Volcanoes of the Tongariro National Park, New Zealand

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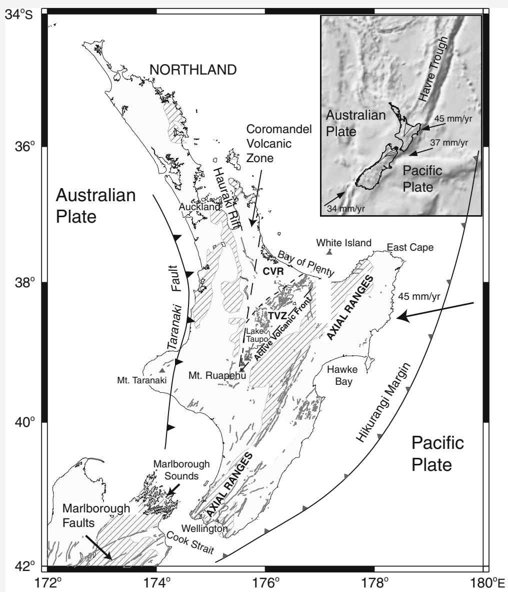
Harry Keys and Karen Williams



Map 1 courtesy of Tim Stern (Victoria University of Wellington) and Geological Society of London

Geographical location including map co-ordinates:
Tongariro National Park, central North Island, New Zealand
A 175 24" 08" E; 39 10" 43" N B - 175 25" 49" E; 39 24" 44" N C - 175 33" 29" E; 39 04" 45" N D - 175 41" 43" E; 38 58" 40" N E - 175 46" 45" E; 39 04" 05" N F - 175 49" 04" E; 39 08" 24" N G - 175 44" 26" E; 39 17" 54" N

Type of volcanoes:
Composite stratovolcanoes

Last known eruption:
21 November 2012

Major attractions:
Tongariro Alpine Crossing and Northern Circuit, Ruapehu Crater Lake, Whakapapa and Turoa ski areas, Round-the-Mountain and other tracks

Status of protection:
National Park, World Heritage Area

Visitor numbers:
Approximately 1 million per year

12.1 Geographical Location

The volcanoes of Tongariro National Park (TNP) are located in the central North Island of New Zealand. Three active volcanoes, Ruapehu (2797 m), Ngauruhoe (2287 m) and Tongariro (1967 m) (Figs. 12.1a–c and 12.2) and several smaller extinct cones comprise the Tongariro Volcanic Centre most of which lies within the national park. The park is 300 km south of Auckland and 300 km north of Wellington with state highways and the main railway giving easy access. Ohakune and Turangi are the two largest towns at the boundaries of the park while Whakapapa Village lies inside the park on the lower slopes of Mt Ruapehu.The Department of Conservation (2013) has detailed maps of the park, including mapping tools for tracks, and information on huts, visitor centres and places of interest.

12.2 Geophysical Aspects and Geological History

The Tongariro Volcanic Centre is 50 km long and 30 km wide with a base level of 350–1000 m above sea level. It lies at the southern end of 20–60 km wide Taupo Volcanic Zone (TVZ) which extends 240 km from Ruapehu in the south to the Okataina Volcanic Centre in the north and offshore to White Island volcano and beyond (Map 1). Ruapehu is the highest and with a volume of 150 km^3 the largest volcano (Hackett and Houghton 1989) and the most active over the last 35 years (Fig. 12.3).

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P. Erfurt-Cooper (ed.), *Volcanic Tourist Destinations*, Geoheritage, Geoparks and Geotourism,
DOI: 10.1007/978-3-642-16191-9_12, © Springer-Verlag Berlin Heidelberg 2014

Fig. 12.1 **a** Winter aerial view from 3000 m/10,000 feet of the three active volcanoes of Tongariro National Park with fault lines prominent. View is from the northwest with Tongariro in the foreground including Te Maari area on *bottom left* looking towards Ruapehu in the distance. *Photo* Paul Dawson. **b** Summer aerial view from the northeast of the three active volcanoes of Tongariro National Park—five months before the eruption from the Te Maari crater area in the foreground. *Photo* Karen Williams. **c** View from near the summit of Mt Tongariro looking south past Ngauruhoe to Ruapehu with the old volcanic remnant of Hauhungatahi on the *right*. *Photo* Harry Keys

(a) (b) (c)

The active volcanoes in New Zealand result from the tectonic setting in which the subducting slab of the Pacific Plate is pushing under the Indian-Australian Plate in an obliquely convergent boundary zone with an eastern expression at the Hikurangi margin and trough just east of the North Island (Map 1). Volcanism in northern New Zealand began about 22 million years ago, consistent with the inception of subduction along the Hikurangi margin

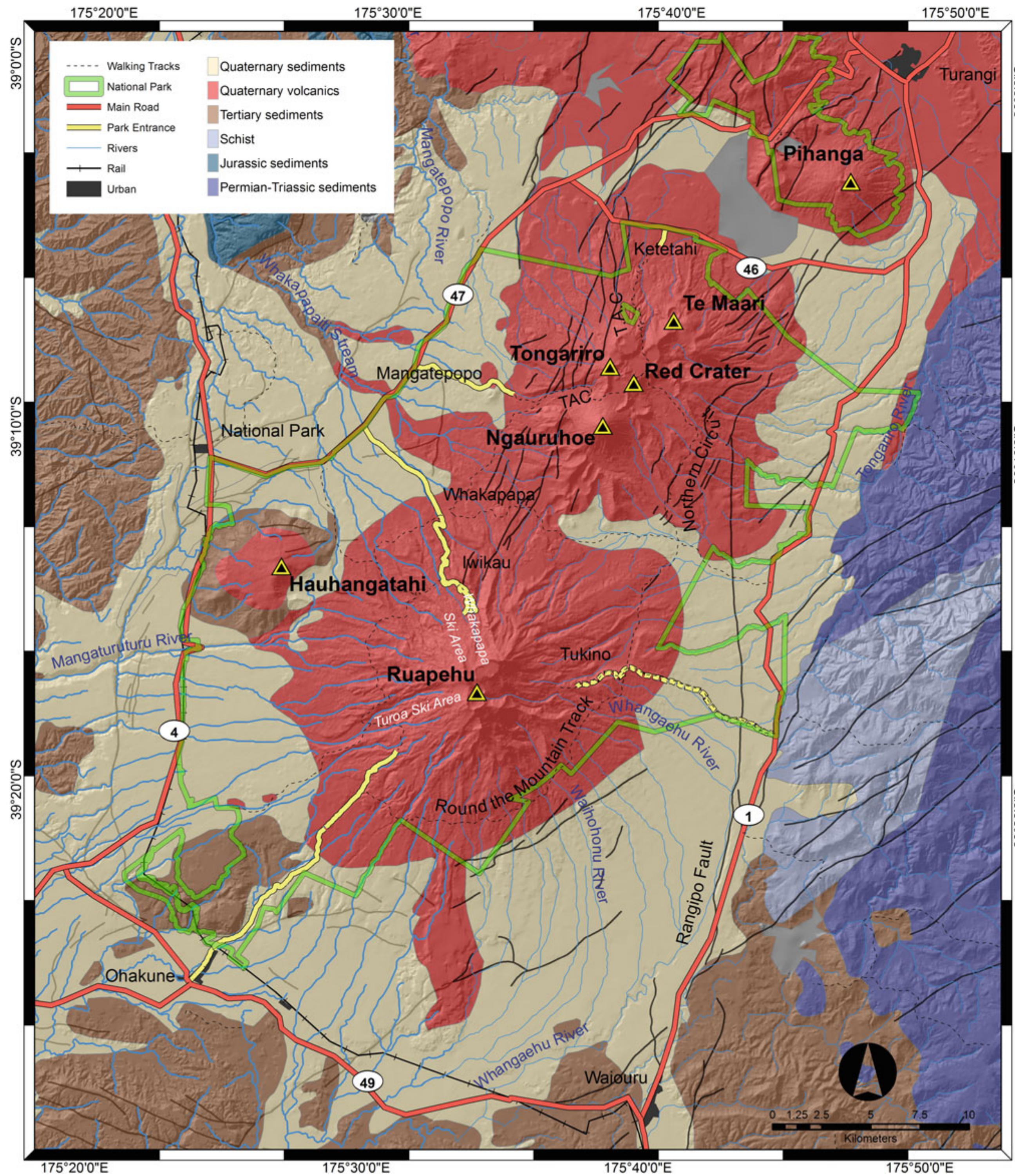

Fig. 12.2 Tongariro National Park with volcanoes and major faults parallel the regional tectonic trend, showing access roads and major tracks including Tongariro Alpine Crossing (TAC). The volcanoes are located at the southern end of the Taupo Volcanic Zone surrounded on three sides by marine sedimentary rocks 4–30 million years old or older *greywacke* and schist >150 million years (Map 1). Map prepared by Jon Procter (Massey University) using regional geology and faults courtesy of GNS Science

(Lamb 2011), and has moved south due to the tectonic motion. The result is a trail of extinct volcanoes that are progressively younger to the east and southeast where the active volcanic front is currently located. Over the last five million years this front has had an apparent southeast migration rate of about 23 mm per year (Stern 2009).

Fig. 12.3 Ruapehu Volcano (2979 m) rises 2000 m above State Highway 1 across the ring plain. Eruptions in 1995 through 1997 provided popular viewing for travellers. *Photo* Harry Keys

Tongariro Volcanic Centre and the TVZ are the current southern part of a 2500 km long chain of active terrestrial and underwater volcanoes and island arcs along the edge of the subducting Pacific Plate. The TVZ forms the eastern portion of the wedge-shaped Central Volcanic Region. This is a thin, spreading segment of the Earth's crust, referred to as a back-arc (Map 1). The region and the TVZ within it are associated with clockwise rotation, hinged apparently near Ruapehu, and southwards movement of the plate boundary over the last four million years (Stern 2009; Lamb 2011). The TVZ became active about two million years ago and has an anomalously high heat flow and widespread geothermal activity. It has been the source of spectacularly explosive rhyolitic eruptions with a pile of volcanogenic material up to 2 km deep in places and pyroclastic material spread out either side of the zone. Typical of the Pacific Ring of Fire however, Tongariro volcanoes are predominantly andesite, with some dacite, basalt and rhyolite.

West, northwest and east of the three main volcanoes in TNP the boundary of the TVZ in this region is marked by prominent active faults (Figs. 12.1a and 12.2). These are controlled by the tectonic pattern but downthrown towards the volcanoes as subsidence has developed in the central axis of the TVZ. The southern termination of the TVZ is 20 km south of Ruapehu's summit at a series of lakes near Ohakune. These lakes occupy extinct craters 30,000 years old that are the most southerly expression of present day volcanism in New Zealand.

Volcanism began in the area of the present TNP about a million years ago. Hauhungatahi in the west is the oldest volcanic feature representing part of a lineation in the Central Volcanic Region (Map 1) that is older than and sub-parallel to the current active volcanic front. It is an eroded andesite volcano dated at ~900,000 years distinctive from the currently low-potassium volcanoes of the active front nearby due to its greater age and high-magnesium andesite chemistry (Cameron et al. 2010). It mantles the top of a sequence of marine sedimentary rock up to 7 million years old.

Ruapehu and Tongariro-Ngauruhoe are active composite stratovolcanoes consisting of alternating layers of volcanic material erupted over the last 300,000 years from multiple vents aligned north-northeast to south-southwest corresponding to the present active volcanic and tectonic trends in the region. Ngauruhoe which is regarded as the youngest cone of Tongariro is now thought to have developed from about 7,000 years ago (Moebis 2011) over some of the oldest Tongariro lavas (Fig. 12.4). In contrast Kakaramea-Tihia and Pihanga comprise a smaller volume, lower and well-vegetated andesitic volcanic massif in the north of the park. They erupted between 230,000 and 20,000 years ago along a line almost at right angles to the present geological trends.

Fig. 12.4 The young Ngauruhoe Volcano (2287 m) developed over an older volcano massif including Tongariro to the north (*right*). Glaciers radiating outwards eroded valleys like this Waihohonu Valley to the southeast. *Photo* Jimmy Johnson

During the last ice age Mt Ruapehu and the Tongariro massif carried glaciers extending down to as low as 1100 m elevation (McArthur and Shepherd 1990). These glaciers and those of the previous two glacial maxima altered the shape of the existing volcanoes by excavating deep valleys (Fig. 12.4) damming and interacting with lava flows and other volcanic material, and depositing material including prominent moraines.

Ruapehu provides a very good example of how a volcano develops over time. It is dissected in places and surrounded by dateable volcanic deposits so that its geological history is well known (Hackett and Houghton 1989; Donoghue et al. 1997; Gamble et al. 2003; Pardo et al. 2012; Price et al. 2012). The oldest dated materials consist of 300,000 year old andesite pebbles deposited on a marine bench now uplifted in the Wanganui district (Neall et al. 1999). These are the remnants of an andesite lava flow which was emplaced following eruptions from an early volcano thought to be in the vicinity of Ruapehu.

Four major phases of growth are recognised with the constructional periods separated by stages of erosion and lower level volcanic activity. On the volcano itself the oldest exposed lava sequences (the *Te Herenga* Formation) are part of a basic andesite cone forming the northern flank of Ruapehu from about 250,000 to 180,000 years ago. Two further major periods of cone growth occurred from 160,000 to 115,000 and 55,000 to 20,000 years ago. After that, lavas younger than 15,000 years old (the *Whakapapa* Formation) were erupted mantling slopes in the northwest, south and elsewhere (Fig. 12.5). Voluminous lahars were generated over much of the life of the volcano, most obviously during the second and third constructional periods and coincident with the last two glacial cycles. Lahar deposits totalling more than 12 km^3 (Neall et al. 1999) have inundated the nearby hill country, creating an extensive ring plain around much of the volcano.

From 27,000 to about 10,000 years ago a sequence of large eruptions (Pardo et al. 2012) produced extensive and revealing layers of tephra around the volcano (Fig. 12.6). These were deposited by explosive eruptions involving up to one cubic kilometre of magma and producing eruption columns possibly up to 40 km high. Most of the youngest lava flows on Ruapehu (Fig. 12.5) were produced during this very active period. The last major eruption in this sequence about 12,000 years ago produced huge pyroclastic density currents down the eastern and western flanks, well past the current State Highway 1. Also around this time a major structural collapse of the northwest flank occurred

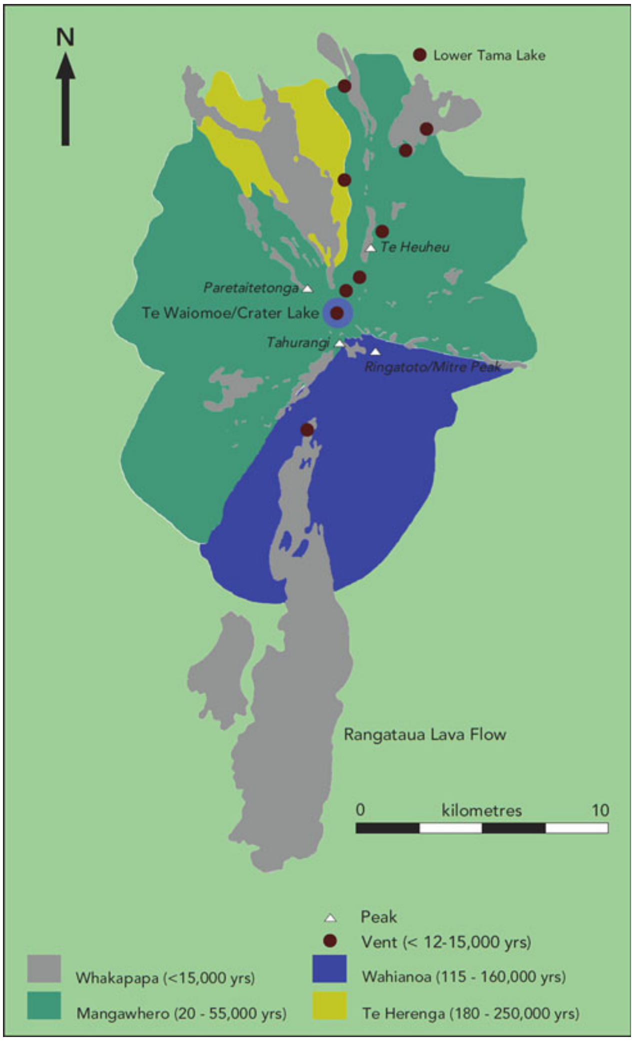

Fig. 12.5 Map of Ruapehu showing extent and recently calculated age ranges of exposed cone-forming lava sequences and young vents, from Hackett and Houghton (1989), Gamble et al. (2003) and Price et al. (2012). Young lava flows from a forthcoming 1:50,000 geological map of TNP are shown courtesy of GNS Science. The Rangataua lava flow sequence is the largest in the national park

and a debris avalanche produced the distinctive mounds through which Highway 48 passes en route to Whakapapa Village (Palmer and Neall 1989).

Over the last 10,000 years activity at Ruapehu summit has been generally smaller and less explosive. A sequence of craters were active in the central and northern summit plateau area between about 9,000 and 3,000 years ago (Palmer 1991) producing lavas through the area now occupied by Whakapapa ski area. They are now full of up to 130 m of glacial ice (Holdsworth 1985). Sometime between 4,500 and 3,500 years ago, collapse of an old hydrothermally altered rim around a southern vent produced a large debris avalanche that swept down the Whangaehu and east across the Rangipo 'desert' destroying a widespread beech forest on the southeastern ring plain (Donoghue and Neall 2001). Since deposition of the Taupo Pumice around the volcano's flanks about 1,800 years ago, a series of 19 widespread thin tephra deposits have been locally preserved, and several are younger than 700 years (Donoghue et al. 1997). It appears the modern Crater Lake came into existence around that time. This youngest crater rim is composed of lavas, agglomerates, scoria, breccia, tuff, tephras and sedimentary material (Hales 2000; Hodgson et al. 2007). Eruptions and collapses of this youngest rim have resulted in a large number of lahars with a wide range of sizes. Some were very large with estimated maximum discharge rates of up to 6,000 m^3 per second, which is much greater than the maximum discharge estimated for the largest Ruapehu lahar (1861) in historical time (Neall et al. 1999).

The Tongariro volcanic complex has also grown since about 300,000 years ago. The oldest dated rocks in place are about 270,000 years old near Tama Lakes with subsequent intervals of rapid cone growth for example at 210,000–200,000, 130,000–65,000, and 27,000 years to the present day (Hobden et al. 1996; Fig. 12.7). The most recent major eruption sequence occurred about 11,000 years ago at the end or just after the last major sequence on Ruapehu (Donoghue et al. 1995; Nairn et al. 1998; Pardo et al. 2012) producing mainly andesite tephras up to 1.25 m thick along the route of the current State Highway 1 (Desert Road).

There has been a long debate about whether volcanism at Tongariro and Ruapehu has occurred or occurs at similar times, possibly driven by tectonic forces which might also drive large rhyolite eruptions. There are gross similarities between the initial and some other periods of major activity or growth of these volcanoes, and some approximate coincidence with the major eruption of Taupo 'super-volcano' 26,000 years ago. But there are also major differences. While different rock dating techniques may not produce entirely compatible results, there appear to be a lack of lavas on Tongariro around 134,000 and between about 65,000 and 25,000 years old, and a lack on Ruapehu around 60,000-100,000 years (Hobden et al. 1996; Gamble et al. 2003). This may be due to an absence of data from several key areas as a result of the loss of parts of the geological record during widespread erosion during the last glaciations or due to inundation by more recent volcanic material. But it is also clear that the two volcanoes have magmatic systems that are chemically different and entirely independent for much of geological time (Gamble et al. 2003) and in the modern day (Moebis 2011). Geological interpretations suggest regional extension and rotation rates across the volcanic region have been consistent over the last four million years, ten thousand years and recent decades (Stern 2009; Lamb 2011). During the period from about 25,000 years ago (or earlier) to 14,000 years ago the major Rangipo Fault southeast of Ruapehu (Fig. 12.3) was moving an order of magnitude faster than now (Villamor et al. 2007). This roughly coincides with

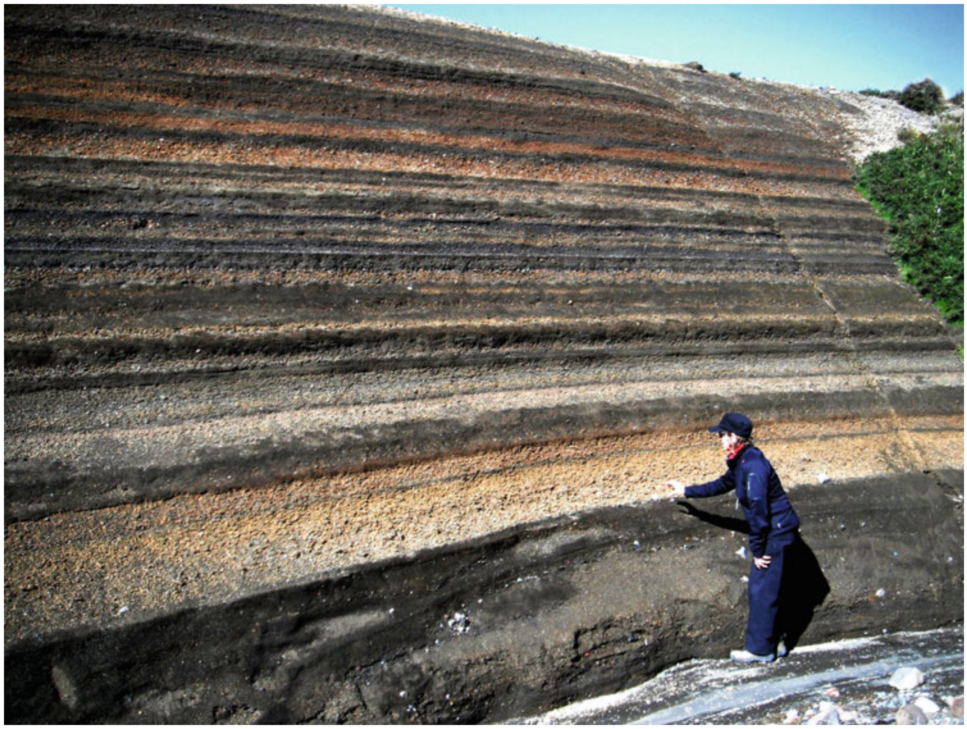

Fig. 12.6 Layers of tephra deposited from a series of large eruptions of Ruapehu and even larger eruptions from caldera volcanoes to the north. There are several spectacular tephra sequences like this beside the Tukino Road and many others beside state highways around the volcanoes. *Photo* Harry Keys

the last period of major volcanism in TNP (Pardo et al. 2012; Nairn et al. 1998). But otherwise there is no direct evidence yet for periods of more rapid tectonic extension or other plate kinematics that might have been associated with higher heat flow, generation of magma or dike intrusion geographically extensive enough to drive simultaneous growth and eruptions of these volcanoes.

12.3 Geological Heritage

Tongariro National Park is inscribed as World Heritage under UNESCO's Natural criteria (vii) and (viii), and Associative Cultural criterion (vi). Criterion (vii) involves "superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance" while (viii) involves "outstanding examples representing major stages of Earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiographic features".

Criterion (vi) is "directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance". The park itself grew from a transaction between the paramount chief of Ngati Tuwharetoa and the colonial government involving the summit areas of the volcanoes to the current extent of protected land. This has become important to New Zealand in the relationships between Maori and other New Zealanders and in a three-way bond with the volcanoes.

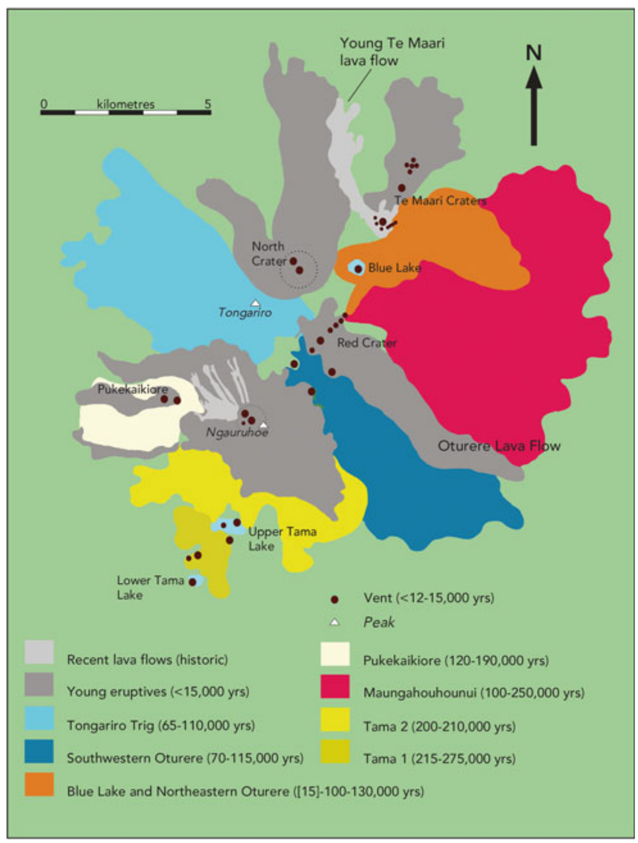

Fig. 12.7 Map of Tongariro-Ngauruhoe adapted from Hobden et al. (1996, 2002), Price et al. (2003) and Nairn (unpublished) showing ages of exposed cone-forming sequences. Young eruptives are from a forthcoming 1:50,000 geological map of TNP courtesy of GNS Science

Fig. 12.8 View from Tukino Road encompassing 1000 m of relief from the summit of Ringatoto Peak (2591 m, *upper right*) to the Whangaehu River in the foreground. This scene includes evidence of recent deepening of the gorge and sediment deposition by the March 2007 lahar, the sequence of 134,000 year old lavas and other material in the middle distance and various younger intrusions, lava flows and deposits. The summit of the glacial horn, Girdlestone Peak, can be seen above the saddle. *Photo* Frank Katavitch

A major political negotiation about the future of the park is currently underway. *Iwi* (Maori tribes) prefer to describe their cultural backgrounds and perspectives on the history of the original transaction themselves. Therefore these cultural heritages are outside the scope of this chapter.

TNP contains and records internationally important geological features and processes and is the only extensive part of the Taupo Volcanic Zone that is still protected in its natural state. The park is the most spectacular and diverse example of andesitic mountain-building in the southwest Pacific (Figs. 12.1a–c, 12.3, 12.4, 12.5, 12.6, 12.7, 12.8, 12.9 and 12.10). This is one of the most frequently active composite volcano complexes in the world and Ruapehu provides a model of volcano evolution. The current volcanic landscape reflects a dynamic balance between cone-building by episodic volcanism and subsequent destruction by glacial, laharic and other erosion processes. Major topographic relief has been produced including the upper Whangaehu Valley which provides a 1,000 m cross-section through the "Wahianoa volcano" and its 300 m thick sequence of lava flows and pyroclastic units around 134,000 years old (Gamble et al. 2003) (Fig. 12.8). A wide variety of volcanic and glacial features, including the world-famous Crater Lake and lesser known features of volcano-glacier interaction, are present.

Reworked volcanic debris from lahars, rivers and landslides, plus airfall and pyroclastic flow deposits, form extensive and classic ring plains surrounding the volcanoes (see Figs. 12.2, 12.3 and 12.6). The park also contains extensive tephra deposits from one of the world's most powerful volcanic eruptions of the last 5,000 years – the Taupo 'super-volcano'. The ring plain contains interesting carbonised examples of forest trees felled by the Taupo blast and lying in a radial direction from it (Fig. 12.9).

Fig. 12.9 Charred and burnt logs of mountain toatoa (*Phyllocladus alpinus*) at Rangipo "desert" lying where they were felled by the hot blast that travelled 80 km from the Taupo eruption in 232 AD. *Photo* Karen Williams

Ruapehu's Crater Lake, prominent in the summit area between the highest peaks, is unique due to its high frequency of eruption, size, warmth, glacial setting and accessibility (Fig. 12.10). Normally it is full to overflowing and 200,000 m^2 in extent, up to 170 m deep with a volume of 7–10 million m^3 of water with a pH level of 1. It is also a *urupa* (burial ground) where chiefs of the *Ngati Rangi iwi* (tribe) were interred in historic time.

Crater Lake is one of only two volcanoes internationally regarded as classic examples of the interaction of magma and lake water. It has become an important volcano "laboratory" for understanding volcanic processes. A notable characteristic of the magmatic-hydrothermal environment of the volcano is the thermal cycling of the lake (excluding the main eruption episodes). Since regular measurements began in the 1960s its temperatures have varied irregularly with time between 9 and 60 °C, at periods ranging between 2 and 4 and 16 months (Fig. 12.11). Correlation between lake temperature and CO_2 discharge from the volcano shows that the heating cycles exhibited in the lake are largely controlled by variations in the rate of magmatic degassing located within about 1000 m beneath the lake (Christenson et al. 2010). Fluid instabilities in the vent system may also contribute (Vandemeulebrouck et al. 2005). Other factors such as the presence of elemental sulphur and other mineral accumulations reducing gas and energy flux up into the lake appear to be secondary to this (Christenson et al. 2010, Fig. 12.12) but do help create anomalous periods with temperatures persistently below 24 °C for 6–12 months (Fig. 12.11). Daily solar heating and cooling cycles of 1–3 °C and approximately monthly cycles of 2–4 °C possibly due to earth tides, are also evident during stable weather conditions.

Phreatomagmatic eruptions, a characteristic of Ruapehu, occur when a significant amount of magmatic fluid interacts with water in the vent or the lake itself with accompanying explosive expulsion of Crater Lake water. In the largest single explosions (or short blast sequences) documented (10 March 1895, 24 April 1975) about 20 % of the lake was expelled not counting the ejected water that flowed back into the lake. Expulsion occurs as jets of tephra (Surtseyan jets) including blocks moving on ballistic trajectories and water (Figs. 12.13 and 12.14). Smaller events referred to as phreatic and hydrothermal eruptions occur with smaller amounts or overpressures of magmatic gas, upwellings of steam or brine from the vent system, or density-driven overturnings in the lake itself. The least energetic of these expel small amounts of water relatively passively over the lake outlet with the smallest measured volume (13 July 2009) equivalent to 0.2 % of the lake.

Lahars, potentially destructive fluid mixtures of volcanic debris and water, are another characteristic of Ruapehu volcano. They are produced by interactions involving volcanic (especially magmatic) processes, lake water and surrounding terrain. It has become clear that most lahars on Ruapehu are formed by explosions through the lake and typically form as dirty snow slurries when erupted water mobilises seasonal snow (Houghton et al. 1987, Cronin et al. 1996). Lahars are also formed by hot volcanic ejecta interacting with snow, tephra deposits mobilised by rain or meltwater, and various kinds of collapse of the rim or breakout of Crater Lake or slopes of the volcano (Manville et al. 2000; Hodgson et al. 2007; Keys and Green 2008). In the last 66 years there have been 17 lahar episodes documented, at intervals of 3 to >10 years, with one to more than 30 lahars per episode. Crater Lake drains into the Whangaehu River so this is the main lahar path but other valleys are occupied depending on eruption magnitude and direction as well as lahar formation process (Fig. 12.15).

The potentially devastating nature of lahars and our experiences with them are well demonstrated by recent history regarding Crater Lake before and after the lahar

(a)
(b)

Fig. 12.10 The warm Crater Lake (Te Waiomoe) occupies the active crater of Ruapehu and is currently about 100 m deep. In 18 March 2007 the outlet and normal overflow were re-established following a breakout though weak tephra deposits from the 1995-1996 eruptions that had dammed the lake (see also Fig. 12.16). *Top photo* Paul Bradshaw. The *second photo* (b) shows upwelling of dirty sediment-laden water. *Photo* Ben Goddard

hazard was understood. Breakout of Crater Lake in December 1953 resulted in a severe lahar which severely damaged a railway bridge across the Whangaehu River leading shortly afterwards to the death of 151 train passengers in the so-called 'Tangiwai Disaster'. This was a significant event in New Zealand's history. The most recent breakout occurred on 18 March 2007 when a mantle of tephra produced in the 1995–1996 eruption episode, collapsed (Fig. 12.16 a–c) as predicted after the lake refilled, and produced a lahar with the largest discharge rate since 1861 (Keys and Green 2008; Williams and Keys 2008; Massey et al. 2010; Fig. 12.17). Active management based on planning that took a long term view of risks, natural processes, and cultural and world heritage values into account, ensured no-one was injured and damage to infrastructure down the Whangaehu Valley was negligible. There is now little foreseeable volcanic risk to infrastructure below 1600 m down this valley or beside the river. Research on the lahar (Manville and Cronin 2007) will have long term benefits for the management of lahar hazards.

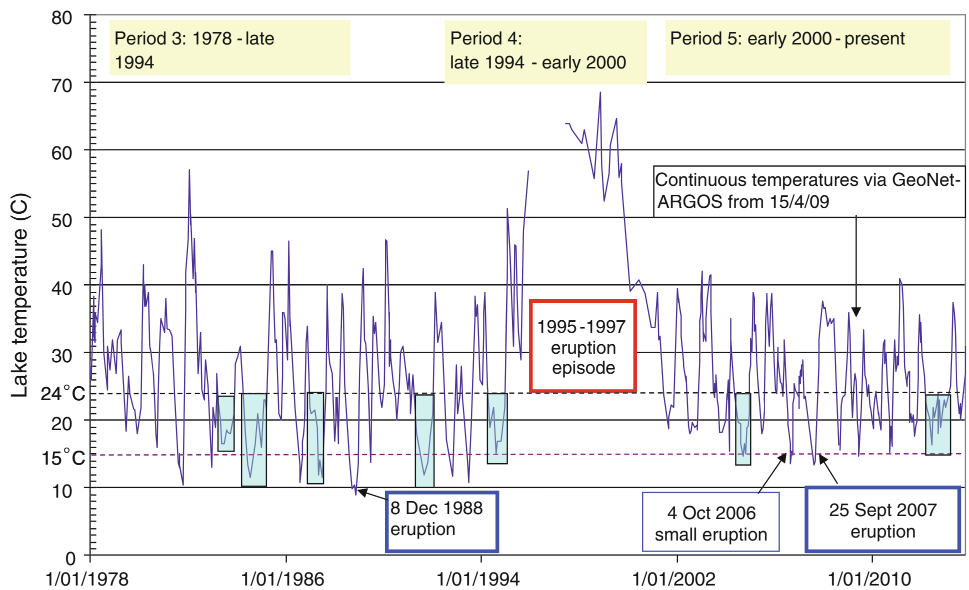

Fig. 12.11 Crater Lake water temperatures measured between 1978 and November 2013 eruptions (data collected by the Department of Scientific and Industrial Research, GNS Science and Department of Conservation). The record can be divided into periods of similar or differing thermal regimes. Anomalous long cool periods (highlighted boxes) are not yet fully understood although there is an increased probability of eruptions during the coolest periods

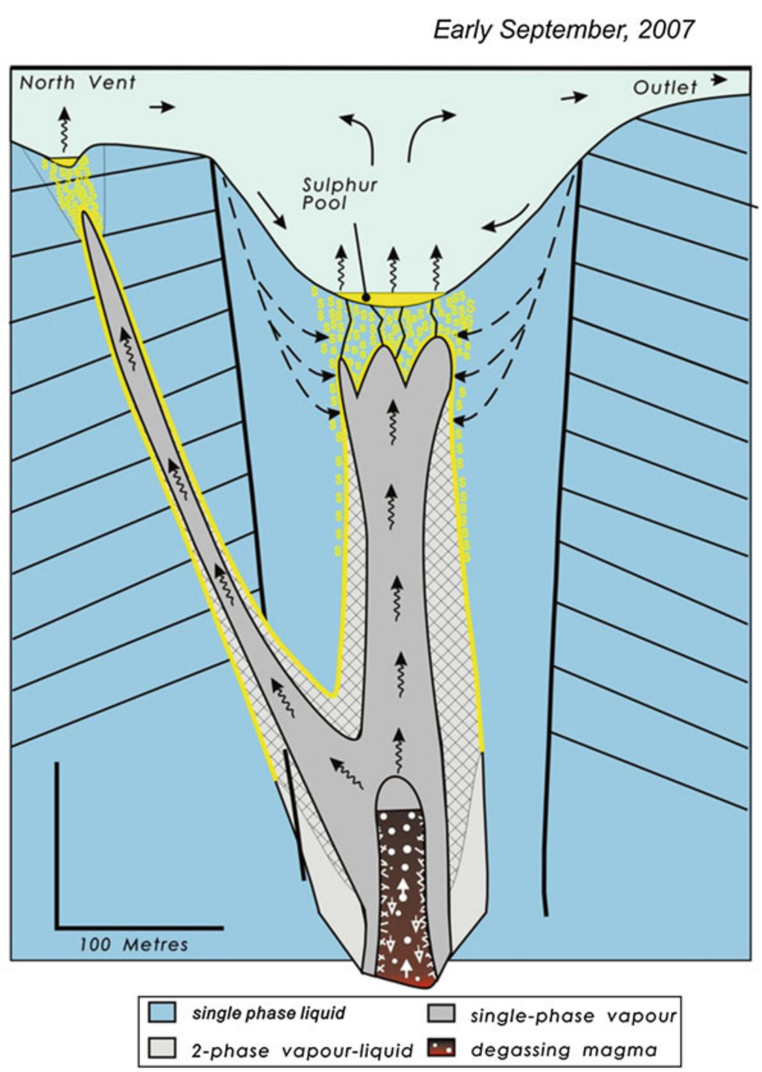

Fig. 12.12 Cross section beneath Crater Lake showing degassing magma high in the vent system, the two vents and the hypothesised "shroud" of elemental sulphur and other minerals (*yellow*). These create a potential for over-pressuring by reducing permeability where it accumulates around the margins of the vapour region (Christenson et al. 2010)

Fig. 12.13 Phreatomagmatic eruption in October 1997 with 400 m tall jets of water and tephra and ballistic bombs trailing steam and almost swallowing a snow boarder (*arrowed*). *Photo* Geoff Mackley

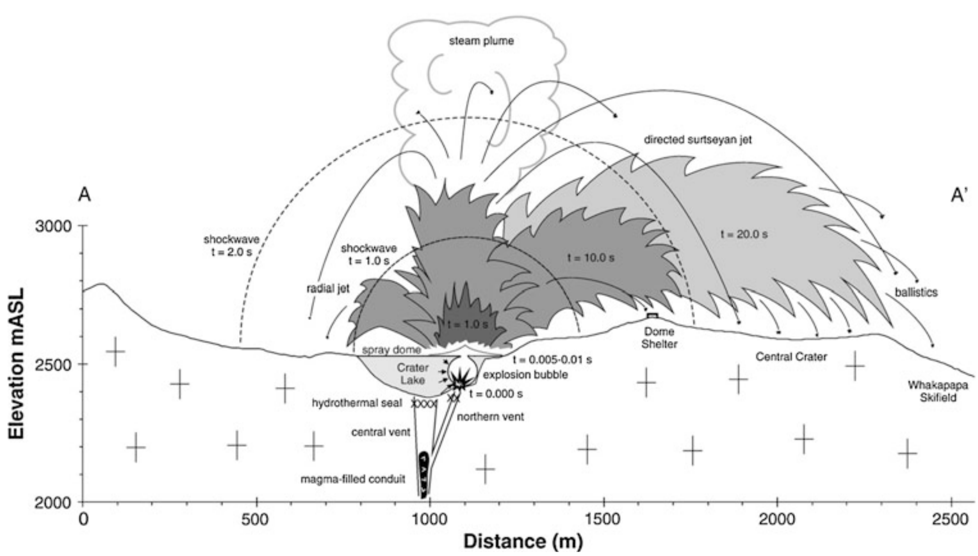

Fig. 12.14 Schematic reconstruction of 25 September 2007 eruption sequence from elapsed time t = 0 to t = 20 s. An explosion through the base of the Crater Lake generated a shockwave and ejected jets of water and tephra plus ballistics directed towards the north and a shelter where two climbers were sleeping. An atmospheric shockwave radiated out from lake surface at c. 1200 km/h, arriving at Dome Shed within 2 s of the explosion, blowing the door open. Within 10 s of the initial explosion Dome Shed had been engulfed by spray and ballistics seriously injuring one climber, while the jets reached their maximum range of c. 2 km in around 20 s. Courtesy of Kilgour, Manville et al. (2010)

Fig. 12.15 Dirty snow and debris mark the path of the lahar from the 25 September 2007 eruption out of Crater Lake down the Whangaehu Glacier. *Photo* Harry Keys

Fig. 12.16 **a** (*before* breakout) **b** and **c** (*after* breakout) showing the 60 m wide and 7.5 m high breach in the tephra dam created on 18 March 2007 and which released 1.3 million cubic metres of Crater Lake water forming the lahar with the largest flow rate since 1861. *Photos* Harry Keys (**a**, **c**), Herb Christopher (**b**)

12.4 Educational Aspects

Numerous school and university groups from New Zealand and overseas visit the park each year to examine aspects of the volcanoes, geology, biology and cultural and social aspects including volcanic risk management. The field guide "Volcanoes of the South Wind" (Williams 2013, now also called "A volcanic field guide to TNP") is used as a text book at many schools. LEARNZ (www.learnz.org.nz), a programme of free virtual field trips has featured TNP on many occasions. The Ruapehu 2012 trip had two sets of background pages available online plus a set of 10 pages fully translated into *te reo* Maori.

12.5 Recent History of Activity

Ruapehu is generally the most active volcano in New Zealand. Over the last 150 years, there have been at least 20 eruptions that produced lahars (Gregg 1960; Otway et al.

Fig. 12.17 Aerial view of the 18 March 2007 lahar at Tangiwai just after the flood peak, with the rail bridge in the foreground and the 1953 memorial area and highway bridge in the middle background. Six years later visible evidence of the lahar passage includes the concrete floor of a toilet block that was swept away, twisted cables of a safety barrier, sediments, and the newly exposed remains of the rear bogie of the locomotive involved in the 1953 disaster. *Photo* Harry Keys

Fig. 12.18 Ruapehu erupting in June 1996. The lobate deposit on the right is from a tephra jet and pyroclastic density current cloud observed the day before. *Photo* Harry Keys

1995; Keys and Green 2010). Many small and even medium-sized eruptive events have not been documented (B Scott, pers. comm.) so statistics are biased towards larger events.

During the two largest and longest recent eruption episodes (1945 and 1995–1996) the lake water was completely boiled/evaporated or ejected out of the crater onto surrounding glaciers, and/or propelled across the outlet and into the Whangaehu catchment. The water displacement was accompanied (1945) or followed (1995) by lava influx up into the crater and then by dry ash eruptions intermittently for five months (1945) and 11 months (1995–1996, 0.07 km^3 of tephra, Fig. 12.18). Water accumulates in the summit crater when these eruptions are over, most rapidly during the summer melt season (Keys and Green 2008). Phreatic eruptions,

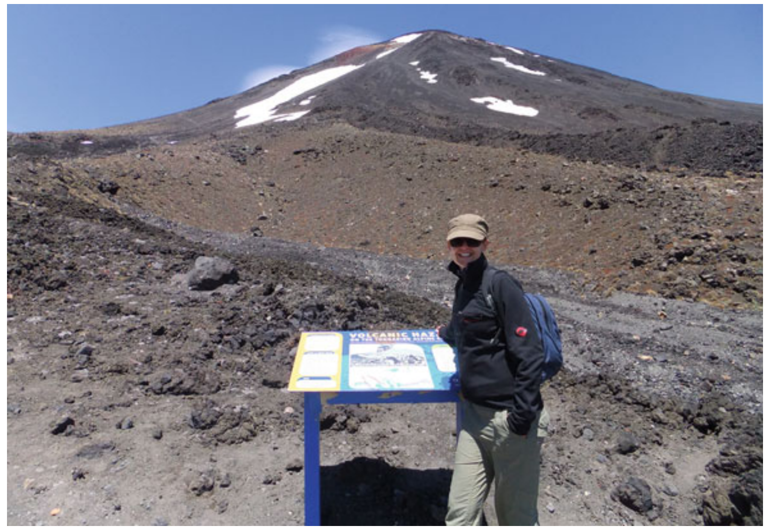

Fig. 12.19 Swiss tourist on the slopes of Ngauruhoe at the interpretation and hazard sign featuring the pyroclastic current deposits from the 1975 eruption. *Photo* Karen Williams

periods of increased heat flow producing dense steam plumes, and some hazardous secondary (rain-induced) lahars followed these eruption episodes for three to seven years.

Most eruptions of Ruapehu in the last 100 years have been short-lived one-off events. The most recent of these in September 2007 (Figs. 12.13, 12.14, and 12.15), October 2006 and December 1988 all occurred near minima in the lake temperature cycle (Fig. 12.11). Some earlier events (April 1968, April 1971, November 1977) occurred near maxima in the cycle. Others also occurred during this 1965 to 1976 period when average heat flow and hence average temperature were high, but near the minima of the temperature cycle at the time (June 1969, April 1975). The 1975 event was the largest of these, and the only one documented as being followed by a second small event (Nairn et al. 1979).

Ngauruhoe used to be regarded as New Zealand's most active volcano but since its last major eruption in 1974–1975 has experienced its longest period of quiescence since the earliest written records in 1839. At that time one large deep vent formed the crater. Subsequent eruptions created a sequence of sub-craters. Eruptions in 1870, 1949 and 1954 produced the only modern lava flows in New Zealand, close to where the Tongariro Alpine Crossing traverses up the lower north-western slopes of the volcano. The 1954–1955 eruption built up a large cone of scoria and lava spatter which buried the earlier sub-craters and the north-western third of the old crater rim. Explosive ash eruptions in January and March 1974 and particularly February 1975 produced columns of ash up to 13 km high, small rocks landed up to at least 2 km away, and numerous avalanches of hot debris (pyroclastic density currents, "block-and-ash flows") travelled down the north-western slopes (Fig. 12.19) to near the floor of the Mangatepopo Valley. Huge blocks of lava in the old crater valley at the base of the 1954–1955 cone and several metres of red welded lava ("spatter") forming the rim of this cone are obvious remnants of this last eruption. Since then temperatures and gas emission have declined to the point where only faint plumes of steam are sometimes seen from fumaroles on the old north-eastern rim and upper north-north-western slopes. Earthquake activity 1–2 km below the northwest slopes commenced intermittently from 2005, probably due to geothermal fluid activity or phase changes in a cooling magma body (Jolly et al. 2012).

Prior to 2012, the last confirmed eruptions from the upper Te Maari crater on the northeast flank of Tongariro were in 1896–1897. Red Crater is thought to have last erupted in the 1920s and 1930s and Te Maari may have had minor activity in this time-frame as well. (B Scott, pers. comm.) with earlier eruptions documented from there and the Te Maari craters between 1839 and 1892. No Maori oral history has come to light, possibly including tephras thought to come from eruptions of Red Crater in the last 320 years (Moebis, 2011) and a large well-preserved lava flow that descended from upper Te Maari into forest about 500 years ago. Lavas that look very young have also flowed from Red Crater and some are younger than 1800 years. Recent magma from Te Maari was rhyolitic and quite different from other Tongariro and Ngauruhoe magmas (Moebis 2011; S Cronin, pers. comm.). This may relate to the age of these magmas or the long duration of activity of the Te Maari craters which at 14,000 years are among the longest-lived of Tongariro's post glacial vents.

Tongariro erupted on 6 August 2012 and again on 21 November from the Upper Te Maari area. The eruption was the first confirmed non-summit, multiple vent eruption seen in living memory and had the most significant effect on forest in the park since the previous eruption of Te Maari more than a century ago. Three weeks of seismic unrest preceded the initial eruption. A week after this seismicity began there were reports from people who had smelt gas

Fig. 12.20 The upper Te Maari eruption area with new vents, fissures and the large chasm formed during the 6 August eruption. *Photo* Harry Keys

Fig. 12.21 Mountain toatoa forest beside the TAC and near it, burned red-brown by the hot acid surges (pyroclastic density currents) during the 6 August eruption. *Photo* Karen Williams

around the volcanoes, and, by 23 July, GNS sampling confirmed there were enhanced levels of volcanic gas being emitted.

The first and largest eruption in the sequence to date occurred at 11:52 pm on 6 August without any immediate precursors (Jolly and Cronin, “The Tongariro Special Issue”, 2014). Reconstruction of events suggests that the eruption was initiated by volcanic gas released from old, but not yet cooled magma and which pressurised (and fluidised) old hydrothermally weathered and weakened rock material until it failed. The resulting landslide “uncorked” the volcano leading to a series of explosions producing a debris flow sequence and several new craters and fissures including a prominent “chasm” about 600 m long and 30 m deep, and reaming out the upper Te Maari Crater (Fig. 12.20). Hydrothermal material and blocks of old lava were ejected up to at least 1 km in all directions. Some of these rocks weighed up to 2 tonnes and were ejected on ballistic trajectories at speeds possibly up to 600–700 km/h as far as 2.3 km in the main blast directions. Many landed around the TAC track and some hit Ketetahi Hut creating numerous craters, holes, spray and rock “shrapnel” deposits and other impacts.

Ground-hugging pyroclastic density currents (surges or blasts) of hot material, gas and steam from multiple vents travelled east, west, northwest and then north extending over 6.4 km^2, inundating 3.7 km of the TAC and causing quite extensive damage to mountain toatoa forest and other trees and shrubs out to 2.7 km from the vents (Fig. 12.21). Deposit morphology suggests maximum velocities up to 500 km/h and average velocities of 40–100 km/h (Gert Lube & Eric Breard, pers. comm.). Investigations of plant dieback suggest temperatures of 50 to <100 °C (Efford et al. submitted) in the nine places where the current crossed the TAC track. Anyone who was on the track might have been in the current for up to 1–5 min. There would have been multiple fatalities if the eruption had occurred in the summer during fine weather.

The last phase of this first eruption was an ash and steam plume that rose 7–9 km high lit up by a dramatic show of lightning with some incandescent rocks and depositing ash up to several centimetres thick around the vents. Most of these phenomena were observed by residents along State Highway 46. Surrounding pine forests and farmland experienced thin but significant ash fall from the plume as it drifted east-northeast as far as the East Coast of New Zealand. Some fluorine and other toxins were present in leachate from this ash.

The early landslide was followed by a debris flow in at least three pulses and together formed a million cubic metre deposits of rocks and mud extending 2 km distant down a valley to the northwest and damaging native forest and shrubs. The upper part of the deposit choked a gorge area and dammed a tributary stream. This developed into a significant lake with a peak volume of about 30,000 m^3, and whose potential breakout threatened up to 1.8 km of the TAC 4–5 km downstream. The dam broke on 13/14 October, during poor weather following heavy rain, causing a hyperconcentrated lahar. This severely damaged 200 m of the track and overflowed a culvert at State Highway 46 depositing sediment and woody debris over the road.

The 21 November eruption occurred from the upper Te Maari crater at 1:25 pm on the Wednesday afternoon in fine clear weather a month after the TAC was fully reopened. Again there were no immediate useful precursors. About 30–70 people were in the 2 km summit hazard zone as close as 1.3 km from the vent with clear views of the eruption that was also recorded by the GeoNet webcam. Tephra jets emerged through dense steam clouds formed moments before. The jets were followed by a vertically ascending plume column and a series of pyroclastic density currents fed partially by column collapse. These surges were observed travelling to the northwest, north then north northwest at average velocities of 50 km/h. The visible component of the currents lifted off the ground and dissipated after 500 m although a Massey University sensor at 900 m detected air warmer than ambient afterwards. No ballistics were observed and no impact craters have since been reported beyond about 200 m at most. The plume rose 3–5 km depositing 15 mm of fine tephra 600 m from the vent and dustings were reported up to 25 km to the north.

The TAC was not impacted during the November eruption. All the significant volcanic hazards were contained well within the 1 km *Rahui* exclusion area (Fig. 12.30) which was established in mid October for eruption risk management purposes by DOC and Ngati Hikairo. However, images of the eruption and young people’s reactions were dramatically presented on television and in other media including the internet.

As of late 2013, all tracks on Tongariro, including the TAC are fully open. The crater area is still very active and risks from further eruptions or secondary lahars are not zero. Activity may now be best regarded as declining degassing of a perturbed hydrothermal system (vent temperatures hotter than 400 °C) and occasional weak seismicity (Bruce Christenson and Art Jolly, pers. comm.). The probability of further eruptive activity including more pyroclastic density currents has decreased but not yet reached background levels and a resumption of activity in the next few months or years can not be ruled out. Plumes of steam evaporating to airborne residues of aerosols and particulates are often still prominent in fine weather.

In historic time the TNP volcanoes have seldom erupted simultaneously. Occasionally eruptions do occur at the same time coincidently because they are so active. 1895 was the last time the three volcanoes erupted at the same time.

12.6 Hazards and Risk Factors

Volcanic activity of the current style and size, especially unpredictable eruptions, poses relatively high risks to recreational users on Ruapehu and Tongariro and historically significant risks to travel networks around it. Risks would be even higher and more widespread if activity similar to that occurring 10,000 years resumed (Pardo et al. 2012). Today, erupted rocks and jets of mud and water, and pyroclastic density currents within TNP (Figs. 12.14, 12.15, 12.18, 12.19, and 12.21) in the Summit Hazard Zones (e.g. Fig. 12.27) represent New Zealand’s highest volcanic risks to people (groups or individuals). People are also threatened by lahars of mud and rocks or dirty snow slurries flowing

Table 12.1 Near-misses from eruptions in Tongariro National Park 1945–2012 compiled from personal records

Eruption	Hazard	Immediate risk	Outcome
Ruapehu: early July 1945 after a short non-explosive period during the 1945 episode	Explosive blast, flying rocks in crater basin	Two people camping in crater basin	One person seriously injured
Ruapehu: 8 May 1971 during 8 month period with occasional eruptions	Phreatomagmatic eruption, cascading water and rocks in crater basin	Two surveyors on Pyramid Peak (Peretini)	Almost washed off peak, rocks narrowly missed them
Ngauruhoe: February 1975 during the 1974/75 episode	Block-and-ash (pyroclastic density currents or "ground-hugging") flows; rock (lapilli) fallout	School party 1 km away near South Crater; hikers in Mangatepopo Valley	Ranger took excellent photos of the flows. Hikers sheltered from fallout
Ruapehu: 23 Sept 1995, a week after main eruptive period started	Phreatomagmatic eruption, falling volcanic blocks in crater basin, lahars in Whakapapaiti and Mangaturuturu valleys	Climbers outside summit craters but just inside recommended and posted area. Skiers in lahar path	Rocks just missed climbers. T- bars closed for day an hour before lahars so people had moved out of valleys
Ruapehu: 12 Oct 1997 during a recognised period of elevated risk following 1995–1996 eruption	Phreatomagmatic eruption, flying blocks	Snow boarder on crater rim well inside recommended and signed no-go area (Fig. 12.13)	Rocks fell short
Ruapehu: 25 Sept 2007, eruption without useful precursors (Fig. 12.15)	Phreatomagmatic eruption, tephra jet and entrained rocks, lahar	Two climbers camping inside Dome equipment shed. Groomer driver at Far West T-bar	One person in shed seriously injured, rescued in nick of time, lost leg. Driver's rapid evasive action saved himself and gave alarm
Te Maari (Tongariro): 6 August 2012 following 3 weeks of unrest	Tephra jets plus pyroclastic density currents and rocks to 2.7 km, ash on highways	Ketetahi Hut, 3.7 km of TAC, alpine vegetation, highways	Eruption occurred at night, no-one on the TAC or in hut at the time
Te Maari (Tongariro): 21 November 2012 (Fig. 12.32)	Tephra jets plus density currents to 500 m	4 scientists, pilot and helicopter landed 200 m from crater (planned pickup)	Flew out of area 4 min before eruption

down valleys (Fig. 12.15) at measured speeds of up to 90 km/h. About half of these events are not predictable at present but records show that their probability at Ruapehu is slightly higher than normal at high and low points of the Crater Lake temperature cycle (Fig. 12.11). There have been numerous near-misses and some serious injuries on the mountain from lahars and other eruption products (Table 12.1), although present-day monitoring techniques reduce the risk considerably (see below).

Larger volcanic explosions on Ruapehu (e.g. 1975) produce larger lahars, and more valleys are affected. Lahars may enter catchments in Whakapapa ski area during small eruptions directed to the north and in medium or larger eruptions (with an annual occurrence likelihood of at least 6 %); while large or very large eruptions may produce lahars in Turoa ski area (annual likelihood of about 2 %) (Keys and Green 2010). On four known occasions lahars have entered Whakapapa ski area within two to five minutes after an eruption and all but one of these occurred during periods of apparently normal background activity.

Volcanic activity at Te Maari craters in 2012 significantly increased the risks to recreational users on Mt Tongariro. Serious near-misses occurred during the initial eruption and previously elsewhere near the TAC (Table 12.1). A resumption of more frequent activity from Tongariro, including Red Crater or Ngauruhoe could disrupt use of the TAC and economic activity based on it. Previously gas was the only volcanic hazard prevailing but it posed little real threat due to the rarity of windless conditions.

Normal mountain hazards have led to at least 20 fatalities on Ruapehu in the last 30 years. General hazards on all the volcanoes include snow avalanches, icy slopes plus vertical holes formed by waterfalls in the seasonal snow pack (Fig. 12.22), and cold, wet and windy weather, hypothermia, rock fall, falls and snow avalanches. A lack of mountain experience including route-finding problems and inadequate clothing and equipment is a common factor in many injuries and near-misses. The gullies on North Crater traversed by the TAC have the potential for causing a multiple fatality event in a snow avalanche.

Fig. 12.22 A large steep-sided 10 m deep waterfall hole in spring on Ruapehu with members of ski patrol and Ruapehu Alpine Rescue Organisation training in rescue techniques. *Photo* Darryl Jones

Fig. 12.23 The new Waihohonu Hut on the Tongariro Northern Circuit (TNC) Great Walk track. *Photo* Karen Williams

12.7 Major Tourist Attractions, Activities and Numbers of Tourists

The major attractions and activities in TNP all involve recreation in some form. There is an extensive range of short walks or longer tracks serviced by huts (Fig. 12.23) and commercial accommodation at Whakapapa Village and towns around the park. A 2010 survey of the interests of hut users showed that geological and volcanological aspects of TNP are one of the main reasons why people, other than skiers and snowboarders, visit the park (Frimmel 2010).

Tracks on Tongariro-Ngauruhoe (TAC and TNC, Fig. 12.2) are visited by some 80,000 people per year, mainly in the October-April period. Most people start these

Fig. 12.24 Emerald Lakes and Red Crater on the Tongariro Alpine Crossing. *Photo* Sarah Thompson

Fig. 12.25 Spring skiing off-piste on the Mangatoetoenui Glacier on the east side of Ruapehu. *Photo* Karen Williams

treks at the Mangatepopo road end which provides the highest access to this massif. The TAC traverses 20 km of dramatic volcanic and alpine terrain including the base of Mt Ngauruhoe (Fig. 12.19), Red and Emerald craters (Fig. 12.24) and many other young volcanic features. The recent eruption of Te Maari has created many new features that can be seen from the track. These include steaming craters, a drained lake, burnt forest and numerous impact craters formed by flying rocks ejected in the first eruption. Volcanic activity will sometimes mean that parts of the TAC track have to be closed.

Whakapapa and Turoa ski areas provide some of the best and most varied skiing and snowboarding terrain in New Zealand (July–October or November) and the highest serviced runs in the country. They have a total of up to 450,000 visitor days during the ski season. There is extensive off-piste skiing (Fig. 12.25) and good opportunities for ski touring. Avalanche control is undertaken in the ski areas but

Fig. 12.26 Climbers on an overnight trip at Ruapehu carrying a bucket and biodegradable bags for collecting human waste. *Photo* Harry Keys

beyond ski area boundaries there is no active control and people are expected to manage their own risks.

Ruapehu's Crater Lake (Fig. 12.10) is a unique and beautiful location. It can be easily viewed from several points on the rim of Crater Basin which is accessed from the top of ski lifts most easily from December to April and, if one is well equipped, during winter as well. Views across Crater Lake Basin and experiencing the Tongariro Alpine Crossing can be special and enriching. Together with the Ruapehu Round-the-Mountain, Tongariro Northern Circuit and other park tracks these places enable good trekking and walking options and other opportunities for appreciation of nature. Numerous other activities involving the outdoors are also possible in the surrounding areas. Visitors to these places are encouraged to think about and respect the park's cultural and world heritage values, including undertaking appropriate management of waste (Fig. 12.26). This includes not standing on the summits of the main peaks or entering Crater Basin.

12.8 Guides, Tours and Rangers Available

A search of the internet will quickly help people find guides, tours and transport options for these places if needed. Ruapehu and the TAC can be visited safely without a guide. People need to be well-equipped for cold mountain weather, have basic map-reading skills and an awareness of the changeability of local weather and snow conditions. Routes up Ruapehu are unmarked. Ruapehu Alpine Lifts (www.mtruapehu.com) runs tours of the ski areas and beyond during the winter season and to the Crater Lake in summer. The Department of Conservation (2013) provides valuable information about maps, routes, recommended equipment and clothing, weather forecasts, guides and other useful information (a PDF brochure "Walks in and around Tongariro National Park" is downloadable). Visitor Centre staff are available to provide information and answer questions on a daily basis, year-round. Rangers may be available with adequate advance notice to assist with school parties and other groups. Information on Tongariro can also be obtained from www.officialtongariro.co.nz and www.tongarirocrossing.org.nz.

12.9 Visitor Information Centres, Interpretive Centres and Volcano Museums

The Visitor Centre in TNP in Whakapapa Village is located on Highway 48 off Highway 47. It has an excellent 3D scale model of the park, interpretation of the volcanoes, flora and fauna and other aspects of the park, plus books, audio-visuals and an internet-based connection to the GeoNet natural hazard monitoring system of New Zealand. Smaller information or visitor centres are located in Ohakune, Turangi, Taumarunui and Taupo. A dedicated Volcanic Activity Centre for visitors is located at Wairakei 8 km north of Taupo. Taupo Museum, 60 km north of the park, has a small amount of volcanic and geothermal interpretation. The larger Te Papa Museum in Wellington, and the Auckland and Rotorua museums also have excellent volcanic displays.

12.9.1 Signage and Information Brochures

The park tracks mentioned previously and many others are well signposted. Brochures and maps are widely available with information on tracks, other features of the area and safety advice.

12.9.2 Hazard Maps

Five separate hazard maps, designed for public use, are available covering the summit hazard zones of the active volcanoes of Ruapehu, Ngauruhoe and Tongariro and the two main ski areas Whakapapa and Turoa. Figure 12.27 refers to the Summit Hazard Zone of Mt Ruapehu extending to about 2 km from Crater Lake. It shows all three ski areas, indicates hazards, offers advice and contains thumbprints of the Whakapapa, and Turoa hazard maps. The ski area maps are posted in numerous places in buildings across the ski areas and on the website www.mtruapehu.com/winter/Volcanic-Hazards/. They can also be found on Google Images. The maps have been distributed to the ski areas, local businesses providing transport and accommodation for visitors, club lodges at the ski areas and others.

Corresponding volcanic hazard maps for the Ngauruhoe-Tongariro massif can also be found on http://info.geonet.org.nz/display/volc/Tongariro. Two interpretation panels addressing hazards on the Tongariro Alpine Crossing include the map noting the main volcanic dangers of block-and-ash flows (pyroclastic density currents) and rock fall on the main route (and easiest access) up Mt Ngauruhoe.

12.10 Risk Management

Ruapehu has one of the most intensive volcanic risk management systems in the world and new additions have been made in 2012 and 2013. Better application to Tongariro and Ngauruhoe has been an important advance. There are several components to volcanic risk management in TNP (Keys and Green 2010):

1. Infrastructure location and design
2. Volcano monitoring and other research
3. Volcanic Alert and Crater Lake Warning levels
4. Decision-making (e.g. which facilities should be closed temporarily)
5. The Eruption Detection Systems (EDS and TEDS) for Ruapehu and Tongariro, and linked responses
6. The East Ruapehu Lahar Alarm Warning System (ERLAWS) and the Whakapapa Village Lahar Alarm Warning System (VLAWS) and linked responses
7. Electronic light signs at the main TAC car parks and on the TAC itself
8. Increased public awareness and ongoing research to improve response.

Vulnerable infrastructure such as roads, rail and power lines, ski lifts, and buildings should be located at sites away from or less likely to be at risk from lahars and other hazards, or designed in ways to withstand these hazards. The damaged Ketetahi Hut will be removed from the Active Volcanic Hazard Zone around Te Maari and a better designed shelter will be built on the site for day use only. On the ring plain most bridges across lahar paths are now designed appropriately (Fig. 12.28). However, some bridges on State Highway 1 east of Ruapehu would not withstand lahar events as large as those 450 and 850 years ago. The northern part of the TAC within 1 km of the Ketetahi car park has been affected by recent secondary lahars which has required rerouting and repairs to the track.

Monitoring of Crater Lake, Ruapehu and the other volcanoes and resulting advisories are well developed. These continue to expand in scope and intensity. GeoNet is a modern geological hazard monitoring system owned by the NZ Earthquake Commission and run by the GNS Science. Skilled staff detect and respond to volcanic activity relying on a network of geophysical instruments and automated software applications. New Zealand, like most countries with active volcanoes, uses a system of six Volcanic Alert Levels (http://info.geonet.org.nz/display/volc/). GNS Science through GeoNet is responsible for setting these Alert

Fig. 12.27 Poster focusing on Summit Hazard Zone of Mt Ruapehu (GNS Science, Department of Conservation and Ruapehu Alpine Lifts) accessible at http://info.geonet.org.nz/display/volc/Ruapehu

Levels, which give an indication of volcano status, as mandated in the National Civil Defence Emergency Management Plan. The system provides primary support for management decisions about public warnings and facility operations but does not completely drive them. Alert levels reflect the past and present situation and changes do not always occur fast enough for the needs of land managers so good communication between specialists and managers

Fig. 12.28 The road bridge at Tangiwai in the process of being raised 2 m and strengthened prior to the 2007 breakout lahar from Ruapehu. *Photo* Harry Keys

Fig. 12.29 When an eruption is detected EDS speakers on Whakapapa ski area broadcast sirens and pre-recorded messages warning people to move out of valleys in case a lahar is approaching. *Photo* Harry Keys

remains important. Many eruptions have happened at Alert Level 1 on Ruapehu (its normal alert level) as did the 2012 eruptions of Te Maari. Information on the alert status of Ruapehu, Tongariro and other volcanoes is available at the web site www.geonet.org.nz. The record of near-misses (Table 12.1) shows that most of these occurred during periods in which elevated risk was or would be recognisable with present-day monitoring techniques. Therefore this

Fig. 12.30 Signs beside the Tongariro Alpine Crossing installed to help reduce volcanic risk to visitors. *Left* Rahui (exclusion area) sign 300 m from the boundary of the Rahui. The steaming craters were formed during the explosions of 6 August 2012. *Right* Electronic red light sign at the northern entry to the Active Volcanic Hazard Zone 3 km from the Te Maari craters. *Photos* Harry Keys

monitoring by GeoNet/GNS Science and information availability has now reduced present-day risk to individuals.

The three early warning systems at Ruapehu (ERLAWS, EDS and VLAWS) have different objectives but management responses are being steadily integrated. ERLAWS primary objective is to provide warnings of major lahars to agencies managing State Highway 1 and electricity infrastructure nearby, enabling multi-agency response on the upper Whangaehu River. The EDS is designed to warn Whakapapa ski area patrons and staff of a potential lahar via sirens (Fig. 12.29) and broadcasted pre-recorded announcements. Staff are also warned via their radios, within 30 s after a potential lahar-generating eruption. Ski area staff response, a critical factor, has been improved by independent social science research and better training in the last decade (Leonard et al. 2008). VLAWS is designed to give residents and visitors in Whakapapa Village at least 15 min warning of a lahar coming down the stream that passes close to part of the village.

Ensuring effective response of the public to warnings at Ruapehu is difficult and complicated by the transient nature of ski area visitors and their limited familiarity with hazards. Management and research are ongoing to raise awareness and includes the hazard posters and the DVD "Staying Safe" (www.mtruapehu.com/winter/Volcanic-Hazards/). Siren audibility has been tested and improved and changes made to improve comprehension and awareness of the warning message including the addition of more useful content. During tests, a minority continue to demonstrate only moderate awareness of the correct actions to take and fail to respond effectively. At least 10 people have remained "at risk" during many publicised and blind tests of the EDS from 2005. Residual risk will never be reduced to zero but work continues.

To reach this level of mitigation, lessons from previous eruptions and lahars since 1953 and 1975 have been, and are still being applied, to improving management of lahar and other risks especially to ski areas on Ruapehu (Keys and Green 2010). The current Eruption Detection System is the result of regular reviews of its performance combined with ongoing analysis of eruption characteristics and lahar magnitude-frequency relationships. These factors combined with technological advances means the system has been completely upgraded since it was installed in 1983. Inter-agency synergies and agency-readiness are strengthened and robust as a result of the experience post 1995–1997 eruptions of Ruapehu. There is still room for improvement in the response of ski area patrons.

Volcanic risk management became more active for the Tongariro-Ngauruhoe massif in July 2012, with limited success initially (see Table 12.1). Awareness of volcanic hazards was not high before the 2012 eruption (Coomber and Leonard 2005). Risk management zones have been created since the 6 August 2012 eruption and the inner zone at least (Fig. 12.30a) will remain in place for some years. A new eruption detection system for the TAC and the Tongariro Northern Circuit is now in place. Electronic light signs that can be changed remotely if volcanic unrest increases have been installed in four places on the TAC. They provide advice of the level of volcanic risk in near real-time (Fig. 12.30b) supported by information on the webpage www.doc.govt.nz/volcanicrisk. The recent experience shows that it is difficult for managers, guides and other concessionaires to mitigate risks to people who are trekking very close to the active volcanoes vents. Efforts have been stepped up to increase public awareness that there is always some volcanic risk, and to inform people of eruption hazards and that they visit the TAC at their own risk.

Fig. 12.31 Turoa carpark and ski area on a beautiful day with fresh snow. *Photo* Karen Williams

Fig. 12.32 The second eruption of upper Te Maari on 21 November 2012 produced pyroclastic density currents clearly visible from the TAC. These were contained hazards well inside the Rahui volcanic risk management zone. *Photo* Neil Fausett

12.11 Economic Importance

Tongariro National Park and rivers flowing from it have major economic importance locally and regionally. They provide many businesses with income and many employment opportunities, especially in communities around the park. Ruapehu Alpine Lifts (Fig. 12.31) operates two ski areas on Mt Ruapehu. It is the largest concessionaire operating on public conservation land in New Zealand and the largest employer in the central North Island. In total, concession-based tourism in TNP contributed $30 million of direct turnover in 2004–2005 and the net economic impact of tourism concessions was four times the direct impacts of the concessions themselves (Wouters 2011). Tongariro concessions generated 450 full-time equivalent jobs, each of which created another 0.3 jobs. The Tongariro and Whanganui rivers which rise on the volcanoes are nationally important for the generation of hydroelectricity.

The Ruapehu eruption episode of 1995–1997, the Tongariro eruptions in 2012 and planning for the 2007 dam break lahar provided clear evidence of this economic importance. The greatest contribution to the cost of the 1995–1997 eruption, estimated in excess of NZ$130 million, was the impact on the alpine recreation and tourism industry in the central North Island. This industry was essentially nonexistent in 1945 when the mountain erupted in a similar fashion (Johnston et al. 2000). The 1995 season was terminated prematurely by ash fall, while the 1996 season was severely compromised by ash falls into July and also prematurely terminated by ash. Numerous local businesses were adversely affected and the Turoa ski area company and some others did not recover. Other significant impacts were felt by the aviation and electricity-generation sectors, including damage of about $10 million to turbine blades in a local hydro-generation station. The complete or partial closure of the TAC between 7 August and 19 October 2012 and again from 22 November to 8 May 2013 resulted in a 50 % reduction of staff and a 40 % reduction in turnover for Tongariro Expeditions, one of the largest concessionaires involved (Jarrod Thomas, pers. comm.).

Government agencies spent NZ$7 million preparing for the 2007 lahar including $4 million to raise and strengthen the highway bridge at Tangiwai (Fig. 12.28). In contrast, Taig (2002) calculated the event could have costed in excess of $40 million if things had gone wrong. Fortunately they did not (Keys and Green 2008).

Acknowledgments We thank Gill Jolly, Steve Sherburn, Bruce Christenson, Nico Fournier, Graham Leonard, Art Jolly, Karen Britten, Agnes Mazot, Mark Chadwick, Brad Scott and other scientists from GNS Science for their great support over the years, particularly during periods of volcanic activity, enhanced unrest or uncertainty. Thanks also to Shane Cronin, Jon Procter, Gert Lube, Eric Breard and others from Massey University, and Hugh Cowan from EQC. We also thank Paul Green, Blake McDavitt and many others from the Department of Conservation, Dave Mazey, Andy Hoyle, Mark Woods, Steve McGill, Steve Manunui and Mark Blair from Ruapehu Alpine Lifts, Keith Wood from Ngati Rangi and Ernslaw1, and Doug Tucker, Veti Bala, Phil Goulter, Gareth Grey and others from Genesis Energy. Sir Tumu Te Heuheu, Te Kanawa Pitiroi, Te Ngaehu and Hinemoa Wanikau from Ngati Tuwharetoa and Che Wilson and Hanna Rainforth from Ngati Rangi have also engaged with us constructively over the years. We are grateful to the NZ Army, NZ Transport Agency, Transpower, NZ Forest Managers, Kiwi Rail, Communication Networks Management Ltd, Cybernetics Ltd and Peter Otway for their support. Tim Stern from Victoria University and friends and colleagues allowed us to use the acknowledged maps, diagrams and photographs.

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