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Volcanic hazard assessment for Ruapehu composite volcano, Taupo Volcanic Zone, New Zealand

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Abstract. Ruapehu is a very active andesitic composite volcano which has erupted five times in the past 10 years. Historical events have included phreatomagmatic eruptions through a hot crater lake and two dome-building episodes. Ski-field facilities, road and rail bridges, alpine huts and portions of a major hydroelectrical power scheme have been damaged or destroyed by these eruptions. Destruction of a rail bridge by a lahar in 1953 caused the loss of 151 lives. Other potential hazards, with Holocene analogues, include Strombolian and sub-Plinian explosive eruptions, lava extrusion from summit or flank vents and collapse of portions of the volcano. The greatest hazards would result from renewed phreatomagmatic activity in Crater Lake or collapse of its weak southeastern wall. Three types of hazard zones can be defined for the phreatomagmatic events: inner zones of extreme risk from ballistic blocks and surges, outer zones of disruption to services from fall deposits and zones of risk from lahars, which consist of tongues down major river valleys. Ruapehu is prone to destructive lahars because of the presence of 10^7 m^3 of hot acid water in Crater Lake and because of the surrounding summit glaciers and ice fields. The greatest risks at Ruapehu are to thousands of skiers on the ski field which crosses a northern lahar path. Three early warning schemes have been established to deal with the lahar problems. Collapse of the southeastern confining wall would release much of the lake into an eastern lahar path causing widespread damage. This is a long-term risk which could only be mitigated by drainage of the lake.

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Introduction

Ruapehu, an active, predominantly andesitic composite volcano, is the highest mountain (2797 m) on the North Island of New Zealand. At least 54 small eruptions have occurred in the last 37 years (Latter 1986), including explosive events in 1969, 1971, 1975, 1977, 1978, 1979, 1980 and 1981-1982, 1985 and 1987. Destructive or potentially destructive lahars accompanied the 1969, 1971, 1975 and 1977 eruptions. All historical activity occurred at the western summit crater, occupied by the 0.16-km^2 Crater Lake (Fig. 1). Persistent fumarolic activity normally maintains lake temperatures of 20-40°C in an otherwise permanently glaciated environment. Six major glaciers and smaller ice tongues extend from the summit to as low as 2000 m. The flanks of the volcano have scant alpine vegetation and are cut by deep steep-walled valleys. The lower slopes (below 1500 m) support sparse forest and tussock and grade into a 6-15-km-wide ring plain underlain by laharic, fluvial and fall deposits.

Installations and settlements

Three ski fields are developed on the mountain (Fig. 2). The largest, Iwikau village, has 50 buildings at and above 1630 m. Ski field use has increased rapidly in recent years and in 1986, 503000 visitors skied on the two major fields on Ruapehu. Lahars destroyed some ski-field facilities in 1969 and 1975. Much of the mountain lies within Tongariro National Park, whose headquarters, Whakapapa village, is the closest permanent settlement (9.5 km) to Crater Lake. Whakapapa village contains two 80-bed hotels, a 200-bed camping ground and accommodations for park

Fig. 1. General view of Ruapehu showing active western crater occupied by Crater Lake and deep valleys which have channelled historical lahars

and ski field staff. Water and electricity supplies for the village have been disrupted by recent eruptions. Another nine villages with populations up to 7000 lie within 50 km of Crater Lake. The national park maintains small alpine huts at five sites on the mountain. Three huts were damaged or destroyed by the 1969 and/or 1975 eruptions.

A major hydroelectrical power scheme diverts many Ruapehu streams northward into Lake Taupo through a complex canal, tunnel and powerhouse system (Fig. 2). The canal systems cross two major lahar paths, and severe damage was caused by the 1975 lahars during construction of the scheme.

The principal road and rail routes for the North Island cross the ring plain east and west of the volcano, and bridges for both have been damaged by recent lahars. Destruction of a rail bridge by a 1953 lahar caused the loss of 151 lives (Healy 1954). The major electricity transmission lines for the country also cross the eastern ring plain and are at risk from larger eruptions.

Historical activity

Ruapehu is a very active volcano, even by the standards of composite volcanoes (Simkin et al. 1981), but volumes of ejecta produced by historical events have been small, in the range 10^4–10^7 m^3. The dormant intervals between eruptive episodes are frequently as low as 1–3 years (Table 1). Both phreatomagmatic and magmatic eruptions have occurred in the 120-year historical record.

Phreatomagmatic activity

Phreatomagmatic eruptions, caused by interaction of small batches of basic andesite magma with Crater Lake water and sediment, have dominated historical activity at Ruapehu. The lake has a flared trumpet shape and a volume of 10^7 m^3. Its dimensions have fluctuated markedly in the last 30 years, with maximum depth varying between

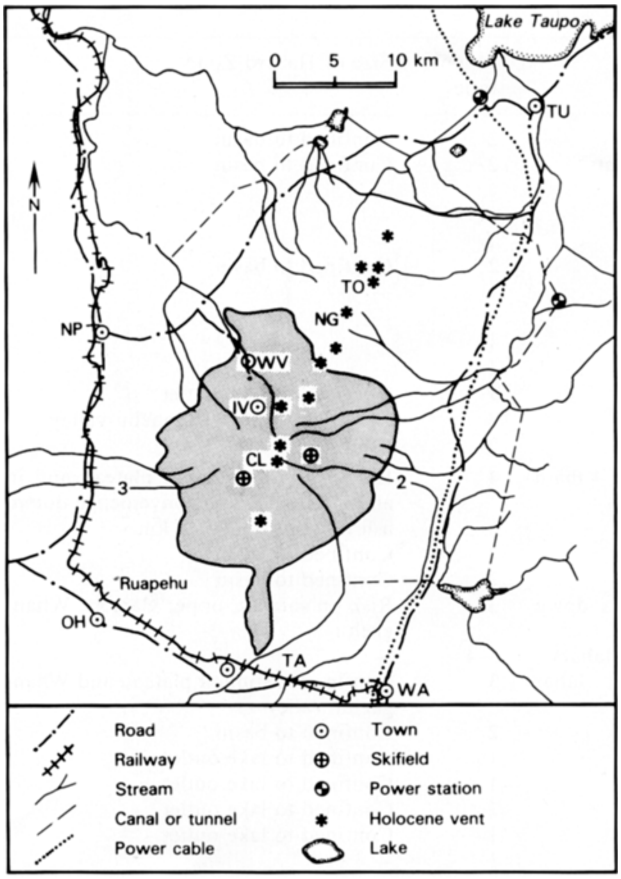

Fig. 2. Sketch map of Ruapehu showing features at risk from renewed volcanism. TU, Turangi; TO, Tongariro; NG, Ngauruhoe; WV, Whakapapa village; IV, Iwikau village; CL, Crater Lake; NP, National Park village; OH, Ohakune; and WA, Waiouru military camp. TA is the Tangiwai road and rail bridges. Principal lahar paths are numbered. These are the (1) Whakapapa, (2) Whangaehu and (3) Mangaturuturu valleys

70 and 300 m (Hurst and Dibble 1981). The lake is highly acid and strongly temperature and density stratified. Lake water, sediment and magma are ejected during the larger phreatomagmatic eruptions and deposited in Crater Lake basin and over the surrounding area (Healy et al. 1978; Nairn et al. 1979). The size of eruptions ranges from small lake-confined explosions, which leave no visible deposits and create a hazard only at the lake outlet, to larger events ejecting up to 30% of the lake water (Fig. 3). During the larger events ballistic clasts fall in a near circular pattern around the vent, defining a region of extreme risk (Fig. 4). Cold, wet pyroclastic surges or blasts are invariably produced, and at the same time, lapilli- and ash-sized clasts rise in the column to heights of 1-5 km and form downwind lobes of tephra (Fig. 5). Most ash falls in the form of a rain of acid mud droplets or accretionary lapilli. Much of the tephra falling within Crater Lake basin is immediately washed back into the lake by water falling from the eruption column. Where surge and fall materials are deposited outside the basin, they frequently move downslope and incorporate snow and ice to form lahars (Fig. 5). The characteristics and effects of the largest recent eruptions are summarised in Table 2.

Magmatic activity

Two purely magmatic events have occurred in historical times, in 1861 and 1945. A major eruption took place in the western summit crater between

Table 1. Summary of all reported volcanic events at Ruapehu volcano, 1945–1986, modified after Gregg (1960). Eruption magnitudes follow an arbitrary scale of 1–5 which is explained later in the text

Event	Nature	Magni tude	Size of Hazard Zone
1945	Dome building and disruption	5	Within 150 km zone
April 1946	Small phreatic/phreatomagmatic event	2–3	Confined to Crater Lake basin
Sept–Oct 1946	Steam columns observed?	1	—
21 Nov 1946	Small phreatic/phreatomagmatic event	2	Confined to basin
8 Febr 1946	Small phreatic/phreatomagmatic event	2	Confined to basin
March 1947	Small phreatic/phreatomagmatic event	2	Confined to basin
28 Apr 1947	Small phreatic/phreatomagmatic event	2	Confined to basin
31 May 1947	Small phreatic/phreatomagmatic event	2	Confined to basin
Jan–Feb 1948	Steam column observed?	1	—
26 July 1950	Small phreatic/phreatomagmatic event	2	Confined to basin
24 Dec 1953	Lahar generated by collapse of ice wall	3	Confined to Whangaehu valley
8 Oct 1984	Steam column observed?	1	—
1955	Pollution of Chateau water supply by newly exposed older ash during dry period	—	Localised to Whakapapa village
23 Oct 1956	Steam column observed?	1	—
18 Nov 1956	Small phreatic/phreatomagmatic event	2	Confined to basin

Table 1.

Event	Nature	Magni tude	Size of Hazard Zone
21 May 1959	Small phreatic/phreatomagmatic event	2	Confined to basin
1 June-31 Aug 1959	6+ small phreatic/phreatomagmatic events	2	Confined to basin
28 April 1964	Steam column observed?	1	—
1-29 June 1964	Steam colums observed?	1	—
23 March 1966	Steam column observed?	1	—
Aug 1966	Small phreatomagmatic event	2	Confined to basin
27 Sept 1966	Small geyserlike events in lake	1	—
24 Oct 1966	Steam columns observed?	1	—
22-24 July 1967	Small geyserlike eruptions	1	—
4 Oct 1967	Steam eruption?	1	—
7 April 1968	Geyerlike events in lake	1	Confined to lake outlet
26 April 1968	Moderate phreatomagmatic event	3	10 km radius & Whangaehu valley
23 May-10 June 1968	Several small phreatomagmatic events	2	Confined to basin
22 June 1969	Major phreatomagmatic event. Lahars in 4 main valleys	4	Risk to life on summit plateau and in all major valleys; inconvenience due to ash fallout up to +25 km
Sept 1970	Small phreatic/phreatomagmatic event	2	Confined to basin
3-7 April 1971	Small phreatic/phreatomagmatic event	2	Confined to basin
8 May 1971	Moderate phreatomagmatic event, lahars down Whangaehu valley	3	Risk on summit, upper glaciers, Whangaehu
15-16 May 1971	Numerous moderate events, Whangaehu lahars	3-4	—
14 July 1971	Small phreatic/phreatomagmatic event lahar down Whangaehu	3	Confined to summit plateau and Whangaehu Valley
Nov 1972	Small phreatic event	2	Confined to basin
Jan 1973	Small phreatic event in lake	1	Confined to lake outlet
Oct-Nov 1973	Several very small phreatic events in lake	1	Confined to lake outlet
Jan-May 1974	Small phreatic events in lake	1	Confined to lake outlet
2-5 Aug 1974	Small phreatic events in lake	1	Confined to lake outlet
8 Aug 1974	Steam column observed?	1	—
Sept-Oct 1974	Numerous steam columns?	1	—
24 Apr 1975	Major phreatomagmatic eruption lahars down 4 main valleys	5	Ash to 130 km radius and 4 main valleys
27 Apr 1975	Moderate phreatomagmatic eruption	2-3	Confined to summit, upper Whangaehu
Oct 1975	Small phreatomagmatic event	2	Confined to basin
6 Apr 1976	Lake-confined phreatic event	1	Confined to lake outlet
Jul-Aug 1977	Several very small phreatic events	1	Confined to lake outlet
2 Nov 1977	Moderate phreatomagmatic event lahar down Whangaehu	3	0.6 km radius & Whangaehu valley
Jan 1978	Vey small phreatic event	1	Confined to lake outlet
7 Mar 1978	Small phreatic event	2	2 km radius
June 1978	Numerous small lake-confined phreatic events	1	Confined to lake outlet
Sept 1978	Small phreatomagmatic event	2	Confined to basin
Jan 1979	Numerous small phreatomagmatic events	1	Confined to outlet
June-July 1979	Numerous lake-confined phreatic/phreatomagmatic events	1	Confined to outlet
Dec 1979	Small phreatic/phreatomagmatic events	2	Confined to basin
Jan 1980	Lake confined phreatic/phreatomagmatic event	1	Confined to lake outlet
Feb-Apr 1980	Numerous small phreatic/phreatomagmatic events	1-2	Confined to basin
Oct 1980	Very small phreatic/phreatomagmatic event	2	Confined to basin
Oct 1981-Apr 1981	Very small phreatic/phreatomagmatic events	1-2	Confined to basin
Jan-Mar 1982	Very small phreatic/phreatomagmatic events	1	Confined to lake outlet
May-June 1985	Very small phreatic/phreatomagmatic events	1	Confined to lake outlet
Feb 1986	Very small phreatic events	1	—

March and November 1945 (Table 2). This eruptive sequence was principally one of magma extrusion (dome building) and explosive eruption. Rise of a dome or plug of lava under the eastern portion of Crater Lake gradually displaced the lake water into the Whangaehu valley. The dome

Fig. 3. Moderate-sized phreatomagmatic eruption at Ruapehu Crater Lake on 8 May 1971. Central slug of the eruption column reached a height of 1.5 km

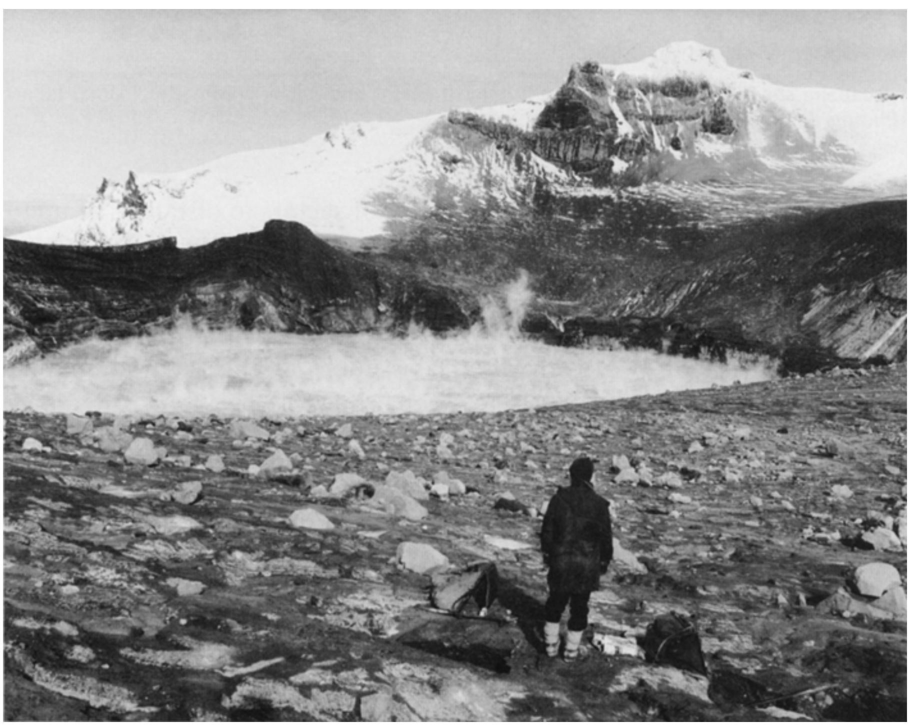

Fig. 4. Scattered large ballistic blocks adjacent to Crater Lake after the 22 June 1969 eruption. Photograph by DL Homer

Fig. 5. View of the northern slopes of Ruapehu showing the downwind fall deposit (right) and valley-confined proximal lahars (left) from the 22 June 1969 eruption. Photograph by TR Wyatt

completely filled the crater in July and a small central vent was established on the dome. This vent became enlarged by explosive eruptions, and two small vents formed to the west, aligned east-west with the principal vent. A climax of explosive activity occurred on 2 August when ash fell 90 km to the south-southwest. Explosive activity then declined but increased to two peaks in late September and in early November. At this stage the dome had been largely destroyed by explosions, and the principal vent had enlarged to form a 100-m-wide, 300-m-deep crater. A lake began to form in the crater and by 1953 had risen to the pre-1945 level.

The principal hazard was fall of ash over a wide area. The long duration of events meant that, as wind conditions changed, the ash was carried over a number of sectors to distances of up to 250 km. The ash and adhering ions contaminated water supplies and caused loss of crops and minor metal corrosion. The 1861 eruption is poorly documented, but seems also to have involved growth of a lava dome in the western summit crater.

Events not immediately preceded by visible explosive activity

A large lahar on 24 December 1953 swept down the Whangaehu valley destroying the Tangiwai railway bridge (Fig. 2, Table 2). The Wellington-Auckland express train was derailed, and 151 lives were lost. This lahar was not preceded by an

Table 2. Summary of characteristics of large historical events

Event	Nature of Event	Change of lake level	Range of ballistic particles	Extent of air-fall ash (downwind)	Lahars generated	Lahar volume (m^3)	Zone of damage from surge
March-Oct 1945	Dome growth and quiet expulsion of lake waters then explosive disruption of dome with small directed blasts	lake empties gradually	2 km	250 km	No	—	?
24. 12. 53	Lahar in Whangaehu produced by collapse of ice and ash wall blocking outlet	8 m	—	—	Whangaehu	1900000	—
26. 4. 68 to 27. 4. 68	Flood in Whangaehu due to lava intrusion in or below lake, followed by very small explosions	3.5 m	?	10 km	Whangaehu	729000	?
22. 6. 69	Major phreatomagmatic eruption generating lahars in 4 valleys, pyroclastic surge in summit area	~2 m	1.2 km	+25 km (not fully recorded) (NNW)	Whangaehu Mangaturuturu Whakapapaiti } Whakapapanui }	67000 24000 117000	3 km
8. 5. 71 to 16. 5. 71	Moderate phreatomagmatic eruptions	~0.5 m	1.4 km	10 km (east)	Whangaehu Whangaehu Whangaehu Whangaehu	41000 72000 58000 18000	<1 km
24. 4. 75	Major phreatomagmatic eruption, generating lahars, pyroclastic surges on summit and upper flanks	8 m	1.6 km	115 km (SE)	Whangaehu Mangaturuturu Whakapapaiti } Whakapapanui }	1800000 600000 900000	2.5 km
2. 11. 77	Moderate phreatomagmatic eruption generating lahar in Whangaehu and surges in basin	0.2m	0.7 km	10km (NE)	Whangaehu	130000	0.6 km

eruption. Healy (1954) suggested that a temporary ash and ice barrier formed after the 1945 eruption, and that its subsequent collapse suddenly lowered the lake level by 8 m.

Another large lahar, accompanied by strong tremor but no major explosive activity, passed down the Whangaehu on 26 April 1968 and was followed by small explosions over the next few days (Paterson 1980). No significant damage resulted. This lahar is interpreted due to spillover, as the product of lava intrusion at or beneath the lake floor.

Prehistorical activity

Modern Ruapehu was constructed in four cone-building episodes over ca. 250 Ka. Holocene eruptions during the most recent episode have come from two summit (central) and four flank vents (Fig. 2) on the southern portion of a 25-km-long lineament that extends across Ruapehu and adjacent Tongariro volcano (Hackett and Houghton, in press). This Holocene activity has included:

1) Strombolian explosive eruptions from two summit and two flank vents,
2) eruption of aa- and block-lava fields from two summit and three flank vents,
3) one, possibly two sub-Plinian eruptions (Hackett and Houghton 1985),
4) a minor cone collapse of the northwestern flank of the volcano, generating a debris avalanche (Hackett and Houghton 1986) and
5) production of two very large lahars whose deposits 160 km from the volcano have been radiocarbon dated at 407 ± 70 and 756 ± 56 a B.P. (Campbell 1973).

Four satellite vents surrounding Ruapehu have shown a range of eruptive styles including Strombolian and maar-forming explosive eruptions and emission of relatively fluid aa lava (Houghton and Hackett 1984). The youngest of these deposits is approximately 25 Ka old.

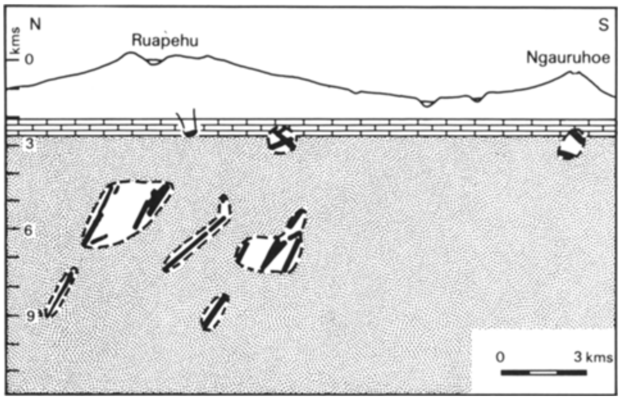

Fig. 6. Cross section showing the distribution of magma at depth as inferred from attenuation of S waves. The secton is drawn along the Holocene vent linement shown in Fig. 2. *Heavy black lines* are abnormally attenuating portions of wave paths, and *dashed lines* outline inferred associated magma bodies (after Latter 1981). *Box pattern* is Tertiary marine sediments; *stipple* is Mesozoic greywacke basement

Geophysical evidence relating to future activity

Seismic refraction studies (Dibble 1972) have been used to establish a model for routine location of earthquakes at and near Ruapehu (Latter 1981). The distribution of abnormally low, dominant S-wave frequencies suggests that pockets of magma are currently present beneath the volcano in the positions shown in Fig. 6. This distribution is in good agreement with the location of the Holocene vents and suggests that other flank and summit vents as well as Crater Lake are potential sites for future volcanism.

Hazard assessment

Six possible forms of renewed volcanism, most with Holocene analogues, have been considered based on the Holocene record and the assumption that events will be of similar frequency and magnitude in the future. These are:

1) phreatomagmatic explosions through Crater Lake,
2) construction and disruption of lava domes at the western summit vent,
3) Strombolian or sub-Plinian eruptions at some point along the Holocene vent lineament,
4) summit or flank extrusion of lava flows,
5) cone collapse and formation of a debris avalanche and
6) formation of a new satellite vent.

Three other hazards may occur with or without accompanying volcanism, i.e.

7) melting of tephra-bearing ice contaminating water supplies,
8) collapse of the unstable southeastern wall bounding Crater Lake and
9) sudden release of lake water into the Whangaehu valley, possibly displaced as a result of injection of magma at or below the lake floor.

Phreatomagmatic explosions

Three types of generalised hazard zones can be established: (A) a nearly circular region of total destruction from ballistic clasts and surges, (B) valley-confined tongues of extreme risk from lahars and (C) a larger circular region enclosing all possible downwind lobes of fall deposits of appreciable thickness.

Lahars associated with the phreatomagmatic eruptions constitute the most likely serious hazard at Ruapehu. Historical lahars occurred most frequently in the Whangaehu valley to the east, less frequently in the Whakapapa valley to the north with its two tributaries, i.e. the Whakapapaiti and the Whakapapanui streams, and least frequently in the Mangaturuturu valley to the west (Fig. 7). The total volume of lahars in any eruption is governed principally by the volume of ejected lake water.

The relative size of lahars in different valleys is influenced by the distribution of fall ejecta from the eruption, and hence chiefly by wind direction. Upper air measurements of wind speed and direction are made routinely at Ohakea, 100 km south of Ruapehu, and are probably representative of high-level winds in Tongariro National Park. Approximately 55% of winds are westerly; southerlies, northerlies and easterlies each account for about 15%.

Lahars occur most frequently in the Whangaehu valley, because of the predominance of westerly winds and because its headwaters are closest to the rim of Crater Lake (Fig. 8). Lahars occur frequently in the Whakapapaiti and Whakapapanui streams because ejecta falling in the northern summit region remobilises and ponds north of Crater Lake before flowing through a narrow notch onto the Whakapapa glacier (Fig. 8). Travel times for lahars to various critical points are shown on Fig. 7. Historical lahars are estimated to have taken approximately 3 min to reach the Whakapapa ski field, leaving little time for evasive measures. On a statistical basis, the highest volcanic risk to human life in New Zealand is from Whakapapa lahars.

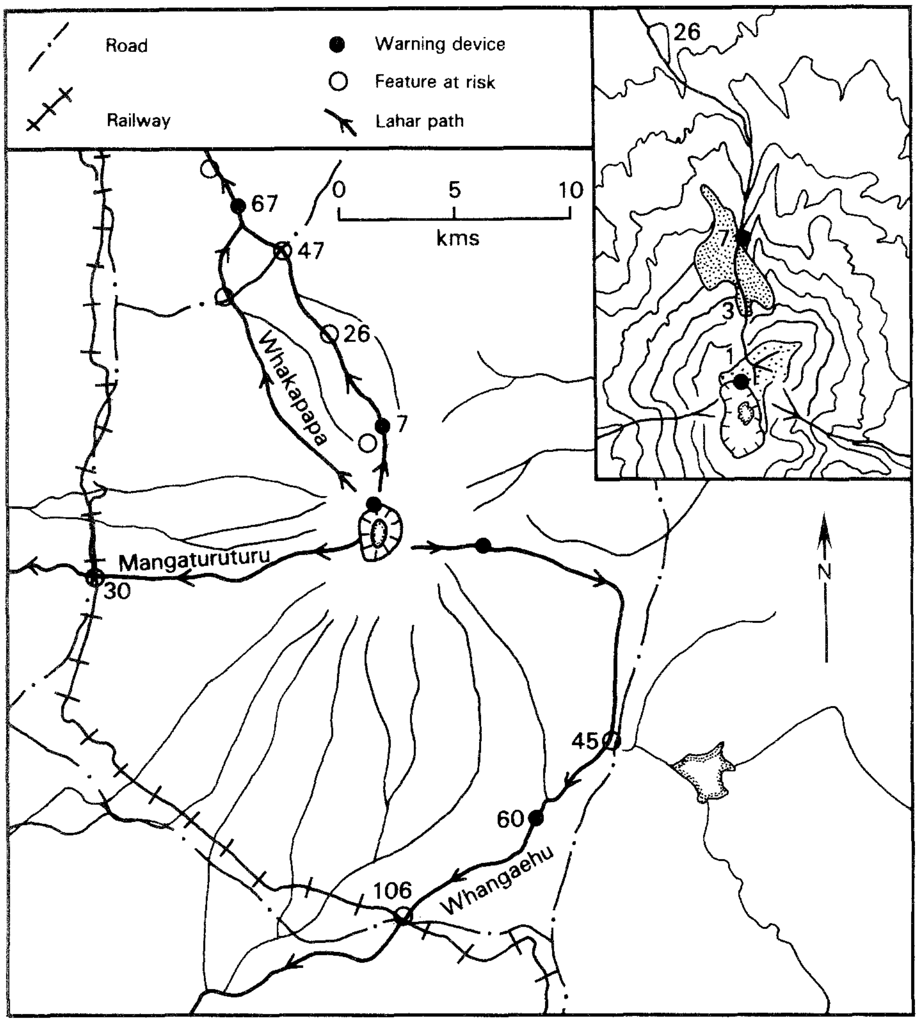

Fig. 7. Principal lahar paths at Ruapehu volcano and source areas for the lahars. *Numbers* are estimated times in minutes for lahars to reach important points along their paths, derived from velocities of historical lahars. *Inset* is topographic map of the summit and northern flanks of Ruapehu showing the ponding area above the northern lahar path *(coarse stipple)* and the position of the ski field *(fine stipple)*

The magnitude of phreatomagmatic eruptions of given frequencies can be assessed from the historical record. This enables civil authorities to compare risk levels with other forms of natural hazards, such as floods and storms. To do this, each historical event was assigned a hazard magnitude on a scale of 1-5 (Table 1). This is not a conventional magnitude scale based on eruptive volume or total energy release; instead it is an areal scale based on the area where the hazards would pose extreme risks to any people or installations that happened to be in that area (Table 3).

Reliability of the data increases with magnitude of the events. Three provisos should be made concerning the completeness of the record for very small (magnitude-1-2) events. These are (1) that some events occur at night or during poor visibility and are undetected, (2) steam columns due to purely atmospheric conditions may be misinterpreted as eruptions and (3) a measure of subjectivity is involved in grouping closely spaced events as one eruption. These limitations of the data do not significantly affect the conclusions of this report concerning serious volcanic risks at Ruapehu, because risks associated with magnitude-1-2 events are small. Detailed investigations have been made of the effects of all moderate to large (magnitude 3-5) eruptions in the period 1945-1981.

These data have been used to assess the size of hazard zones for events with return periods of (1) 1-3 years, (2) 10-30 years and (3) 100 years. Zones for (1) and (2) have been interpolated from the historical data, whereas zones for (3) are extrapolated assuming ejection of 60% of the water of Crater Lake.

Phreatomagmatic eruptions with a 1-3-year or greater frequency pose relatively little risk at Ruapehu (Fig. 9). Anyone in the basin of Crater Lake may be at risk from explosively projected ballistic blocks, and observers at the lake outlet could be

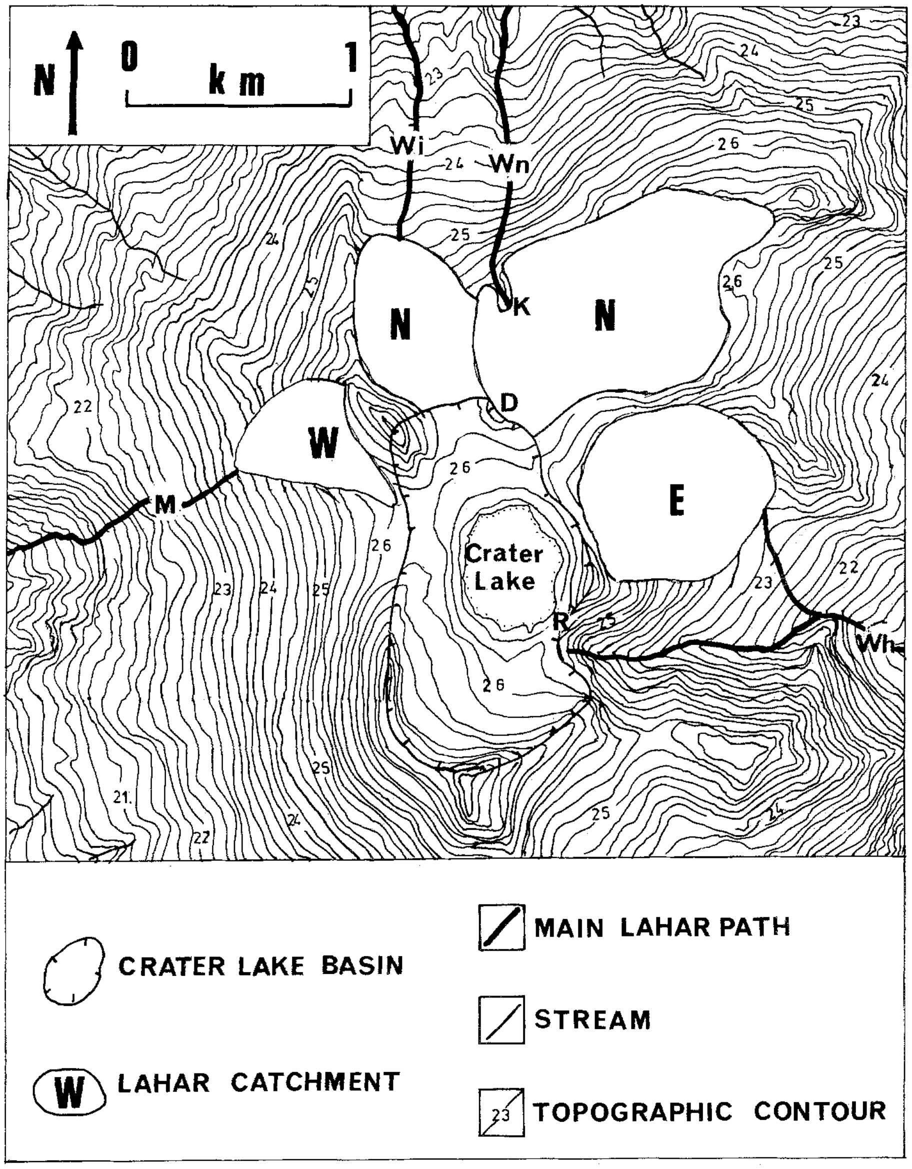

Fig. 8. Topographic map of summit of Ruapehu. *Contour interval* is 20 m; *numbered contours* are in hundreds of metres. The unstippled areas are catchment areas for historical northern *(N)*, eastern *(E)* and western *(W)* lahars. *R* is lowest point on crater rim. *K* is low notch on rim of northern summit plateau. *D*, dome shelter seismometer; *Wi*, Whakapapaiti stream; *M*, Mangaturuturu River; *Wn*, Whakapapanui stream; *Wh*, Whangaehu River

Table 3. Magnitude scale for hazard zones established for historical eruptions at Ruapehu, and return periods calculated from Table 1

Magnitude	Approximate area of zone of extreme risk from ballistic blocks, surges and lahars (m^2)	Total range of fall ejecta (m)	Return period (a)
1	$<10^3$	$<10^2$	1
2	10^3–10^4	10^2–10^3	2
3	10^4–10^5	10^3–10^4	5
4	10^5–10^6	10^4–10^5	9
5	$>10^6$	$>10^5$	18

washed into the ice cave by waves produced by an eruption. Skiing may be disrupted temporarily by ash falling onto the ski fields.

Substantial risks accompany eruptions with return periods of 10–30 years (Fig. 10). Risk to human life is extreme within 1 km of Crater Lake, where the abundance of ballistic blocks is likely to exceed 1 per 10 m^2. Pyroclastic surges or blasts will be sufficiently energetic to scour ice and rock within several hundred metres of the lake. Few observers within this region would survive. Lahar risk is high, as eruptions of this size eject between 5% and 30% of the lake water. The resulting lahars would be initially densely concentrated, moving at up to 12 m/s with sufficient force to damage

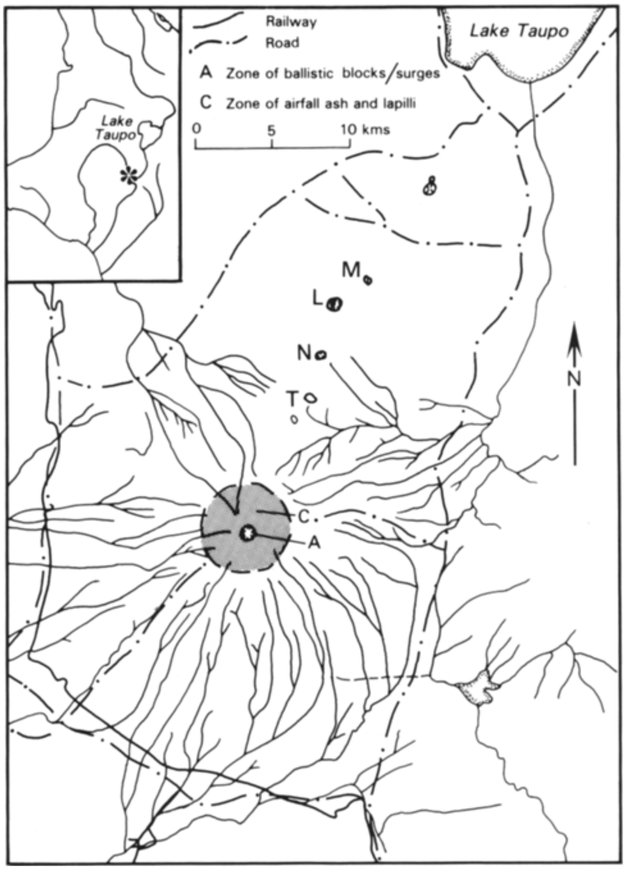

Fig. 9. Zones of volcanic risk associated with phreatomagmatic eruptions of return period 1-3 years interpolated from the historical record. *M* and *L* are Te Mari and North craters of Tongariro, respectively. *N* is Ngauruhoe and *T* is Tama Lakes. *A* is zone of extreme risk from pyroclastic surges and ballistic clasts; *C* encompasses all possible downwind lobes of fall deposits

bridges and buildings. As lahars reach lower gradients at the base of the cone they will decelerate and, by incorporating water and depositing material, become dilute and floodlike. Damage, if not destruction, of footbridges in the Whangaehu and possible Whakapapa and Mangaturuturu valleys is likely. Some minor lahar damage is likely on the Whakapapa ski field, especially if a southerly wind prevails. Major damage to road and rail bridges beyond the volcano is unlikely. Severe fish loss would occur in the Whakapapa and Mangaturuturu rivers.

Air-fall ash is likely to extend 10–30 km downwind, temporarily contaminating water supplies in the sector of deposition. More serious disruptions of water, drainage and possibly electricity supplies are likely on and below the Whakapapa ski field, where ash falls over 1 cm thick will probably be recorded.

Hazards associated with a phreatomagmatic eruption of 100-year frequency cover correspondingly larger areas (Fig. 11). Zone A, affected by blocks and pyroclastic surges, has a 3 km radius. Very high abundances of ballistic blocks (forming a nearly continuous layer in the summit area) mean little likelihood of survivors in this zone. In addition, potentially destructive surges in this zone may damage or destroy three alpine huts or shelters.

Lahar damage will be very high and most severe in valleys downwind of the vent. An easterly wind would carry ejecta to the headwaters of the Mangaturuturu and lead to severe lahar damage of the rail bridge. Likewise a southerly wind would result in very large lahars in both the Whakapapaiti and Whakapapanui, widespread damage on the ski field and destruction of road bridges on two state highways.

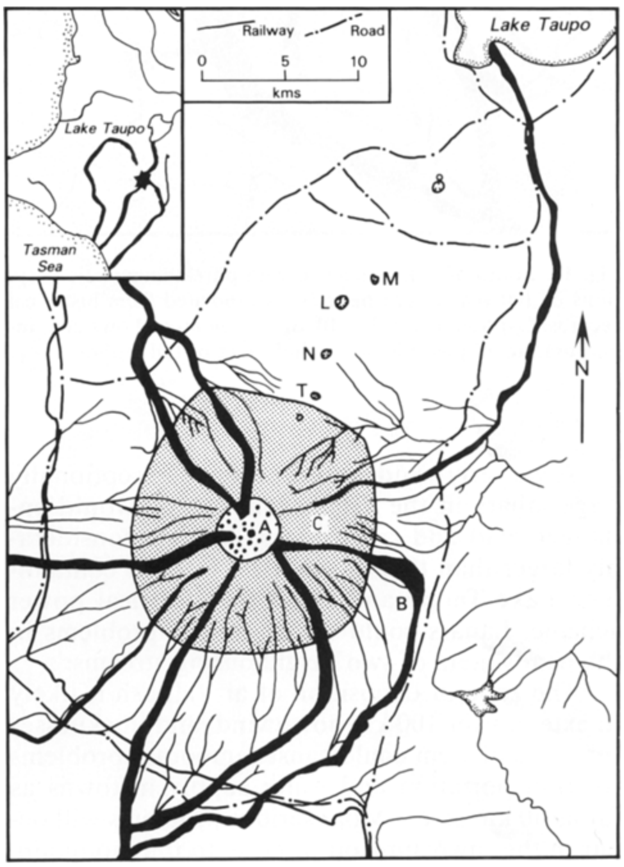

Fig. 10. Zones of volcanic risk associated with phreatomagmatic eruptions of 10–30-year return period interpolated from historical records. Depositional zones for any given eruption are strongly wind dependent. *A*, zone of extreme damage from ballistic blocks and surges; *B*, zone of extreme damage from lahars; *C*, zone encompassing all possible downwind lobes of fall deposits. *Inset* shows major streams and rivers which may be contaminated by lahars

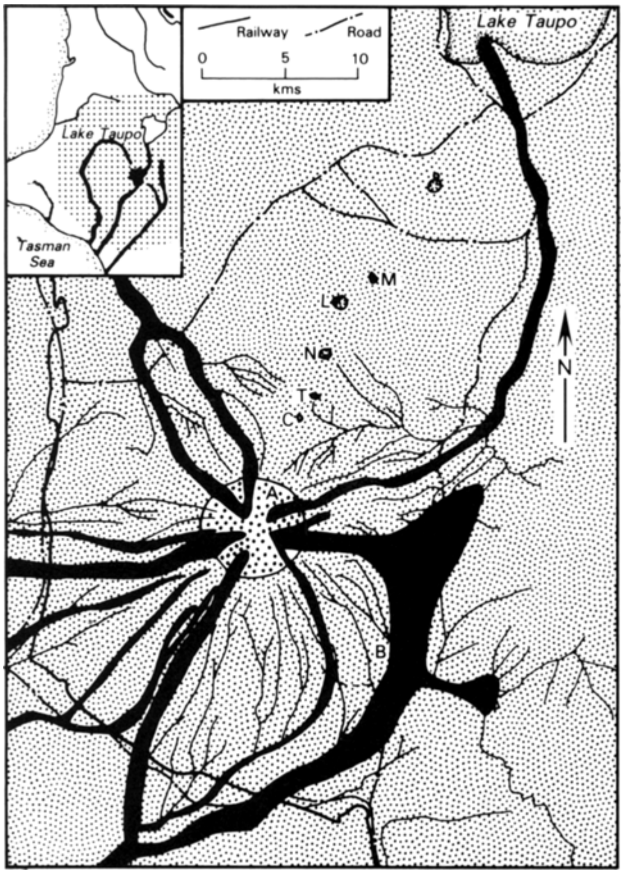

Fig. 11. Zones of risk associated with phreatomagmatic eruptions of 100-year return periods, extrapolated from historical records. Caption as for Fig. 10. *Stipple on inset* shows area incorporating all possible downwind lobes of fall tephra

A westerly wind would produce exceptionally large lahars in the Whangaehu which would endanger road and rail bridges. A lahar considerably larger than that of April 1975 could contaminate Lake Taupo and affect the electrical power scheme. Lahars could create similar problems in the headwaters of two neighbouring streams.

The zone of deposition of air-fall ash is likely to extend over 100 km downwind, and thicknesses in excess of 1 cm could cause temporary problems for transportation and water supply in towns as far as 50 km away. More serious problems will occur in the townships on or close to the mountain, where up to 10 cm of ash may accumulate.

Larger phreatomagmatic events have occurred in prehistorical time. An eruption ejecting 80%–100% of the water within Crater Lake would produce lahars in the major valleys similar to those of 407 and 756 a B.P. Hazards due to airborne tephra and surges can be extrapolated from Figs. 9–11, but it is the magnitude of the lahar risk associated with events that occur perhaps once per 400–500 years that is most significant. Such a lahar on the northern slopes would damage part, if not all, of Iwikau Village. The Mangaturuturu rail and road bridge would almost surely be destroyed. A lahar in the Whangaehu valley would probably reach the sea and possibly cross State Highway 1 north of Waiouru. Debris carried into Lake Taupo would probably affect the valuable trout fishing industry.

Extrusion of a lava dome in Crater Lake basin

The frequency of magmatic eruptions at the active crater is uncertain, although two have been recorded in historical times in 1945 and 1861. The style of historical eruptions is dome extrusion accompanied by minor explosive activity, followed by more violent explosive disruption and collapse of the dome. The expulsion of the lake into the Whangaehu could be either gradual, as in 1945, or sudden, generating lahars. Hazards for an eruption like that of 1945 can be assessed with some certainty. An initial extrusion of lava may be accompanied by explosive clearing of the vent posing hazards similar to those of small phreatomagmatic eruptions. Hazards during dome growth are confined to the summit area and are principally related to small directed blasts devastating areas of no more than a few km^2 or less, or to partial dome collapse.

Hazards are appreciably higher during major dome disruption and collapse. For example, ash fell up to 250 km from the vent during 1945, and crop damage and reduced dairy production were recorded over an area up to 50 km from the mountain. Magmatic eruptions typically last longer than phreatomagmatic explosions, and with changing wind direction the sector of deposition is likely to be wider. Airborne ash can cause decreased visibility, pollution of water and corrosion of metal surfaces over a radius of 50 km. Damage to electrical transmission lines east of the mountain seems probable, because of the prevalence of westerly winds. Aircraft on major routes would require new flight paths. Incandescent ballistic blocks would probably fall over several square kilometres. Dome collapse is likely to be accompanied by pyroclastic avalanches and hot, dry pyroclastic surges. The flows may extend several kilometres down major valleys, and surges would cause damage within 3 km of the vent.

Magmatic explosive eruptions

Strombolian eruptions along the Holocene vent lineament pose few hazards because of the limited dispersal of the ejecta. Deposits of such eruptions are likely to form cones of coarse ejecta surrounding the vents, as well as downwind lobes of tephra. Pre-existing Holocene cones cover areas of less than 1 km^2, and any new cones of similar size would affect no settled areas. Collapse of the cone walls, lava flows or small scoria flows constitute more significant, but still minor hazards. Distal tephra fall beyond the cone would pose problems similar to those of the fall deposits of phreatomagmatic eruptions, such as disruption of water and electricity supplies, particularly to the two villages on the northern flank of the volcano. Each of the largest explosive eruptions at Ruapehu in the last 15000 years has ejected approximately 10^8 m^3 of tephra. The likelihood of much larger Plinian eruptions ejecting several km^3 of material is slight, and the risk from such events at Ruapehu is appreciably less than that from the rhyolitic volcanoes to the north. Hazards associated with a sub-Plinian event ejecting 10^8 m^3 of tephra include:

1) ballistic bombs in a 2–5 km radius on and around the summit,
2) pyroclastic flows channelled down major river valleys onto the flanks of the mountain,
3) lahars of a size comparable to the 407 and 756 a B.P. events,
4) highly destructive pyroclastic surges or directed blasts extending up to 3–5 km from vent and
5) greater than 1 mm fall of tephra over several hundred kilometres downwind of the vent.

Extrusion of lava flows

A predominant mode of eruption of Ruapehu throughout prehistoric time has been extrusion and autobrecciation of lava flows. Summit lava flows have been emitted from three vent areas in the last 15000 years, i.e. from the Whakapapa area, from Te Heuheu and from near Crater Lake basin. Lava extrusion itself poses a greater risk to installations than to human life because time is generally available for evacuation. However, autobrecciation of lava is a common feature, which could produce mobile incandescent pyroclastic avalanches on steep slopes.

Renewed extrusion of lava from the two southerly summit vents poses little threat because of the absence of settlements and installations in the probable flow path. However, renewed activity at the Whakapapa vent could threaten Iwikau and Whakapapa villages. Previous flows have extended 8 km from source beyond Iwikau village. Future flows would be channelled either eastward or nothward. Lava flows on the northern course might not reach Whakapapa village, but associated pyroclastic avalanches might follow the Whakapapanui stream and cause extensive damage.

Post-glacial extrusion of lava flows occurred at three flank vents. Renewed activity will probably again be along the vent alignment and is unlikely to threaten existing settlements. The proportion of lava flows to pyroclastic material is much higher for flank eruptions than for summit eruptions at Ruapehu, and risk is correspondingly less.

Sector collapse

A major collapse, similar to that on the northwestern flank of the volcano 9500 years ago (Hackett and Houghton, in press), would have serious consequences at Ruapehu. The frequency of such events is not established, as the deposits of earlier collapses have yet to be identified. Prime areas for such collapses are the hydrothermally altered cores of the early cones, which are now exposed on the flanks of the modern volcano. In the long term, this represents the most potentially destructive hazard at Ruapehu.

Renewal of activity at parasitic centres

The locations of parasitic centres appear less rigorously controlled than those of flank vents, and there is no means of predicting the location of future activity. The parasitic vents erupt more fluid, basic magma than do vents on the stratovolcano. The resulting eruption style of alternating Strombolian explosions and fluid lava flows of limited extent is accompanied by relatively low risk. Hazards increase if the vent lies in swampy or water-saturated ground, such as Ohakune, where phreatomagmatic explosions may occur.

Future parasitic eruptions are unlikely to pose significant risks at distances of more than 1 km from the vent; thus activity would have to be centred on Ohakune or Whakapapa to constitute an appreciable risk.

Contamination of water supply

The Whakapapa village was partially evacuated in 1955 when 1945 ash, exposed as ice melted, contaminated the village water supply. The glaciers and ice fields on Ruapehu are currently retreating, and similar problems could recur. However, no immediate problem exists, and alternative supplies of water can now be arranged, but at considerable cost.

Collapse of Crater Lake wall

The southeastern wall of Crater Lake, largely composed of bedded tephra and thin lava flows, represents the narrowest and lowest part of the rim (Fig. 8) standing about 45 m above lake level. Landslides have already taken place into the lake from this part of the wall which is now very steep (O'Shea 1954). The outer slopes of the wall overlooking the Whangaehu valley are also susceptible to landsliding. Limited amounts of Crater Lake water seep through this wall into the Whangaehu valley (Beetham et al. 1980). Repeated surveys of the summit area have shown seasonal southward movement of the eastern wall in summer, which is only partially recovered during the following winter. Cumulative southward movement of the wall between March 1976 and May 1981 was 70 mm (P. M. Otway, personal communication). Failure of the wall, with or without eruption, would have a catastrophic effect on the eastern and southeastern side of the mountain. The resulting lahar would almost certainly cross and block State Highway 1, destroy electricity transmission lines and possibly reach a military camp 23 km southeast of Crater Lake, which would normally serve as a coordination centre during a volcanic crisis. This scenario poses the second greatest risk at Ruapehu.

Other lahars not preceded by explosive volcanism

The size of lahars like the 26 April 1968 event is limited unless the wall of Crater Lake basin also collapses. The danger from such lahars can be mitigated by measures described below.

Monitoring and mitigation

Ruapehu volcanism is monitored by studies of seismicity (Latter 1986), lake temperature and chemistry (Giggenbach and Glover 1975), horizontal deformation and tilt-levelling (Otway 1986) and measurement of total magnetic-field strength (Whiteford 1982). None of these techniques has enabled specific phreatomagmatic eruptions to be accurately predicted, although all are useful in defining extended periods of high risk. Phreatomagmatic explosions with no seismic or detectable deformation precursors have occurred in the last 30 years. Three warning schemes exist on the mountain, and all rely on early detection of lahars and not solely on precursory events.

The greatest risks to human life at Ruapehu are on the Whakapapa ski field. A lahar produced by ejecta falling and ponding on the northern summit plateau (Fig. 8) would flow onto the glacier above the ski field and reach the upper ski field 3 min after the explosion (Fig. 7). It would leave the ski field via the steep gorge of the Whakapapaiti stream 7 min after eruption.

The seismograph at Dome Shelter (Fig. 8) performs two functions in a two-stage warning scheme installed in 1984 (Hewson and Latter 1975). A microprocessor automatically compares the signal at this station and a second station 33 km from Crater Lake. If an earthquake centred on Ruapehu and exceeding an arbitrary magnitude (currently 3.5 on the Richter scale) is detected, a limited alarm is triggered in the National Park Headquarters in Whakapapa village. If the radio signal from the seismometer is then lost, a destructive eruption is assumed to have occurred and automatic warnings are broadcast over loudspeakers on the skifield. The warning time is of necessity short, but the lahar path is narrow and skiers need move no more than 50 m laterally to be out of danger. The lahar triggers a further warning device as it leaves the ski field, and a further 20 min will elapse before the lahar passes the Park Headquarters. A separate device further downstream triggers closure of water intakes for the hydroelectrical power scheme.

Another lahar-warning scheme installed in the Whangaehu valley 6 km below Crater Lake detects lahars threatening installations on the eastern flank of the volcano, particularly road and rail bridges.

Possible further steps

An additional step, which would drastically reduce or eliminate lahar risk, is partial or complete draining of Crater Lake. Gradual lowering of the southern wall of the basin is the most practical solution, given the altitude and prevailing climate. This course is probably not feasible within a national park, and construction of diversion barriers may be an alternative, especially to protect the state highway and electricity lines east of the mountain from large Whangaehu lahars.

The Whakapapa lahar-warning scheme, which gives the earliest warning, should be automatically linked with rail, electrical and civil authorities.

Further detailed stratigraphic and volcanological studies are needed to clarify aspects of the volcano's history, particularly events that led to the large prehistoric lahars and sector collapses.

Contingency plans should be formulated for the scenarios given above. In addition there should be public discussion of these plans and establishment of a communication system which would function even during a major phreatomagmatic eruption.

The probable cost of these measures is slight by comparison to the cost of even a moderate lahar on the Whakapapa ski field.

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