation alone and require crustal assimilation (e.g., Graham et al. 1995). This is supported by the presence of ancient xenocrystic zircons (>90 Ma) found in TVZ rhyolites and dacites (Charlier et al. 2005), that are consistent with incorporation of Mesozoic greywacke or plutonic forerunners to the silicic eruptives. Some co-magmatic zircons in rhyolites erupted at Taupo and Okataina calderas pre-date eruption ages by 50–100 ka (e.g., Charlier et al. 2005; Storm et al. 2012), pointing to multi-cycle crystallisation and melting of silicic intrusions in the upper crust. A multilevel magmatic system is likely to occur beneath the calderas driven by deep mafic intrusion and involving a mid-crustal (~8–10 km depth) crystal-mush zone that undergoes ‘freeze-thaw’ episodes and melt extraction following tectonic and intrusive disturbances (Charlier et al. 2005; Shane et al. 2008a, b; Storm et al. 2012). Many of the rhyolites erupted from Okataina caldera display direct evidence of mixing or mingling with mafic magma that may have acted as a trigger for eruption, and many of the eruptions tapped multiple rhyolite melt bodies (e.g., Nairn et al. 2004; Shane et al. 2008a, b).

2.3.3 *Pre-TVZ Silicic Volcanism*

During the Miocene and Pliocene, known arc-related rhyolite volcanism occurred in the Coromandel Volcanic Zone (Fig. 2.1). Briggs et al. (2005) recognised two early Quaternary silicic volcanic centres at the south end of the zone, that pre-date silicic

volcanism in the TVZ. It is not known whether they represent calderas because of burial and poor exposure. The erupted rocks represent calc-alkaline, arc-related magmas similar to those of the TVZ. The Kaimai Volcanic Centre (2.87–2.09 Ma) (Fig. 2.1) includes voluminous rhyolite domes and the Waiteariki Ignimbrite (2.09 ± 0.03 Ma). The Tauranga Volcanic Centre (2.69–1.90 Ma) (Fig. 2.1) includes groups of rhyolitic and dacitic domes (2.69–1.95 Ma) and Papamoa Ignimbrites (2.40–1.90 Ma). The rhyolite record between the formation of these volcanic centres and the onset of ignimbrite eruptions at 1.6 Ma (at Mangakino caldera) in the TVZ, is poorly known. However, deep-sea tephra records confirm activity did occur without significant hiatus (Carter et al. 2003).

2.3.4 Central TVZ Eruptive History

The stratigraphy of the central TVZ is severely impacted by poor exposure and obliteration and burial by succeeding caldera-forming eruptions. Distal pyroclastic records in sedimentary basins provide evidence for additional activity not evident at the proximal sites (Shane et al. 1996; Carter et al. 2003). The eruptive history of the central TVZ has been extensively reviewed by Wilson et al. (1995a, 2009). The earliest activity is marked by eroded andesite edifices on the western margin of the zone with ages in the range ~ 2 –1.6 Ma. Wilson et al. (2009) recognize at least 25 caldera-forming ignimbrite eruptions with magma volumes in the range 30 to $>1000 \text{ km}^3$ that have occurred in the last 1.6 Ma. These represent a minimum of $\sim 6000 \text{ km}^3$ of dacite-rhyolite magma. At least 8 major caldera centres are recognized (Fig. 2.2), but others may be buried and/or obliterated. Many of the calderas lack significant physiographic form and are inferred from sub-surface and regional geophysical data. Much of the present topography has been constructed by extensive ignimbrite sheets beyond the caldera margins, and nested and overlapping intra-caldera lava domes. Some of the calderas are composite structures that have been produced by more than one collapse event. There is no overall temporal-spatial trends in activity and/or magma composition within the zone. Although, eight of the major ignimbrite eruptions are thought to have occurred during the interval 340–240 ka, a significant increase in frequency.

The largest known ignimbrite eruptions have volumes $>1000 \text{ km}^3$ of magma. The 1 Ma Kidnappers ignimbrite from Mangakino caldera is a very low-aspect ratio deposit of non-welded pyroclastic flows (Wilson et al. 1995b), that covers much of the central North Island (Fig. 2.1). It is associated with the Potaka Tephra found widely in surrounding ocean basins (Shane et al. 1996). Its widespread emplacement reflects both an energetic eruption and the lower relief topography of central North Island at the time (Shane et al. 2006). Another large magnitude event was the Whakamaru ignimbrite(s), erupted from central TVZ at ~ 340 –320 ka (Fig. 2.1). These crystal-rich welded ignimbrites form thick valley-pond and sheet deposits and have been variously grouped as a series of eruptions or events of a single episode (Wilson et al. 2009). Some workers have proposed these deposits are

associated with the widespread Rangitawa Tephra, found throughout New Zealand and in the surrounding ocean basins (Pillans et al. 1996).

The post-60 ka rhyolite volcanism of TVZ is better known and the multitude of small-magnitude eruptions is largely an artefact of better preservation and exposure of the time interval. Based on proximal post-60 ka records, Wilson et al. (2009) report 3 major caldera-forming events: 1.8 ka Taupo (35 km³, Taupo caldera), 27 ka Oruanui (530 km³, Taupo caldera) and 45 ka Rotoiti (100 km³, Okataina caldera). Each produced extensive non-welded ignimbrite sheets and were associated with regional ash fall. In addition, at least 65 smaller magnitude eruptions (<0.01–17.5 km³) occurred, totaling ~137 km³ magma, and representing 3 basaltic, 8 dacitic and 54 rhyolitic events (Wilson et al. 2009). Although small in magnitude compared to the caldera-forming events, the rhyolite eruptions were typically sub-plinian and plinian, and dispersed ash and lapilli over hundreds of kilometers downwind. Nearly all of this activity has been associated with the Okataina or Taupo calderas.

Pyroclastic deposits other than rhyolitic in the central portion of the TVZ are rare and/or poorly exposed. Limited drill core data indicate the presence of andesite composite volcanoes buried at depth and rare, often weathered and eroded andesitic edifices (Rolles Peak and Manawahe) do occur and are surrounded by sheets of ignimbrite (see Wilson et al. 1995a, b, c). A few dacite dome complexes, including Edgumbe and Tauhara, also occur and are of small volume (<~3 km³). Small volume (0.001–0.1 km³) monogenetic basaltic eruptions have also occurred in the TVZ forming tuff rings or scoria cones and lavas, but are uncommon (Nairn 2002; Wilson et al. 1995a, b, c).

2.3.5 *Caldera Volcanism: Exemplified by Okataina Caldera*

Okataina is the best exposed and the most recently active rhyolite caldera in the TVZ (Figs. 2.2 and 2.3). This well-studied volcano exemplifies the styles and patterns of volcanism in such systems. Okataina caldera (also Okataina Volcanic centre) is a locus of rhyolite domes within the rifted TVZ, and flanked beyond its margin by incised ignimbrite sheets (Nairn 2002; Cole et al. 2010). The largest constructional features are two intra-caldera lava dome massifs (Haroharo and Tarawera), up to 1000 m in elevation (Fig. 2.3). Lava flows and domes have ponded drainage systems within the caldera producing lakes. Parts of the caldera margin are marked by scalloped slump scars cut into pre-caldera domes and pyroclastics in the north and west, but much the margin is obscured by mantling volcanic deposits. The overall caldera is a composite collapse feature (Cole et al. 2010), strongly controlled by regional faulting patterns of the TVZ. Various geophysical data sets reveal a 9 by 15 km negative gravity anomaly representing non-consolidated pyroclastic fill overlying fractured greywacke to depths of ~3 km (Seebeck et al. 2010).

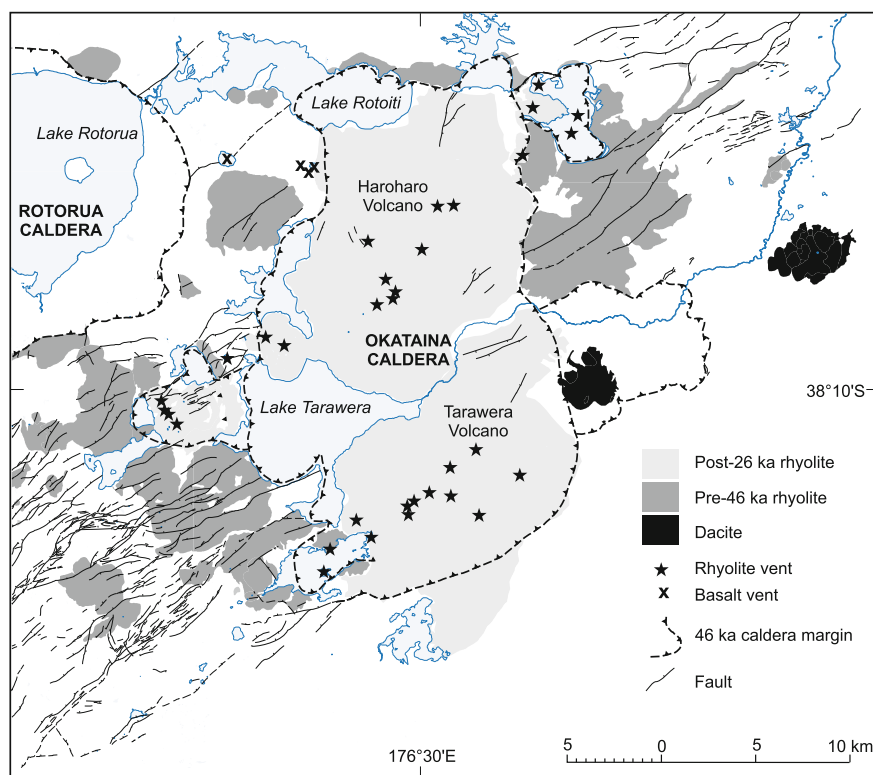


Fig. 2.3 Map of Okataina volcano showing the location of the 45 ka caldera, post-26 ka vents, intra-caldera volcanoes (Tarawera and Haroharo), and the distribution of rhyolite lava, based on Nairn (2002)

The earliest volcanism at Okataina is difficult to determine because neighboring, poorly-dated and contemporaneous calderas could be the source of some deposits, and much of the early record of volcanism has been obliterated by later eruptions. At least 2 or 3 major, overlapping caldera-forming events have occurred. The earliest event potentially representing caldera formation are the “quartz–biotite tuffs” or ignimbrites ($\sim 90 \text{ km}^3$) dated at $\sim 550 \text{ ka}$ (Cole et al. 2010). The Matahina Ignimbrite eruption dated at 325 ka (Cole et al. 2010) was also a major collapse event (Nairn 2002), and produced a welded ignimbrite ($>160 \text{ km}^3$ of magma) that locally ranges up to 150 m thick and covers an area of $\sim 2000 \text{ km}^2$. Lava dome complexes pre-date the Matahina ignimbrite eruption, but are poorly dated. Similarly, the interval between the Matahina and $\sim 46 \text{ ka}$ Rotoiti ignimbrites is poorly known, but includes volumetrically minor pyroclastic deposits that are mostly pre-240 ka (Nairn 2002), and more voluminous lavas in southwest sector of the caldera system (Cole et al. 2010).

The post-46 ka rhyolite magmatic history of Okataina caldera is well established and can be divided into four volcanological and temporal divisions (summarized from Shane et al. 2005a, b, 2008a; Smith et al. 2006a, b). (1) At 46 ka, high-SiO₂ cummingtonite-bearing rhyolite was erupted during the caldera-forming Rotoiti event. This eruption involved $\sim 100 \text{ km}^3$ of magma and produced much of the present caldera margin (Fig. 2.3). An extensive ignimbrite sheet was emplaced mostly to the north of the caldera, and a widespread tephra (Rotoehu) was dispersed over much of central North Island and off-shore. The temporally associated Earthquake Flat event was a smaller volume ($\sim 10 \text{ km}^3$) biotite-bearing, crystal-rich rhyolite, erupted on the western margin of the caldera. This resulted in localized thick deposits of non-welded ignimbrite and no significant ash fall. (2) Small to moderate-sized ($<20 \text{ km}^3$) rhyodacite plinian eruptions (older Mangaone deposits) occurred within the caldera during $\sim 42\text{--}35$ ka. The vents are now buried. These high-temperature, crystal-poor deposits have an orthopyroxene-clinopyroxene $\pm$ hornblende mineralogy. The eruptions produced coarse lapilli and block fall beds, but there is no evidence of lava extrusion, although such deposits may now be buried. (3) Small to moderate-sized ($\sim 1\text{--}12 \text{ km}^3$), high-SiO₂ rhyolite plinian eruptions occurred within the caldera at $\sim 35\text{--}32$ ka. These crystal-poor deposits (younger Mangaone deposits) display an orthopyroxene-hornblende mineralogy. Fall beds of lapilli and blocks are the only remains of these events. One exception, is an ignimbrite-forming event that occurred at ~ 33 ka (Kawerau ignimbrite, $>20 \text{ km}^3$). (4) Post-26 ka activity occurred along two linear vent zones at Haroharo and Tarawera volcanoes (Fig. 2.3) that extend beyond the caldera margin and produced caldera-infilling crystal-rich lavas and pyroclastics. More than 80 km^3 of magma was erupted in the nine eruptive episodes, with each dispersing $1\text{--}20 \text{ km}^3$ of pyroclastic material and extruding $\sim 1 \text{ km}^3$ of lava as flows and domes. Haroharo deposits are typically cummingtonite-bearing, while biotite is more dominant in the deposits from Tarawera. A few exceptions in mineralogy occur at both centres, but all post-26 ka rhyolites were high-SiO₂ ($>74 \text{ wt\%}$).

Petrological studies indicate that the emptying of the magmatic reservoir by the 46 ka caldera event promoted mafic magma recharge by eliminating silicic magma density barriers, producing more frequent eruptions of higher temperature rhyodacites. Subsequently, the redevelopment of the high-SiO₂ magma reservoir post-26 ka has dampened the impact of recharge events and resulted in a lower eruption frequency of cooler, more silicic magmas (e.g., Shane et al. 2005b).

2.3.6 Intra-caldera Volcanism: Exemplified by Tarawera Volcano

The Tarawera volcanic complex (or volcano) exemplifies the style of intra-caldera volcanism (Nairn 2002; Nairn et al. 2004; Shane et al. 2008a, b). It comprises

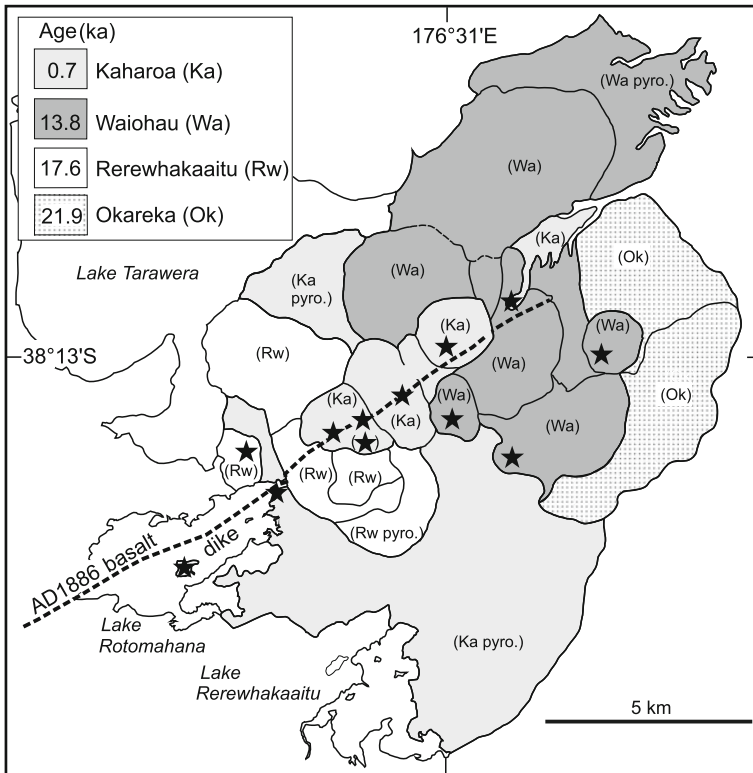


Fig. 2.4 Lava flows and domes of the intra-caldera Tarawera volcano, within Okataina volcano (redrawn from Nairn 2002). The dashed line marks the en-echelon fissure system of the basaltic dikes of the 1886 eruption

nested and overlapping rhyolite lava domes and flows, with intercalated pyroclastic flow and fall deposits (Fig. 2.4). It was constructed during the last 22 ka from vents in the southeast part of the Okataina caldera. About 30 km³ of magma has been erupted during four major rhyolite episodes occurring at 21.8, 17.6, 13.6 and 0.7 ka. Multiple vents were involved in each eruption episode at Tarawera, and together define a 5 km wide, SW–NE trending zone. Each episode has involved the co-eruption of physiochemically discrete rhyolite magma batches, in various sequential and/or simultaneous order. The eruptions, typically <5–10 km³ of magma, involved sub-plinian and plinian-style pyroclastic falls and flows, and multiple lava dome extrusions. But there is no common pattern of activity or events in the four episodes. Deposits from each eruptive episode lack paleosols or significant hiatuses, suggesting that activity lasted <100 years. Minimum eruption durations of ~5–10 years have been estimated from the rates of historic silicic dome extrusion observed elsewhere. There is no consistent relationship between duration of quiescence and volume of the subsequent episode.

Although predominantly rhyolitic, Tarawera volcanic complex volcanism is driven by mafic dyke intrusion along linear vent systems. Evidence for basaltic magma is found in every Tarawera eruption episode. The 21.8 ka episode started with the sub-plinian eruption of basaltic scoria ($<0.1 \text{ km}^3$). Other evidence for basaltic magma involvement variously includes basalt-rhyolite hybrid and mingled pumices, and microscopic mafic glass blebs and associated mineral phases. The only historic eruption (in AD1886) was entirely basaltic ($\sim 1 \text{ km}^3$ of magma), erupted from multiple vents on a 17 km long northeast-trending dike system extending across and beyond the massif (Nairn and Cole 1981) (Fig. 2.5a). Hydrothermal eruptions occurred close in time to the 17.6 and 0.7 ka episodes, from vents up to $\sim 20 \text{ km}$ to NE and SW of Tarawera. These hydrothermal events suggest that intrusion of basalt occurred as laterally extensive dikes (Nairn 2002).

Faults within the OVC are rare in contrast to the numerous fault traces beyond the caldera margin (Nairn 2002; Villamor et al. 2011) (Fig. 2.3). However, the loci of post-26 ka eruptions along SW–NE lineaments (e.g., Tarawera) within the caldera implies structural control. Villamor et al. (2011) have reported that some post-26 ka fault ruptures outside the caldera coincide with eruptions, but most do not (70 %). Therefore, they concluded that most of the faulting was driven by tectonic processes. However, it is not clear whether tectonism controls the tempo of mafic magma ascent and eruption, or if deep-seated mafic magma production drives rifting.

2.3.7 *Contrasts in Caldera Volcano Activity*

The pattern of intra-caldera activity at the contemporaneously active Taupo volcano differs greatly from that at Okataina, demonstrating local contrasts in mantle and crustal volcanotectonic settings. At Taupo volcano, a major caldera-forming eruption at 27 ka involving $\sim 500 \text{ km}^3$ of magma (Oruanui event), was followed by about 28 significantly smaller pyroclastic eruptions (Wilson 1993). All of these are represented by fall deposits and yet only three are known to be associated with lava dome extrusion. However, the hypothesized vents are mostly beneath Lake Taupo, and thus little is known about proximal facies. The intra-caldera eruptions varied greatly in size (~ 0.01 to 44 km^3 of magma) and in repose time (estimated 20 years–about 6000 years). The eruptions were mostly sub-plinian to plinian in style and involved various degrees of phreatomagmatic interaction. These frequency-magnitude characteristics contrast with the contemporaneous Okataina volcano activity of larger volume lava dome extrusions accompanied by ash-fall separated by longer repose periods (>1000 years), and eruption loci at two separate vent zones.

Impact on sedimentation

Volcanism in the TVZ has also had a major impact on the landscape and sedimentation systems via post-eruption remobilization of pyroclastic deposits. Manville and Wilson (2004) highlight the sedimentation impact in the central North

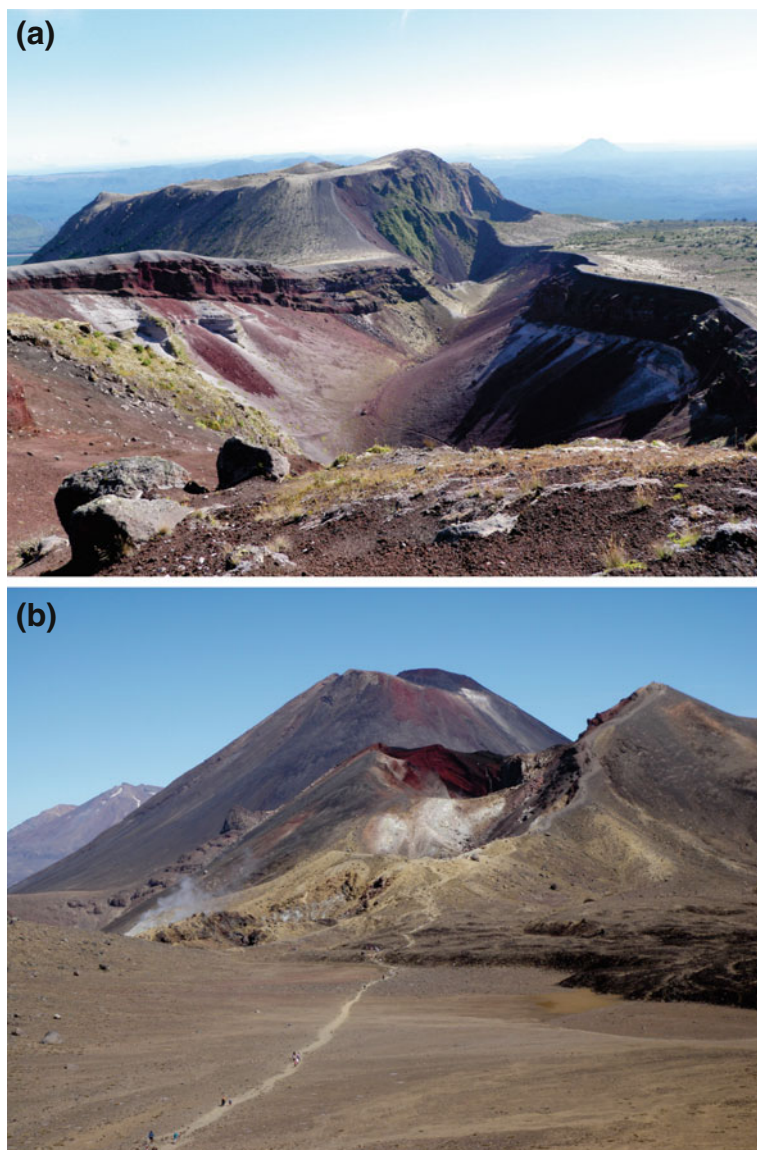


Fig. 2.5 **a** Basaltic fissure across the summit of Tarawera volcano formed during the 1886 eruption. Red and black basaltic scoria mantles lava domes that were erupted during the 0.7 ka event. White rhyolite pumice falls from the 0.7 ka (Kaharoa) eruption are exposed in the fissure walls. **b** Summit of the Tongariro massif. The Red Crater vents and lava flow is in the foreground, and Ngauruhoe volcano in the background. Ruapehu volcano is partly visible in the distance (left of Ngauruhoe)

Island following the 27 ka Oruanui eruption from Taupo volcano. The post-eruption sediment transport was enhanced because the eruption preceded the last glacial maximum, a period of diminished vegetation that promoted erosion. Following caldera formation, lake formation ultimately lead to a breach in the margin producing in a catastrophic flood. A combination of the availability of non-consolidated pyroclastic deposits and the denuded landscape resulted in extensive fluvial aggradation up to hundreds of kilometers north of the caldera, and major river drainage migration. The pyroclastic deposits also became a source for localized aeolian dune fields. The impact of the eruption on sedimentation systems lasted for thousands of years. The occurrence of thick remobilized rhyolite pyroclastic deposits in distant basins surrounding the TVZ demonstrate the importance of such processes throughout the Quaternary (e.g., Shane et al. 1996).

2.4 Tongariro Volcanic Centre

2.4.1 *Setting and Magma Genesis*

The Tongariro volcanic centre comprises four major andesite massifs, Kakaramaea, Pihanga, Tongariro and Ruapehu, and at least four smaller volcanic centres, Maungakatote, Pukeonake, Hauhungatahi and Ohakune (Cole 1978; Cole et al. 1986) (Fig. 2.6). The volcanoes lie 80 km above the Wadati-Benioff zone surface of Pacific plate slab at the southern termination of the TVZ within a narrow graben-like setting.

Parental mafic magmas to these arc-type volcanoes originate from partial melting of the mantle wedge above the subducting slab. The andesites are therefore likely to be secondary magmas derived by fractional crystallisation of parental basalts and/or re-melting of mafic intrusive forerunners, followed by mixing and mingling processes between batches of magmas and crustal assimilation. The magmas of the Tongariro and Ruapehu volcanoes display non-systematic shifts in geochemistry and isotopic signatures throughout volcanoes' histories. Temporally and chemically distinctive batches of melt aggregate and ascend from a mantle source and experience variable and non-systematic mixing and contamination events during transit through the lithosphere (e.g., Gamble et al. 1999; Price et al. 2010, 2012). The magmatic system beneath the volcanoes have been variously depicted as a semi-connected network of sills and dykes (Cameron et al. 2010).

2.4.2 *Eruptive History*

The oldest volcano in the Tongariro volcanic centre is Hauhungatahi (1521 m) dated at 933 ± 46 ka (Cameron et al. 2010). It is an eroded and fault-bounded structure of andesite lava flows, pyroclastics and intercalated lahars, unconformably

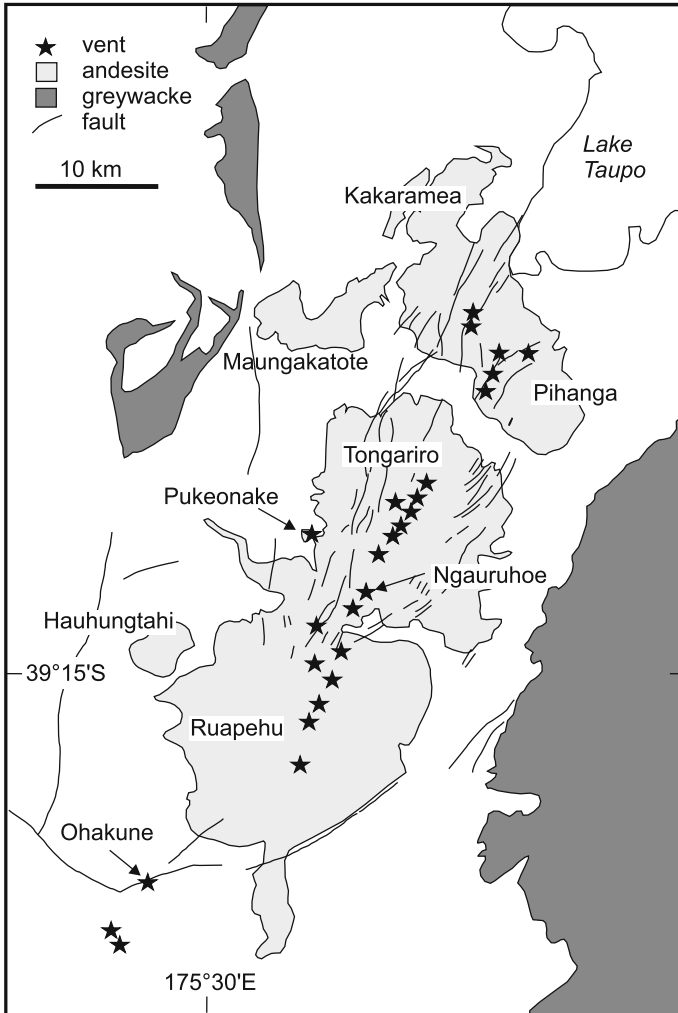


Fig. 2.6 Simplified map of the Tongariro volcanic centre, showing the location of volcanic massifs and vents (based partly on Cole 1990; Nairn et al. 1998)

overlying Miocene marine sediments. The eruptive histories of Kakaramaea, Pihanga and Maungakatote volcanoes are poorly established (Cole 1978). The highly eroded Maungakatote volcano comprises two partially coalesced andesite cones thought to post-date ~ 330 ka. An age of about 220 ka has been reported for Kakaramaea volcano, a 120 km^2 fault-bounded massif with a NNE-trending vent zone. Pihanga volcano displays multiple craters and cones, some of which post-date 20 ka.

In contrast, the chronologies of the Ruapehu and Tongariro volcanoes are better established and both volcanoes have been frequently active in historic time. A range

of proximal to distal volcanic facies are exposed on these volcanoes. In the summit areas plug intrusions, welded fall deposits and vent breccia are exposed. The flanks are characteristic by blocky lava flows, and autoclastic breccia, and distal ring plains comprise lahar and debris avalanche deposits intercalated with fall deposits.

Ruapehu is a 2797 m andesite-dacite stratovolcano with a main edifice volume of $\sim 150 \text{ km}^3$, in addition to an extensive ring plain of remobilized deposits. The magmas erupted are predominantly andesite with subordinate basalt and dacite. Volcaniclastic deposits suggest volcanism may have commenced as early as 300–350 ka. Gamble et al. (2003) reported pulses of increased lava flow emission at 200, 134, 45, 22 and <15 ka. An overall lava production rate of $0.6 \text{ km}^3/\text{ka}$ is estimated, but this is a minimum as volcaniclastic and pyroclastic deposits are not included. Only the youngest part of the explosive eruptive record is known. It reveals heightened activity at 27–10 ka with at least 33 tephra layers including deposits of larger plinian events with volumes in the range $0.3\text{--}0.6 \text{ km}^3$ (Pardo et al. 2012). Post-10 ka explosive eruptions appear to have been of smaller scale. However, the volcano has produced widespread tephra fall events every 50–100 years. The last significant magmatic eruption was in 1995–1996 with a volume of about 0.02 km^3 .

Tongariro is a $\sim 60 \text{ km}^3$ in volume, massif comprising ~ 17 overlapping composite cones with volumes in the range $0.3\text{--}12 \text{ km}^3$ (Hobden et al. 1999) (Fig. 2.5b). The massif includes the historically, frequently active Ngauruhoe volcano. Tongariro displays a NNE-trending, 13 km by 5 km vent zone. Cone growth has varied from $1 \text{ km}^3/\text{ka}$ of magma over periods of about 10 ka– $0.1 \text{ km}^3/\text{ka}$ over periods of about 50 ka (Hobden et al. 1999). Products are predominantly andesite with subordinate basaltic andesite and dacite. There is no spatial-temporal trends in eruptions on the massif. However, vent locations on Tongariro and the neighboring flanks of Ruapehu volcano are structurally controlled and volcanic episodes may be linked to periods of intense rifting. This is exemplified by a series of eruptions and faulting events along linear vent zones at ~ 10 ka within a graben structure connecting the two volcanoes (Nairn et al. 1998).

Ngauruhoe (2287 m in elevation, 900 m from base to summit) is the youngest cone of Tongariro massif, and has erupted basaltic andesite and andesite. Most of the cone (2.2 km^3 magma) was built post-2 ka (Hobden et al. 2002). The volcano is characterized by a simple composite cone and lava flows that extend considerable distances from the base of the volcano. Moebis et al. (2011) have recognized 127 tephra layers from Ngauruhoe spanning the last 7 ka. Historically, the volcano has erupted every 2–3 years. But the last eruption was 1974–1975. That event was characterized by vulcanian-style activity and block-and-ash flows. Price et al. (2010) suggest that single batches of magma sourced from episodic mafic recharge have been erupted with no systematic trend through time. Although isotopic signatures suggest the oldest magmas display the least crustal contamination.

The TVC also contains some satellite vent volcanoes constructed on the larger edifices that erupted low-silica, olivine andesite. They are poorly dated. The pre-27 ka. Pukeonake cone is a 143 m high, likely monogenetic, scoria cone on the

distal flanks of Tongariro volcano. Ohakune comprises several low tuff rings and cones on the outer southern flanks of Ruapehu volcano, and represent the southernmost vents of the TVZ.

2.5 Kermadec Arc Volcanoes

2.5.1 *Setting and Magma Genesis*

Seafloor exploration has revealed many previously unknown submarine volcanoes along the Tonga-Kermadec subduction system (Fig. 2.7). The subduction system results from the convergence of the Pacific and Australian plates, with the three microplates accommodating back arc spreading and rifting basins behind the arc front (Gamble et al. 1993; Wright et al. 2006; Graham et al. 2008). From $\sim 37^\circ$ to 30°S , the system comprises the narrow submarine Kermadec Ridge with an active arc front and the Havre Trough, to the west, a deep and structurally complex region of back-arc rifting (Fig. 2.7). The Havre Trough separates the Kermadec Ridge from the Colville Ridge. The latter marking the location of an earlier, now uplifted, arc system. At 36°S , the convergent rate is ~ 50 mm/year and the rate increases northwards along with steepening of the west-dipping Pacific plate.

The eruptive products are typical calc-alkaline arc magmas with those erupted south of about 30°S displaying evidence of contamination from subducting sediment (Gamble et al. 1996). In general, basalts and basaltic andesites dominate in thinner crustal sectors of the arc, while dacites with basalts and basaltic andesites occur in thicker crustal settings (Wright et al. 2006). Two end-member models of either fractional crystallization of basaltic magma (supported by isotopic uniformity), or crustal anatexis (based on the sheer volume of material in some eruptions) have been proposed for the generation of the silicic magmas (Smith et al. 2006a, b, c; Barker et al. 2013).

2.5.2 *Volcanoes*

At least 35 stratovolcanoes with basal diameters of >5 km are known from the arc segment 30° – $36^\circ 30'\text{S}$, north of North Island (Wright et al. 2006) (Fig. 2.7). Their sizes range up to ~ 25 km in diameter and volumes up to >250 km³. Total relief at individual massifs is in the range ~ 400 to >2500 m. Some display large collapse calderas >3 km in diameter. The volcanoes are typically spaced 30–50 km apart. Many of the edifices display pillow lavas and sheet lavas, and talus breccias on their flanks, and evidence of flank collapses. Scoriaceous hyalclastite occurs at shallower ocean depths (~ 500 m). Macauley (~ 30 km wide, 1.3 km relief, 269 km³ volume) and Havre (~ 25 km wide, 1 km relief and 91 km³ volume)

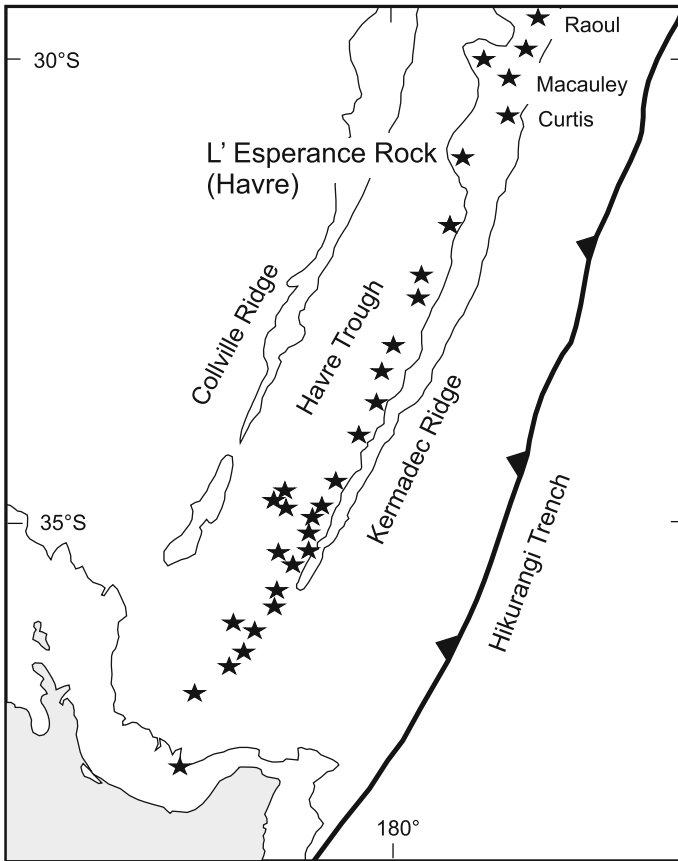


Fig. 2.7 The location of major submarine volcanoes in the southern Tonga-Kermadec arc (from Wright et al. 2006). Volcanic islands are labelled

volcanoes are large silicic caldera complexes, and variously display satellite cones and domes, and large scale submarine pyroclastic deposits. The Macauley caldera has dimensions of 11 by 8 km.

The volcanic islands of Macauley (part of Macauley volcano), Raoul, Curtis and L'Esperance (part of Havre volcano) ($29^{\circ}14'S$ to $31^{\circ}15'S$) are the only emergent parts of the arc. Combined they represent an area of $<35 \text{ km}^2$ (Fig. 2.7). Porphyritic basaltic-andesitic lavas form most of islands, except Curtis Island that is composed of dacitic pyroclastic deposits. Dacitic pyroclastic flows occur on Raoul and Macauley Islands. Deep-sea coring has revealed tephra layers from Raoul and Macauley volcanoes, up to 100 km distant and extending back $>50 \text{ ka}$ (Shane and Wright 2011), demonstrating a long history of explosive activity. Historic eruptions have been recorded on Raoul Island, and active fumaroles and hot springs are present on Raoul

and Macauley and Curtis Islands and/or their submarine flanks. Many of the other Kermadec arc submarine volcanoes are also sites of active volcanic and hydrothermal venting (e.g., de Ronde et al. 2001), and flank collapse.

2.6 Taranaki Volcanoes

2.6.1 *Setting and Magma Genesis*

The Taranaki volcanoes are a chain of remnant calc-alkaline andesite edifices that progressively young to the southeast along the “Taranaki volcanic lineament” (Neall et al. 1986) (Fig. 2.1). The youngest edifice, Taranaki volcano (or Egmont Volcano, to avoid confusion with the larger volcanic centre) lies 180 km to the west of the Hikurangi Trench, and 180–250 km above a westward-dipping Wadati-Benioff zone. Thus, these arc volcanoes are relatively isolated in relation to the Quaternary arc in North Island. Based on seismic data, Sherburn and White (2005) estimate a relative shallow brittle–ductile transition of ~ 10 km beneath Egmont volcano and a zone of higher crustal heat flow extending down to ~ 22 km.

The Taranaki volcanoes and the Alexandra volcanic field (Fig. 2.1) (discussed below) are both located in cross-arc lineaments and associated with relatively potassic volcanism. Thus, Price et al. (1992) suggested that volcanism along the lineaments could be a surface expression of fractures in the subducting slab that are orthogonal to the Hikurangi Trench. Alternatively, the Taranaki volcanoes have been interpreted as a remnant of an earlier arc because of their proposed alignment with late Pliocene volcanoes in northern North Island (Briggs et al. 1989; Booden et al. 2011).

Stern et al. (2006) have suggested that Taranaki magmatism could be associated with lithospheric delamination rather than the present-day subduction system. Thrusting and crustal thickening during the Miocene in western North Island may have produced a cold, dense root zone in the lower lithosphere which delaminated due to instability. Ascending hot asthenosphere would then occupy the delaminated zones providing heat for partial melting.

Magmas from the youngest edifice (Egmont) are well studied and are characterized by high-K andesites with a ferromagnesian mineralogy dominated by amphibole and clinopyroxene (Price et al. 1992, 1999, in press). Compared to magmas erupted from the Tongariro centre volcanoes, a more depleted mantle wedge, compositionally different slab-derived fluids, and a cooler and thicker crust have all contributed to the generation of magmas (Price et al. 1999). The older part of the magmatic record of Egmont is based on clasts in debris avalanche deposits. Pre-100 ka magmas are more diverse and include primitive basalts. Higher silica magmas dominate the younger part of the record, and overall there is a progressive enrichment in K_2O and large ion lithophile elements, reflecting a gradual evolution

to high-K andesite (Zernack et al. 2012). These authors suggest that the lower crust has been thermally primed by repeated mafic intrusion overtime, promoting crustal melting and the production of more evolved compositions.

2.6.2 *Volcanoes*

The oldest centre is the Sugar Loaf Islands and on-shore volcanic spires of the Partutu edifice (1.7 Ma) (Neall et al. 1986). However, their location, age and contrasting petrology raise a question over their genetic link to the younger Taranaki volcanoes (Price et al. 1999). Kaitake volcano (0.575 Ma), is a deeply eroded stratovolcano remnant of low elevation (68 m) comprising lavas and intrusive rocks of predominantly hornblende andesite and diorite. Extensive debris avalanche deposits are associated with the edifice. Pouakai volcano (0.25 Ma) lies 10 km SE of Kaitake with an elevation up to 1399 m. Erupted products are hornblende andesites, and volcanoclastic ring plain was constructed.

Egmont Volcano (Mt Taranaki) is a 2518 m high stratovolcano. Numerous episodes of cone collapse have resulted in the construction of an extensive ring plain of debris avalanche, laharcic and associated fluvial deposits ($\sim 150 \text{ km}^3$ of material), which partly cover much of the Pouakai edifice. At least 15 major debris avalanches have occurred over the last 200 ka (Zernack et al. 2011). Individual flows have volumes up to $\sim 8 \text{ km}^3$ and run-out distances of up to 45 km. Their average frequency was 1 per 13 ka, and tempo increased over the last 40 ka (Zernack et al. 2011). Explosive vulcanian to subplinian eruptions and effusive lava flows and domes characterize Egmont's history. Much of the main cone (12 km^3 of magma) was constructed over the last 7 ka (Neall et al. 1986). Turner et al. (2009) report at least 138 tephra fall events in the last 10 ka, with recent eruptions include events in AD1755, 1800 and 1854.

2.7 Other Volcanoes

2.7.1 *Mayor Island*

Mayor Island (Tuhua) is an isolated edifice off-shore of the Bay of Plenty in a back-arc setting relative to the TVZ (Fig. 2.1). It is notable for its peralkaline magma compositions comprising rhyolite and basalt. The 700 m lava shield-like structure has been active since at least 130 ka and displays evidence of two caldera collapse events and lava dome extrusion (Houghton et al. 1992). Wilson et al. (1995c) reported 17 pyroclastic eruptions over the last 60 ka. Seven widespread tephra from Mayor Island occur in deep sea sediments dated at >45, <45, 41, 37, 22, 14 and 7 ka (Shane et al. 2006). The 7 ka event is particularly widespread, being found on-shore of North Island.

2.7.2 *Solander Islands*

The Solander Islands are a small ($\sim 1 \text{ km}^2$) area of eroded volcanic peaks, 40 km south of Fiordland (Fig. 2.1), and once formed a 10-km in diameter edifice (Mortimer et al. 2013). The volcanic centre is significant because it only known subduction-related volcanism on the Pacific-Australia plate boundary south of the South Island. Subduction in the region is highly oblique and involves the eastward subduction of Eocene–Miocene crust of the Australian Plate beneath Fiordland at the Puysegur Trench. A sequence of subaerial adakitic andesite domes, block and ash flows, and phreatomagmatic deposits occur on the largest island, Hautere. Mortimer et al. (2013) suggest activity occurred in the interval 100–350 ka. An andesite dome on Little Solander Island has an age of 20–50 ka.

2.8 Intra-plate Basalt Volcanoes

2.8.1 *Introduction*

Quaternary intra-plate basalt volcanoes occur in broad fields in northern North Island (Fig. 2.1). They are situated on the Australian plate well behind the convergent plate margin. The erupted magmas are mostly alkalic and sub-alkalic basalts that lack geochemical signatures associated with subduction systems and crustal contamination. Volcanism in some of the North Island fields commenced prior to the Quaternary (Smith et al. 1993). Most of the individual volcanoes within the fields are considered to be ‘monogenetic’, constructed in one, relatively short episode lasting perhaps months to a few years, and producing small volumes of magma ($<0.01 \text{ km}^3$). Such small magma volumes are unlikely to maintain thermally viable conduits through the lithosphere ($>30\text{--}70 \text{ km}$) that would be conducive to ascent from their deep lithosphere and asthenosphere sources for prolonged periods. Thus, new volcanoes form in new locations, a feature of monogenetic volcanism. However, recent studies of volcanoes in ‘monogenetic’ fields are revealing examples of repeated activity at some edifices, including Rangitoto volcano in Auckland (Shane et al. 2013).

2.8.2 *Magma Genesis*

Magmas from small intra-plate basaltic volcanoes are the result of partial melting of the mantle, and are relatively unmodified by the processes of crustal storage such as fractional crystallization and assimilation. However, temporal compositional and isotopic trends, and discrete magma batches are recognized in erupted products from many of these volcanoes. A variety of explanations have been offered and common themes involve a magmatic column extending through the upper mantle

that experienced variable degrees of partial melting and mixing of melts derived from various depths and/or compositional zones.

Models of magma production at Rangitoto volcano of the Auckland volcanic field are typical of recent concepts. Workers have highlighted the importance of batch partial melting of mantle sources and aggregation of melts over a range of pressures to explain much of the compositional variation at this volcano (Huang et al. 1997; McGee et al. 2011, 2013). The more alkalic and incompatible element-enriched composition of alkalic basalts is considered to reflect a lower degree of partial melting and a deeper, garnet-bearing source (asthenosphere), while sub-alkalic basalts that make-up most of the edifice, are considered to involve the mixing of these partial melts with shallower spinel-bearing lithosphere (McGee et al. 2011).

Although a comprehensive study is lacking, petrological differences between the various fields are recognized (Huang et al. 2000). For example, in northern North Island, the Kaikohe-Bay of Islands field volcanoes have erupted alkali basalts with geochemical signatures that reflect derivation from shallower mantle depths than those of the Auckland Volcanic Field. In contrast, some of the basalts from the Puhupuhi-Whangarei field display trace element signatures, such as a negative Nb anomaly, usually associated with the mantle wedge-derived melts in subduction systems. However, there was no subduction system in the Northland area during the Quaternary, and the geochemistry may reflect a relict mantle signature from the mid-Cenozoic subduction system (Huang et al. 2000).

A broad similarly ocean island basalt-like mantle source is proposed for all late Cenozoic intra-plate basalts (e.g., Hoernle et al. 2006). The cause of mantle melting is poorly understood. There is no geophysical evidence for plume-like structures beneath New Zealand, and the spatial-temporal pattern of volcanism is inconsistent with fixed plumes or rift systems. This has led some workers to propose decompression melting of the mantle via lithospheric delamination to explain the magmatism (Hoernle et al. 2006; Timm et al. 2010). They propose regional thickening of the crust during the Mesozoic produced a lithospheric ‘keel’ that become unstable and gravitationally detached into the asthenosphere, allowing localized upwelling and magmatism.

2.8.3 Volcano Fields

The intra-plate basalt fields in the North Island comprise numerous small volcanic edifices including small scoria cones, maars, low lava shields and lava flows, spread over areas of hundreds of square kilometers. Eruptive styles are typically Hawaiian-Strombolian and can include extensive valley-filling lava flows. Phreatomagmatic eruptions have also been common. Edifices reach heights of a maximum of a few hundred meters, and some of the longer lava flows can be traced on the order of 10–20 km. The longevity of activity in the fields is on the order of hundreds of thousands of years to a few million years. The volcanic loci generally

lack geometric patterns that could be structurally controlled. Limited geochronology in most of the fields hinders temporal-spatial investigations. However, studies to date have failed to reveal evolutionary trends in composition or eruption location within the individual fields.

2.8.4 Northland Fields

The Kaikohe-Bay of Islands field (Fig. 2.1) has periodically erupted over the last 10 million years, producing basaltic scoria cones, low shields and extensive lava fields (Smith et al. 1993). The magmas are mostly alkali basalts. At least 12 volcanoes have erupted in the last 500,000 years, but the field is considered dormant. The youngest volcano, Tananui, is dated at $\sim 43,000$ years (^{40}Ar – ^{39}Ar , Shane unpublished data), and comprises three scoria cones (~ 100 m height) and extensive lava field that extends about 20 km to the west. Horspool et al. (2006) estimate a crustal thickness of ~ 26 km beneath the field based on seismic data and detected a mid-crustal low velocity zone at 10–19 km depth that they interpret as a body of partial melt. The presence of an active geothermal site in the Kaikohe-Bay of Islands field is consistent with a cooling magma body. Such a body may have resulted from crustal melting induced by basaltic intrusion.

The Puhupuhi-Whangarei field (Fig. 2.1) was periodically active over at least 9 Ma (Smith et al. 1993), with eruptions of alkalic and subordinate sub-alkalic basalts. Edifices include low lava shields, scoria cones and lava flows. The more voluminous flows are up to 15 km in length and can be 80 m thick valley-filling units. Quaternary-age volcanism was restricted to the southern part of the field around Whangarei City (Smith et al. 1993). The youngest volcanoes, Mauru, Hurupaki, and Pukepoto, all comprise a scoria cone and extensive lava flow, and are dated at ~ 300 ka. Similar aged lava occurs within the city.

2.8.5 Auckland Field

The Auckland Volcanic Field is one of the better studied intra-plate basalt systems because Auckland City is built on top of the field, necessitating hazard and risk assessment (Figs. 2.1 and 2.8). The field comprises ~ 50 scoria cones, maars, and associated lava fields, scattered over a 360 km^2 area. Kereszturi et al. (2014) estimated a minimum total volume of magma erupted of $\sim 1.7 \text{ km}^3$ representing $\sim 1.4 \text{ km}^3$ of lava flows and the remainder being pyroclastic deposits. Alkalic basalts are the most common magmas erupted. However, individual volcanoes are known to erupt magma from sources at different depths and with different parental compositions from within the mantle (e.g. Needham et al. 2011; McGee et al. 2013). The Auckland Field is situated on crust of ~ 30 km thickness, and overlies a zone of lower S-wave velocities at a depth of 80 km that could represent the magma source (Horspool et al. 2006).

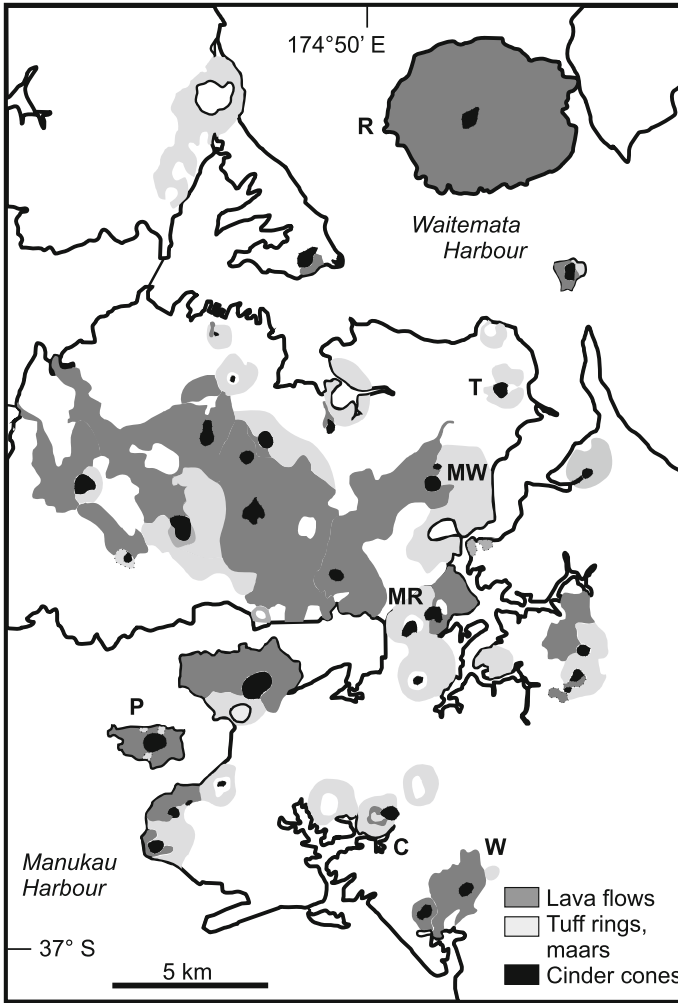


Fig. 2.8 Map of the Auckland volcanic field (redrawn from Molloy et al. 2009). Volcanoes referred to in the text: *R* Rangitoto; *T* Taylors Hill; *MR* Mt Richmond; *P* Puketutu; *C* Crater Hill; and *W* Wiri

Activity in the Auckland Field commenced at ~ 250 ka and continued intermittently to ~ 0.5 ka. Little is known about the history of magma output because of limited surface exposures and difficulties in potassium-argon dating arising from excess argon in many of the lavas (Cassata et al. 2008). However, unlike other intra-plate basalt fields, the Auckland Field has a tephrostratigraphic record based on ash layers preserved in maar lake sediments which have allowed a eruptive chronology to be developed (Molloy et al. 2009). Twenty-four basalt tephra layers over the last 80 ka are recorded, representing an average eruption frequency of one

per 3.5 ka. For simplicity, it could be assumed that each tephra represents a monogenetic volcano. The recurrence times vary from <0.5 to ~ 20 ka and show no temporal trend. The tephra record shows heightened activity at ~ 32 ka. This is related to a period of simultaneous eruptions from several volcanoes across the field (Wiri, Crater Hill, Puketutu, Mt Richmond and Taylor Hill) (Fig. 2.8) that display concordant ^{40}Ar – ^{39}Ar ages and all record the same anomalous paleomagnetic direction reflecting an excursion (Cassata et al. 2008; Cassidy 2006).

The heightened activity at ~ 32 ka does not necessarily relate to volumetric magma output. There are few tephra layers in the post-20 ka record and few volcanoes are inferred to have been active. However, the youngest volcano in the field (Rangitoto) (Fig. 2.8) last erupted at ~ 550 – 500 cal years BP (Needham et al. 2011), and is the largest, comprising ~ 0.7 km³ of the ~ 1.7 km³ of magma erupted in the field (Kereszturi et al. 2014). This points to changing magmatic output and vent patterns with time.

Rangitoto volcano has received much attention because of its young age and large size compared to the rest of the field. It is a composite basalt edifice comprising a radial lava field (low shield) and summit scoria cones that has erupted multiple batches of magma. Thus, it does not fit the traditional monogenetic classification of a volcano. The duration of volcanism based on studies of microscopic tephra layers preserved in lake sediments and radiocarbon dating of lava flows in drill cores suggest activity spanned the interval ~ 6000 – 500 years ago (Shane et al. 2013; Linnell et al. 2016). Thus, its voluminous character may be the result of prolonged or repeated activity at a central vent region.

2.8.6 *Fields South of Auckland*

The South Auckland Field comprises at least 97 volcanic centres in an area of about 300 km² (Briggs et al. 1994) (Fig. 2.1). Fifty-nine of the centres are magmatic scoria cones and associated lava flows, and 38 are phreatomagmatic tuff rings and maars, up to 2.5 km in diameter. Some of the volcanoes appear to lie on lineaments associated local faulting. K–Ar dating of 33 centres produce reliable ages in the range 0.56–1.59 ka. The youngest volcano is Pukehohe Cone (0.56 ± 0.05 ka) (Briggs et al. 1994).

The Ngatutura Field represents a low magma productive system (~ 1 km³) active in the interval 1.54–1.83 Ma (Briggs et al. 1989) (Fig. 2.1). It comprises at least 16 small ‘monogenetic’ volcanoes including scoria cones, lava flows and tuff rings.

The Alexandra Field comprises large subduction-related volcanoes and smaller intra-plate centres that were active during the interval 1.60–2.74 Ma (Fig. 2.1). The entire field has an estimated erupted magma volume of 55 km³, spread over an area of ~ 450 km² (Briggs et al. 1989). The subduction-related volcanoes represent about 50 km³ of the magma production, comprising mostly calc-alkaline basalt and subordinate andesite with minor ankaramites. These volcanoes are large, low-slope,

polygenetic stratovolcanoes. The largest two, Pirongia (1.60–2.74 Ma) and Karioi (2.16–2.92 Ma), were the sites of prolonged activity. Although the magmas display geochemical features typical of subduction systems, they are unusual in the location, far west of the Quaternary arc in central North Island. Interbedded with these subduction-related deposits, are intra-plate alkaline basalt deposits of the Okete Volcanics. These comprise at least 27 centres including scoria cones, lava flows and tuff rings. An estimate of 5 km³ of magma was erupted in the interval 2.69–1.8 Ma (Briggs et al. 1989).

Cenozoic intra-plate volcanism was both voluminous and common in the South Island (e.g., Hoernle et al. 2006) and on the Campbell Plateau and Chatham Rise (Gamble et al. 1986) (Fig. 2.1), but nearly all of the activity was pre-Quaternary. An exception is the Timaru basalt (Duggan and Reay 1986) dated at 2.6 ± 0.4 Ma (Hoernle et al. 2006) (Fig. 2.1). This comprises a range of intra-plate sub-alkalic and alkali basalt and basaltic andesites erupted in a 130 km² sheet with an average thickness <5 m. The lava sheet comprises several flow units that lack hiatuses, and overlie basaltic tuff (Duggan and Reay 1986). On the Chatham Rise and Campbell Plateau, the only known Quaternary volcanism occurred on the Antipodes Islands (<0.5 Ma, Gamble et al. 1986; Timm et al. 2009; Scott et al. 2013) (Fig. 2.1). These small sub-Antarctic islands are less than 4 km wide and include sea stacks. Rock types include intra-plate alkali basalts, basanites and nepheline hawaiites in the form of tuff ring and fall deposits with subordinate lava and intrusions.

2.9 Tephrochronology

Tephrochronology involves the use of tephra layers to date and correlate geologic sequences. Many pyroclastic falls and flows are emplaced effectively instantaneously (hours to days), and some have been dispersed over distances up to thousands of kilometers from the source volcano. Hence, tephra layers are important age horizons in many New Zealand Quaternary studies (see reviews by Lowe 1990, Shane 2000, Lowe et al. 2008). The basic field concepts of identifying and tracing tephra layers based on their lithology and stratigraphic position in proximal volcanic settings (within ~50 km from source) have been instrumental in deciphering the eruptive histories of rhyolite caldera volcanoes in the TVZ (e.g., Nairn 2002; Wilson 1993). Farther from source, thin tephra layers deposited in marine, lake or swamp sediments have been utilized to reconstruct volcano histories where the proximal record at the volcano has been obliterated or buried by subsequent events, or eroded (e.g., Shane et al. 2006; Molloy et al. 2009; Turner et al. 2009, and many others). In these more distal settings, the tephra identification is difficult because the layers lack distinctive lithological characteristics. Thus, the tephra layers are commonly identified by a combination of methods such as mineralogy, geochemistry of glass or minerals, and stratigraphic control and/or direct dating.

The tephrostratigraphic framework for the last ~50 ka is well developed in New Zealand, and based mostly by rhyolite tephra from Okataina and Taupo

volcanoes. However, accurate geochronology remains a major issue. This is exemplified by the age of the widespread Rotoehu tephra and associated Rotoiti ignimbrite erupted from Okataina volcano, which underpins the well-studied ~ 0 –50 ka time interval. The tephra layer is older than 40 ka and thus, not easily amenable to radiocarbon dating. In addition, it lacks high-K phases with high closure temperatures such as sanidine that are ideal for ^{40}Ar – ^{39}Ar dating. Various studies using direct and indirect chronological techniques including isotopic, radiometric, radiation exposure, and stratigraphic approaches produced a range in ages of ~ 30 –60 ka for Rotoehu tephra (see review in Danisik et al. 2012). Using the relatively novel approach of combined $^{238}\text{U}/^{230}\text{Th}$ disequilibrium and (U–Th)/He zircon ages coupled with new radiocarbon data, Danisik et al. (2012) were able to constrain the age to 46 ka. Pillans et al. (1996) summarize similar difficulties in dating older tephra layers such as the ~ 0.3 Ma Rangitawa tephra.

Current and future advances in tephrochronology include the detection and correlation of disseminated ash and microscopic layers in sediments that are not visible to the unaided eye. These deposits have the potential to reveal eruptions that were weakly explosive or were associated with limited ash dispersal (e.g., Shane et al. 2013). Microscopic tephra also have the potential act as age horizons beyond the range of visible tephra deposition from large magnitude events.

2.10 Concluding Remarks and Research Questions

Despite advancement in geochronology, in particular the wider application of step-heated ^{40}Ar – ^{39}Ar dating, the chronology of many of New Zealand's volcanic fields and individual volcanoes remain poorly known and are often constrained by a single age determination. This is particularly a problem for the intra-plate basaltic fields where many of the numerous edifices not have been dated, preventing the investigation of spatial-temporal-compositional trends, and the estimation of volcano longevity. Such information is important for the assessment of future hazards and risks to society. Further investigation of tephra records in marine and lake sediment records provide opportunities to elucidate the chronology of volcanoes that are not amenable to dating using their proximal deposits due to poor exposure or preservation, and/or issues with isotopic systematics. Paleomagnetic secular variation records of sediments containing distal tephra and of lava flows sequences on volcano flanks provides a relatively a little investigated approach for constraining New Zealand volcanism.

Subduction is the driving mechanism for the most frequent volcanism and voluminous magmatic production in New Zealand during the Quaternary. However, the tectonic control on the location of many volcanoes is not fully understood. For example, Taranaki arc volcano is spatially isolated from the contemporaneous 'arc' of subduction zone volcanoes. Similarly, the widespread intra-plate basaltic fields are not associated with an obvious mantle plume or a rift system.

Voluminous magmatism and extensive rifting and faulting characterize the Taupo Volcanic Zone. However, the relationship between individual faulting events and eruptions is relatively unknown mostly due to limitations on dating fault displacements. There is a wide spectrum of frequency-magnitude relationships for rhyolite eruptions at Okataina and Taupo volcanoes. In particular, caldera-forming events are an order or orders of magnitude larger than intra-caldera eruptions. The underlying causes of such behavior are not known. Mafic magmatism originating in the mantle drives these rhyolite volcanoes. However, does tectonism control the tempo of mafic magma ascent and eruption, or does deep-seated mafic magma production drive rifting?

References

- Bannister S, Bryan CJ, Bibby HM (2004) Shear wave velocity variation across the Taupo Volcanic Zone, New Zealand, from receiver function inversion. *Geophys J Int* 159:291–310.
- Barker SJ, Wilson CJN, Baker JA, Millet MA, Rotella MD, Wright IC, Wysoczanski RJ (2013) Geochemistry and Petrogenesis of Silicic Magmas in the Intra-Oceanic Kermadec Arc. *J Petrol* 54:351–391.
- Booden M.A, Smith I.E.M, Black PM, Mauk JL (2011) Geochemistry of the Early Miocene volcanic succession of Northland, New Zealand, and implications for the evolution of subduction in the southwest Pacific. *J Volcanol Geoth Res* 199:25–37.
- Briggs RM, Okada T, Itaya T, Shibuya H, Smith I (1994) K-Ar ages, paleomagnetism, and geochemistry of the South Auckland volcanic field, North Island, New Zealand. *NZ J Geol Geophys* 37:143–153.
- Briggs RM, Itaya T, Lowe DJ, Keane AJ (1989) Ages of the Pliocene-Pleistocene Alexandra and Ngatutura Volcanics, western North Island, New Zealand, and some geological implications. *NZ J Geol Geophys* 32:417–427.
- Briggs RM, Houghton BF, McWilliams M, Wilson CJN (2005) 40Ar/39Ar ages of silicic volcanic rocks in the Tauranga-Kaimai area, New Zealand: Dating the transition between volcanism in the Coromandel Arc and the Taupo Volcanic Zone. *NZ J Geol Geophys* 48:459–469.
- Bryan CJ, Sherburn S, Bibby HM, Bannister SC, Hurst AW (1999) Shallow seismicity of the central Taupo Volcanic Zone, New Zealand: its distribution and nature. *NZ J Geol Geophys* 42:533–542.
- Cameron E, Gamble J, Price R, Smith I, McIntosh W, Gardner M (2010) The petrology, geochronology and geochemistry of Hauhungatahi volcano, S.W. Taupo Volcanic Zone. *J Volcanol Geoth Res* 190:179–191.
- Carter L, Shane P, Alloway B, et al. (2003) Demise of one volcanic zone and birth of another: a 12 Ma marine record of major rhyolitic eruptions from New Zealand. *Geology* 31:493–496.
- Cassata WS, Singer BS, Cassidy J (2008) Laschamp and Mono Lake geomagnetic excursions recorded in New Zealand. *Earth Planet Sci Lett* 268:76–88.
- Cassidy J (2006) Geomagnetic excursion captured by multiple volcanoes in a monogenetic field. *Geophysical Res Lett* 33, L21310, doi:[10.1029/2006GL027284](https://doi.org/10.1029/2006GL027284)
- Charlier BLA, Wilson CJN, Lowenstern JB, Blake S, van Calsteren PW, Davidson JP (2005) Magma generation at a large, hyperactive silicic volcano (Taupo, New Zealand) revealed by U-Th and U-Pb systematics in zircons. *J Petrol* 46:3–32.
- Cole JW (1990) Structural control and origin of volcanism in the Taupo volcanic zone, New Zealand. *Bull Volcanol* 52:445–459.
- Cole JW (1978) Andesites of the Tongariro Volcanic Centre, North Island, New Zealand. *J Volcanol Geoth Res* 3:121–153.

- Cole JW, Graham IJ, Hackett WR, Houghton BF (1986) Volcanology and Petrology of the Quaternary Composite Volcanoes of Tongariro Volcanic Centre, Taupo Volcanic Zone. *Royal Soc NZ Bull* 23:224-249.
- Cole JW, Spinks KD, Deering CD, Nairn IA, Leonard GS (2010) Volcanic and structural evolution of the Okataina Volcanic Centre; dominantly silicic volcanism associated with the Taupo Rift, New Zealand. *J Volcanol Geoth Res* 190:123-135.
- Danisik M, Shane P, Schmitt AK, Hogg A, Santos GM, Storm S, Evans NJ, Fifield LK, Lindsay J (2012) Re-anchoring the late Pleistocene tephrochronology of North Island (New Zealand) based on concordant radiocarbon ages and combined $^{238}\text{U}/^{230}\text{Th}$ disequilibrium and (U-Th)/He zircon ages. *Earth Planet Sci Lett* 349-350:240-250.
- Duggan MB, Reay A (1986) The Timaru basalt. *Royal Soc NZ Bull* 23:264-277.
- de Ronde CEJ, Baker ET, Massoth GJ, Lupton JE, Wright IC, Feeley R, Greene RR (2001) Intraoceanic subduction-related hydrothermal venting, Kermadec volcanic arc, New Zealand. *Earth Planet Sci Lett* 193:359-369.
- Gamble JA, Morris PA, Adams CJ (1986) The geology, petrology and geochemistry of Cenozoic volcanic rocks of the Campbell Plateau and Chatham Rise. *Royal Soc NZ Bull* 23:343-365.
- Gamble JA, Wright IC, Baker JA (1993) Seafloor geology and petrology of the oceanic to continental transition zone of the Kermadec-Havre-Taupo volcanic arc system, New Zealand. *NZ J Geol Geophys* 36:417-435.
- Gamble JA, Woodhead J, Wright IC, Smith IEM (1996) Basalt and sediment geochemistry and magma petrogenesis in a transect from oceanic island arc to rifted continental margin arc: the Kermadec-Hikurangi margin, SW Pacific. *J Petrol* 37:1523-1546.
- Gamble JA, Wood CP, Price RC, Smith IEM, Stewart RB, Waight T (1999) A fifty year perspective of magmatic evolution on Ruapehu Volcano, New Zealand: verification of open system behaviour in an arc volcano. *Earth Planet Sci Lett* 170:301-314.
- Gamble JA, Price RC, Smith IE, McIntosh WC, Dunbar NW (2003). $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of magmatic activity, magma flux and hazards at Ruapehu volcano, Taupo Volcanic Zone, New Zealand. *J Volcanol Geoth Res* 120:271-287.
- Graham IJ, Cole JW, Briggs RM, Gamble JA, Smith IEM (1995) Petrology and petrogenesis of volcanic rocks from the Taupo Volcanic Zone: a review. *J Volcanol Geoth Res* 68:59-87.
- Graham IJ, Reyes AG, Wright IC, et al. (2008) Structure and petrology of newly discovered volcanic centers in the northern Kermadec- southern Tofua arc, South Pacific Ocean. *J Geophysical Res* 113:B08-S02.
- Harrison AJ, White RS (2004) Crustal stretching of the Taupo Volcanic Zone, New Zealand: stretching and igneous intrusion. *Geophysical Res Lett* 31 (1-4), L13615. doi.org/10.1029/2004GL019858.
- Heise W, Caldwell TG, Bibby HM, Bennie SL (2010) Three-dimensional electrical resistivity image of magma beneath an active continental rift, Taupo Volcanic Zone, New Zealand. *Geophysical Res Lett* 37, L10301. doi.org/10.1029/2010GL043110.
- Hobden BJ, Houghton BF, Davidson JP, Weaver SD (1999) Small and short-lived magma batches at composite volcanoes: time windows at Tongariro volcano, New Zealand. *J Geological Soc* 156:865-868.
- Hobden BJ, Houghton BF, Nairn IA (2002) Growth of a young, frequently active composite cone: Ngauruhoe volcano, New Zealand. *Bull Volcanol* 64:392-409.
- Hoernle K, White JDL, van den Bogaard P, Hauff F, Coombs DS, Werner R, Timm C, Garbe-Schönberg D, Reay A, Cooper AF (2006) Cenozoic intraplate volcanism on New Zealand: upwelling induced by lithospheric removal. *Earth Planet Sci Lett* 248:350-367.
- Horspool NA, Savage MK, Bannister S (2006) Implications for intraplate volcanism and back-arc deformation in northwestern New Zealand, from joint inversion of receiver functions and surface waves. *Geophysical J Internat* 166:1466-1483.
- Houghton BF, Weaver SD, Wilson CJN, Lanphere MA (1992) Evolution of a Quaternary peralkaline volcano: Mayor Island, New Zealand. *J Volcanol Geoth Res* 5:217-236.

- Huang YM, Hawkesworth C, van Calsteren P, Smith I, Black P (1997) Melt generation models for the Auckland volcanic field, New Zealand: Constraints from U-Th isotopes. *Earth Planet Sci Lett* 149:67-84.
- Huang Y, Hawkesworth C, Smith I et al. (2000) Geochemistry of late Cenozoic basaltic volcanism in Northland and Coromandel, New Zealand: implications for mantle enrichment processes. *Chem Geology* 164:219-238.
- Kereszturi G, Cappello A, Ganci G, Procter J, Németh K, Del Negro C, Cronin SJ (2014) Numerical simulation of basaltic lava flows in the Auckland Volcanic Field, New Zealand – implication for volcanic hazard assessment. *Bull Volcanol* 76:879-896.
- Lowe DJ (1990) Tephra studies in New Zealand: an historical review. *J Roy Soc N.Z* 20:119-149.
- Lowe DJ, Shane PAR, Alloway BV, Newnham RW (2008) Fingerprints and age models for widespread New Zealand tephra marker beds erupted since 30,000 yr ago as a framework for NZ-INTIMATE. *Quaternary Sci Rev* 27:95-126.
- Linnell T, Shane P, Smith I, Augustinus P, Cronin S, Lindsay J, Maas R (2016) Long-lived shield volcanism within a monogenetic basaltic field: the conundrum of Rangitoto Volcano, New Zealand. *Geol Soc Am Bull.* doi:[10.1130/B31392.1](https://doi.org/10.1130/B31392.1)
- Manville V, Wilson CJN (2004) The 26.5 ka Oruanui eruption, New Zealand: A review of the roles of volcanism and climate in the post-eruptive sedimentary response. *NZ J Geol Geophys* 47:525-547.
- McGee LE, Beier C, Smith IEM et al. (2011) Dynamics of melting beneath a small-scale basaltic system: a U-Th-Ra study from Rangitoto volcano, Auckland volcanic field, New Zealand. *Contrib Miner Petrol* 162:547-563.
- McGee LE, Smith IEM, Millet M-A, Handley HK, Lindsay JM (2013) Asthenospheric control of melting processes in a monogenetic basaltic system: a case study of the Auckland Volcanic Field, New Zealand. *J Petrol* 54:2125-2153.
- Moebis A, Cronin SJ, Neall VE, Smith IE (2011) Unravelling a complex volcanic history from fine-grained, intricate Holocene ash sequences at the Tongariro Volcanic Centre, New Zealand. *Quatern Internat* 246:352-363.
- Molloy C, Shane P, Augustinus P (2009) Eruption recurrence rates in a basaltic volcanic field based on tephra layers in maar sediments: implications for hazards in the Auckland Volcanic Field. *Geol Soc Am Bull* 121:1666-1677.
- Mortimer N, Gans PB, Foley FV, Turner MB, Daczko N, Robertson M, Turnbull IM (2013) Geology and age of Solander Volcano, Fiordland, New Zealand. *J Geol* 121:475-487.
- Nairn IA (2002) Geology of the Okataina Volcanic Centre: Institute of Geological and Nuclear Sciences geological map 25, scale 1:50,000, 1 sheet
- Nairn IA, Cole JW (1981) Basalt dikes in the 1886 AD Tarawera Rift. *NZ J Geol Geophys* 24:585-592.
- Nairn IA, Kobayashi T, Nakagawa M (1998) The 10 ka multiple vent pyroclastic eruption sequence at Tongariro Volcanic Centre, Taupo Volcanic Zone, New Zealand. Part 1: Eruption processes during regional extension. *J Volcanol Geoth Res* 86:9-44.
- Nairn IA, Shane P, Cole JW, Leonard GJ, Self S, Pearson N (2004) Rhyolite magma processes of the ~AD1315 Kaharoa eruptive episode, Tarawera volcano, New Zealand. *J Volcanol Geoth Res* 131:265-294.
- Neall VE, Stewart RB, Smith IEM (1986) History and petrology of the Taranaki volcanoes. *Royal Soc NZ Bull* 23:251-263.
- Needham AJ, Lindsay JM, Smith IEM, Augustinus P, Shane PA (2011) Sequential eruption of alkaline and sub-alkaline magmas from a small monogenetic volcano in the Auckland Volcanic Field, New Zealand. *J Volcanol Geoth Res* 201:126-142.
- Pardo N, Cronin S, Palmer A, Procter J, Smith I (2012) Andesitic Plinian eruptions at Mt. Ruapehu: quantifying the uppermost limits of eruptive parameters. *Bull Volcanol* 74:1161-1185.
- Pillans B, Froggatt P, Kohn BP and others (1996) Multi-method dating comparison for mid-Pleistocene Rangitawa Tephra, New Zealand. *Quaternary Science Reviews (Quaternary Geochronology)* 15:641-653.

- Price RC, McCulloch MT, Smith IEM, Stewart RB (1992) Pb-Nd-Sr isotopic compositions and trace element characteristics of young volcanic rocks and Egmont Volcano and comparisons with basalts and andesites from the Taupo Volcanic Zone, New Zealand. *Geochim Cosmochim Acta* 56:941–953.
- Price RC, Stewart RB, Woodhead JD, Smith IEM (1999) Petrogenesis of high-K arc magmas: evidence from Egmont volcano, North Island, New Zealand. *Journal of Petrology* 40: 167–197.
- Price RC, Turner S, Cook et al. (2010) Crustal and mantle influences and U–Th–Ra disequilibrium in andesitic lavas of Ngauruhoe volcano, New Zealand. *Chem Geology* 277:355–373.
- Price RC, Gamble JA, Smith IEM, Maas R, Waight T, Stewart RB, Woodhead J (2012) The anatomy of an andesite volcano: a time-stratigraphic study of andesite petrogenesis and crustal evolution at Ruapehu volcano, New Zealand. *J Petrol* 53:2139–2189.
- Price RC, Smith IEM, Stewart RB, Gamble JA, Gruender K, Maas R (in press) High-K andesite petrogenesis and crustal evolution: Evidence from mafic and ultramafic xenoliths, Egmont Volcano (Mt. Taranaki) and comparisons with Ruapehu Volcano, North Island, New Zealand. *Geochimica et Cosmochimica Acta*
- Scott JM, Turnbull IM, Auer A, Palin JM (2013) The sub-Antarctic Antipodes Volcano: a < 0.5 Ma HIMU-like Surtseyan volcanic outpost on the edge of the Campbell Plateau, New Zealand. *NZ J Geol Geophys* 56:134–153.
- Seebeck H, Nicol A, Stern TA, Bibby HM, Stagpoole V (2010) Fault controls on the geometry and location of the Okataina Caldera, Taupo Volcanic Zone, New Zealand. *J Volcanol Geoth Res* 190:136–151.
- Seebeck H, Nicol A, Giba M, Pettinga J, Walsh J (2014) Geometry of the subducting Pacific plate since 20 Ma, Hikurangi margin, New Zealand. *J Geol Soc* 171:131–143.
- Shane P (2000) Tephrochronology: a New Zealand case study. *Earth Sci Rev* 49:223–259.
- Shane P, Wright I (2011) Late Quaternary tephra layers around Raoul and Macauley Islands, Kermadec Arc: implications for volcanic sources, explosive volcanism and tephrochronology. *J Quatern Sci* 26:422–432.
- Shane PAR, Black TM, Alloway BV, Westgate JA (1996) Early to middle Pleistocene tephrochronology of North Island, New Zealand: implications for volcanism, tectonism and paleoenvironments. *Geol Soc Am Bull* 108:915–925.
- Shane P, Nairn IA, Smith VC (2005a) Magma mingling in the ~50 ka Rotoiti eruption from Okataina Volcanic Centre: implications for geochemical diversity and chronology of large volume rhyolites. *J Volcanol Geoth Res* 139:295–313.
- Shane P, Smith VC, Nairn IA (2005b) High temperature rhyodacites of the 36 ka Hauparu pyroclastic eruption, Okataina Volcanic Centre, New Zealand: change in a silicic magmatic system following caldera collapse. *J Volcanol Geoth Res* 147:357–376.
- Shane P, Nairn IA, Smith VC, Darragh MB, Beggs KF, Cole JW (2008a) Silicic recharge of multiple rhyolite magmas by basaltic intrusion during the 22.6 ka Okareka Eruption Episode, New Zealand. *Lithos* 103:527–549.
- Shane P, Smith V, Nairn I (2008b) Millennial timescale resolution of rhyolite magma recharge at Tarawera volcano: insights from quartz chemistry and melt inclusions. *Contrib Miner Petrol* 156:397–411.
- Shane P, Sikes EL, Guilderson TP (2006) Tephra beds in deep-sea cores off northern New Zealand: implications for the history of Taupo Volcanic Zone, Mayor Island and White Island volcanoes. *J Volcanol Geoth Res* 154:276–290.
- Shane P, Gehrels M, Zawalna-Geer A, Augustinus P, Lindsay J, Chaillou I (2013) Longevity of a small shield volcano revealed by crypto-tephra studies (Rangitoto volcano, New Zealand): change in eruptive behavior of a basaltic field. *J Volcanol Geoth Res* 257:174–183.
- Sherburn S, White RS (2005) Crustal seismicity in Taranaki, New Zealand using accurate hypocentres from a dense network. *Geophysical J Internat* 162:494–506.
- Smith IEM, Okada T, Itaya T, Black P (1993) Age relationships and tectonic implications of late Cenozoic basaltic volcanism in Northland, New Zealand. *NZ J Geol Geophys* 36:385–393.
- Smith IEM, Worthington TJ, Price RC, et al. 2006. Petrogenesis of dacite in an oceanic subduction environment: Raoul Island, Kermadec arc. *J Volcanol Geoth Res* 156: 252– 265.

- Smith VC, Shane P, Nairn IA, Williams CH (2006) Geochemistry and magmatic properties of eruption episodes from Haroharo Linear Vent Zone, Okataina Volcanic Centre, New Zealand during the last 10 kyr. *Bull Volcanol* 69:57–88.
- Stern TA, Stratford WR, Salmon ML (2006) Subduction evolution and mantle dynamics at a continental margin, central North Island, New Zealand. *Rev Geophys*, RG4002 (Paper 2005RG00017).
- Stern T, Benson A (2011) Wide-angle seismic imaging beneath an andesitic arc: Central North Island, New Zealand. *J Geophys Res* 116, B09308. <http://dx.doi.org/10.1029/JB008337>, 2011.
- Storm S, Shane P, Schmitt AK, Lindsay JM (2012) Decoupled crystallization and eruption histories of the rhyolite magmatic system at Tarawera volcano revealed by zircon ages and growth rates. *Contrib Miner Petrol* 163:505–519.
- Stratford WR, Stern TA (2004) Strong seismic reflections and melts in the mantle of a continental back-arc basin. *Geophys Res Lett* 31:L06622. doi:[10.1029/2003GL019232](https://doi.org/10.1029/2003GL019232).
- Timm C, Hoernle K, van den Bogaard P, Bindeman I, Weaver S (2009) Geochemical evolution of intraplate volcanism at Banks Peninsula, New Zealand: interaction between asthenospheric and lithospheric melts. *J Petrol* 50:989–1023.
- Timm C, Hoernle K, Werner R, Hauff F, van den Bogaard P, White J, Mortimer N, Garbe-Schonberg D (2010) Temporal and geochemical evolution of the Cenozoic intraplate volcanism of Zealandia. *Earth Sci Rev*. doi:[10.1016/j.earscirev.2009.10.002](https://doi.org/10.1016/j.earscirev.2009.10.002).
- Turner MB, Beddington MS, Cronin SJ, Stewart RB (2009) Merging eruption datasets: building an integrated Holocene eruptive record for Mt Taranaki, New Zealand. *Bull Volcanol* 71:903–918.
- Villamor P, Berryman KR, Nairn IA, Wilson K, Litchfield N, Ries W (2011) Associations between volcanic eruptions from Okataina volcanic center and surface rupture of nearby active faults, Taupo rift, New Zealand: insights into the nature of volcanotectonic interactions. *Geol Soc Am Bull* 123:1383–1405. doi:[10.1130/b30184.1](https://doi.org/10.1130/b30184.1)
- Wallace LM, Beavan J, McCaffrey R, Darby D (2004) Subduction zone coupling and tectonic block rotations in the North Island, New Zealand. *J Geophys Res* 109:B12496. doi.org/10.1029/2004JB003241.
- Wilson CJN (1993) Stratigraphy, chronology, styles and dynamics of the late Quaternary eruptions from Taupo volcano, New Zealand. *Phil Trans R Soc Series A* 343:205–306.
- Wilson CJN, Houghton BF, McWilliams MO, Lanphere MA, Weaver SD, Briggs RM (1995a) Volcanic and structural evolution of the Taupo Volcanic Zone, New Zealand: a review. *J Volcanol Geoth Res* 68:1–28.
- Wilson CJN, Houghton BF, Kamp PJJ et al. (1995b) An exceptionally widespread ignimbrite with implications for pyroclastic flow emplacement. *Nature* 378:605–607.
- Wilson CJN, Houghton BF, Pillans BJ, Weaver SD (1995c) Taupo Volcanic Zone calc-alkaline tephra on the peralkaline Mayor Island volcano, New Zealand: identification and uses as marker horizons. *J Volcanol Geoth Res* 69:303–311.
- Wilson CJN, Gravley DM, Leonard GS, Rowland JV (2009) Volcanism in the central Taupo Volcanic Zone, New Zealand: tempo, styles and controls. In: Thordarson, T., Self, S., Larsen, G., Rowland, S.K., Hoskuldsson, A. (Eds.), *Studies in Volcanology: The Legacy of George Walker*. Special Publications of IAVCEI, 2, pp. 225–247.
- Wright IC, Worthington TJ, Gamble JA (2006) New multibeam mapping and geochemistry of the 308–358 sector, and overview of southern Kermadec volcanism. *J Volcanol Geoth Res* 149:263–296.
- Zernack AV, Cronin SJ, Neall VE, Procter JN (2011) A medial to distal volcanoclastic record of an andesite stratovolcano: Detailed stratigraphy of the ring-plain succession of south-west Taranaki, New Zealand. *Internat J Earth Sci* 100:1936–1966.
- Zernack AV, Price RC, Smith IEM, Cronin SJ, Stewart RB (2012) Temporal evolution of a high-K andesitic magmatic system: Taranaki Volcano, New Zealand. *J Petrol* 53:325–363.

Landscape and Quaternary Environmental Change in
New Zealand

Shulmeister, J. (Ed.)

2017, XIII, 334 p. 78 illus., 53 illus. in color., Hardcover

ISBN: 978-94-6239-236-6

A product of Atlantis Press