TEPHRA

KIA TAKATŪ TAHI TĀTOU October 1995, Volume 14, Number 2

VOLCANIC HAZARDS IN NEW ZEALAND

A special feature in association with Ruapehu '95
Volcanic Hazard Awareness Week, 16-23 October 1995

Foreword
A Foreword from the Director of Civil Defence.

Volcanoes of New Zealand
Colin J.N. Wilson, Bruce F. Houghton & Bradley J. Scott. Institute of Geological & Nuclear Sciences.

Surveillance of New Zealand's Volcancoes
Bradley J. Scott, Bruce F. Houghton and Colin J.N. Wilson, Institute of Geological & Nuclear Sciences.

The Potential Volcanic Threat at Ruapehu
V.E. Neall, S.J. Cronin, S.L. Donoghue, K.A. Hodgson, J.A. Lecointre and A.M. Purves. Department of Soil Science, Massey University.

Living with Volcanoes
David Johnston and Bruce F. Houghton. Department of Soil Science, Massey University, Institute of Geological & Nuclear Sciences.

Lessons from Rabaul
Summarised Results of a Fact-Finding Visit.

Bibliography

Civil Defence, New Zealand
TEPHRA Vol 14 No 2 *October 1995*

A FOREWORD FROM PAUL OFFICER

Of Bishop Berkeley's theory of the non-existence of matter Dr Johnson said "I refute it thus", striking his foot vigorously against a large stone.

On the whole our sympathy is with Johnson. It is commonsense to agree that matter exists and that rocks are solid. Yet we now know that the actual space within the rock is mostly empty and that the impression of solidity comes from the interaction of atoms which are mostly themselves empty space.

We tend to believe our sense and to take most seriously the things they report, especially things seen and touched or felt: the earth, the wind and so on. Some, but not many, have a lively appreciation of less easily perceived forces, such as the electromagnetic forces exemplified by the solar wind which occasionally becomes visible in the aurora. Very few comprehend the great thermonuclear forces which fuel the sun or which invisible, unheard and unfelt beneath our feet drive dynamics of our planet and cause, as a sort of by product, the periodical convulsions that shape its elastic skin.

Similarly, we are creatures of time. The beating of our pulses, the daily rhythm of waking and sleeping, the annual cycle of seasons (whether four in mid latitudes or two as in regions nearer the equator or the poles) mark time for us. On the whole our attention is concentrated on the shorter rhythms. In industrialised countries this often includes the weekly pattern of work and leisure, and the annual break for holidays.

When we turn to the phenomena that require emergency management we find different time-scales, less easy to maintain in the mind's focus. We may face traffic hazards every day, but flood hazards are at most seasonal, and even in flood prone countries like New Zealand we may have some years pass between major events. Geographers note that where the flood interval in a community exceeds five or seven years, there is a significant loss of attention to the hazard.

What then of longer term cycles? In July 1995 the town of Thames and neighbouring Hauraki Plains in the North Island suffered a storm surge. There was no rain, so no one expected water. But the sea rose over a metre above normal high tide and large areas were inundated. This had last happened in 1938, almost too long ago for local memory.

This issue of *Tephra* focuses on the volcanic hazard. This is partly to commemorate the 50th anniversary of the Mt Ruapehu eruption in1945 and I am delighted to offer *Tephra* as a means of reaching a wider audience with important reflections on New Zealand volcanoes from staff of the Institute of Geological & Nuclear Sciences. This issue also includes a report of our fact-finding team's visit to Rabaul. I thank the Government of Papua New Guinea and of the Province of East New Britain for their support in this visit.

One message from Rabaul concerns the residents of Matupit Island. They evacuated their homes because elders who could recall the 1937 eruption, or who had carefully remembered their elders speaking of it, recognised signs, such as reports of earth worms and insects coming out of the ground, as being indicators of an impending event more severe than the 1983-85 activity.

Beyond the memory of the oldest people, or the reported tradition of a stable community, we leave the period for which human recollection can help us. No one can blame the residents of Kobe for not remembering that there had been an earthquake 400 years ago. The years of geological time, the thousands (or more) of years between volcanic events, for example, in many still active fields are for most of us mere digits in scientific reports, without relationship to everyday life.

So we must turn from memory to imagination to attempt an appreciation of the hazards that may confront us. To some extent this is the role of science fiction. But it is also possible that the creative skills and intuitive insight of able scientists, linked to their more widely recognised analytical abilities, can alert us in ways we can appreciate to the immense forces at steady and ceaseless work in the planet we live on. I welcome the opportunities I have had this year, and which we share in this issue of *Tephra* to present work from some of our leading researchers on a hazard which because of our capture by time, by the day to day, is the most underrated in New Zealand.

At the time of writing, as if awakened by some geological clock, Ruapehu has stirred and cleared its throat. We do not know whether this is the precursor of some more violent event. The scale and unpredictability of volcanoes requires continued vigilance, caution and considerable humility.

We should remain mindful that in the end all activity is interrelated and all phenomena, animate and inanimate are interconnected. This interdependence of all around us is a theme to which we may wish to return.

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TEPHRA Vol 14 No 2 *October 1995*

VOLCANOES OF NEW ZEALAND

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Photo by Arthur Pengelly

Introduction

Volcanism has played a dynamic role in forming the New Zealand landscape, with the greatest impacts on the landscape and environment during the last 1.6 million years. Much of the outstanding landscape of the central North Island owes its shape to volcanism, and volcanic soils support large parts of the farming and forestry sectors of the economy. However, volcanism has its disadvantages. Deaths due directly or indirectly to volcanism (and associated hydrothermal explosions) represent the biggest single source of fatalities from natural disasters in New Zealand during the last 150 years (Table 1). Past economic losses due to volcanism are trivial in comparison to those from earthquakes or flooding. However, studies of the volcanic eruptions in recent prehistory show only a fraction of the types and sizes of volcanic events that have occurred in the past and will occur again in the future. Contingency plans for our volcanoes must include scenarios based on recent prehistory as well as the short recorded history.

Table 1: Summary of deaths in volcanic areas during the past 150 years

Year	Location (eruption)	Cause - hazard	Fatalities
1846	Waihi (Lake Taupo)	debris avalanche/mudflow from thermal area	c.60
1886	1886 Tarawera Rift	large volcanic eruption	>108
1903	Waimangu (Tarawera)	hydrothermal explosion	4
1910	Waihi (Lake Taupo)	debris avalanche from crater wall	1
1914	White Island	debris avalanche/mudflow from thermal area	11
1917	Waimangu (Tarawera)	hydrothermal explosion	2
1953	Tangiwai (Ruapehu)	lahar and flood from Crater Lake	151
			Total > 337

Types of Volcanic Activity

Types of magma (molten rock)

We divide naturally occurring magma into types according to their silica content which controls their **viscosity** (ease of flowing) and hence influences their eruptive styles. The most silica-poor (4752% SiO2) fluid magmas are **basalts**, then come intermediate compositions called **andesites** and **dacites**. The most silica-rich, viscous magmas (>72% SiO2) are **rhyolites**. Magmas contain dissolved gases, mostly steam (H2O) but also with lesser amounts of noxious or toxic gases such as carbon dioxide (CO2), sulphur compounds (H2S, SO2), and chlorine (Cl2).

Types of eruption

There are two major types: **effusive,** where liquid magma emerges passively at the earth's surface to form a **lava flow**; and **explosive,** where escaping gases tear the magma apart into fragments. The fragments are termed **pyroclasts** ('fiery broken') and explosive eruptions form **pyroclastic deposits**. In any magma, if the gas content is low, or the viscosity is low so that gases can easily escape, then a lava flow is the likely end product. Thus basalts often erupt as lava flows. Conversely, high viscosity, gas-rich rhyolites tend to erupt explosively and violently, and form pyroclastic deposits.

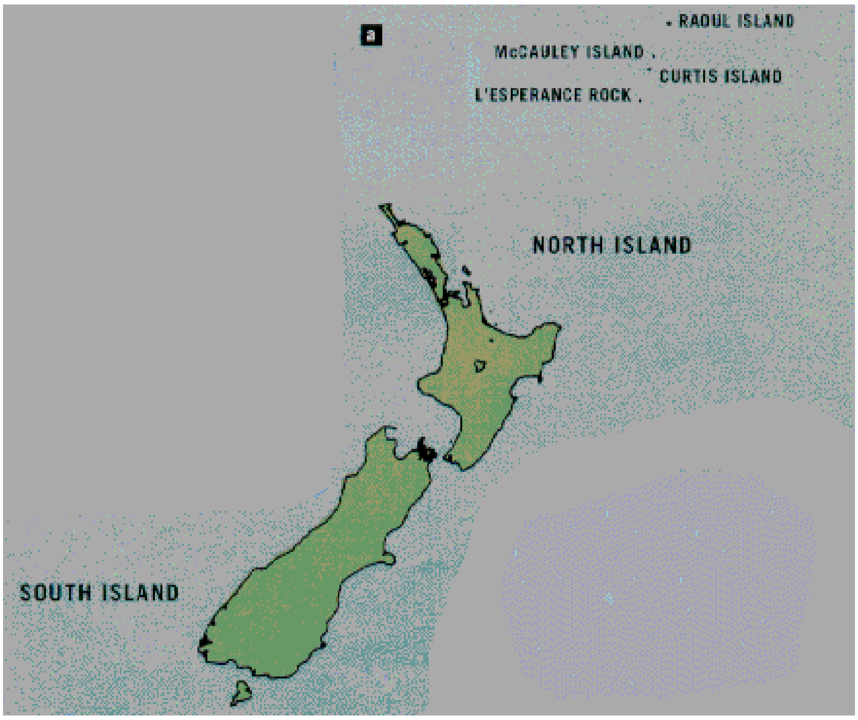
Types of explosive eruption

Volcanic explosions occur in two different ways. In 'dry' explosive activity, gases dissolved in the magma escape, tearing the magma apart in the process. 'Wet' activity is where the hot magma meets a supply of water (for example, a lake), flashing the water to steam and making the eruption violently explosive. There are also two types of product. **Fall** deposits result when the fragments are carried up in an eruption column high above the earth's surface and then are 'rained' out over the landscape to form a 'blanket'. **Flow** deposits (ignimbrite) form when the fragments travel laterally as a kind of high-speed avalanche across the landscape.

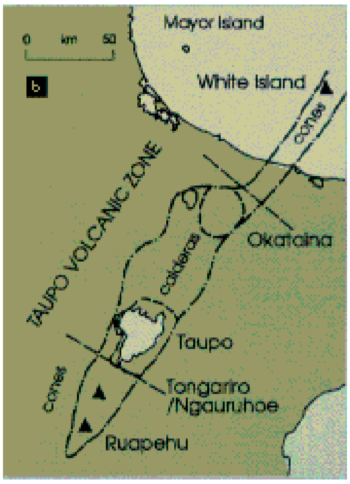
Volcanism in New Zealand

The New Zealand region is characterised by both a high density of active volcanoes and a high frequency of eruptions. Volcanic activity in New Zealand occurs in six areas (Fig. 1), five in the North Island and one offshore to the northeast in the Kermadec Islands.

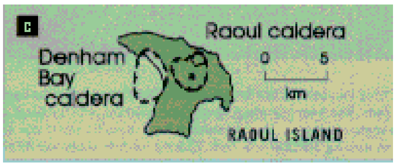
Maps to show locations of the young volcanoes in New Zealand.



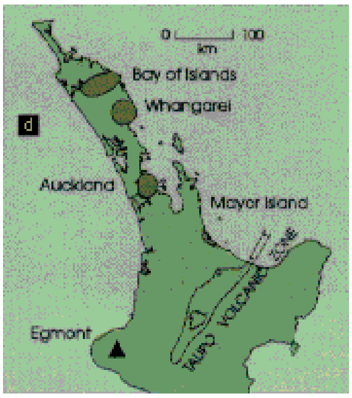
(a) Main map to show the positions of the Kermadec Islands (Raoul, McCauley, Curtis, L'Esperance) relative to the North and South Islands.



(b) Enlargement of TVZ to show the segments dominated by cone volcanoes (White Island, Tongariro/Ngauruhoe, Ruapehu) and caldera volcanoes (Okataina and Taupo). Note that the north-northeast continuation of the TVZ trend beyond White Island links up with (and continues beyond) the volcanoes of the Kermadec Islands.



(c) Enlargement of Raoul Island, the most frequently and recently active of the Kermadec Islands, showing positions of the two historically active calderas.



(d) Location of volcano fields in Northland and Auckland (grey ovals), the cone volcano of Egmont, caldera volcano of Mayor Island, and the Taupo Volcanic Zone (TVZ).

There are three major types of volcano in New Zealand.

Idealised cross-sections of the three main types of young volcano in New Zealand. In each *example, the products of a single eruption are marked (stipple for pyroclastic deposits, black for lava). Note that in the volcano field, each volcano represents the product of a single eruption and is fed by a single dike. In the cone volcano, each cone is made up from the deposits of many eruptions, fed by numerous dikes which repeatedly follow the same pathway. For the caldera volcano, the typical products of a large eruption are shown. These are very widespread, but also accumulate to great thicknesses in the down-dropped caldera.*

Volcanic fields

Volcanic fields such as Auckland, are where small eruptions occur over a wide geographic area, and are spaced over long time intervals (thousands of years). Each eruption builds a single small volcano (e.g. Mount Eden, Rangitoto), which does not erupt again. The next eruption in the field occurs at a different location, and this site cannot be predicted until the eruption is imminent.

Cone volcanoes

Cone volcanoes such as Egmont and Ruapehu are characterised by a succession of small to moderate eruptions occuring from roughly the same point on the earth's surface. The products of successive eruptions accumulate close to the vents to form a large cone, which is the volcano itself. Over a long period of time several cones may form which overlap and are built up on top of each other. The same route to the surface is used repeatedly by the magma so sites of future eruptions can largely be predicted.

Caldera volcanoes

Caldera volcanoes such as Taupo and Okataina (which includes Tarawera) exhibit a history of moderate to large eruptions. Eruptions at these volcanoes are occasionally so large that the ground surface collapses into the 'hole' (caldera) left behind by the emptying of the underground magma chamber. The pyroclastic products are usually spread so widely that no large cone forms, except where lava flows may pile up on top of each other (for example, Mt. Tarawera). In the large caldera-forming eruptions, a lot of the erupted material accumulates within the caldera itself as it collapses, and the old land surface may be buried to several kilometres depth.

New Zealand Volcanoes

1. Distribution

Volcanoes in New Zealand are not randomly scattered, but are grouped into areas of more intensive and long-lived activity, whose position (and the compositions of the magmas erupted) can be related to the large-scale movement of plates in the New Zealand region. Most New Zealand volcanism in the past 1.6 million years has occurred in the Taupo Volcanic Zone (Fig.1), an elongate area from White Island to Ruapehu, which has been by far the most frequently active area, both in historic times and over the last 1.6 million years. Taupo Volcanic Zone (TVZ) is extremely active on a world scale; it includes three frequently active cone volcanoes (Ruapehu, Tongariro/Ngauruhoe, White Island) and the two most productive caldera volcanoes in the world (Taupo, Okataina).

2. Individual areas and volcanoes:

Tarawera 1886 AD Eruption
A view looking northeast along the vents of the 1886AD eruption, from Frying Pan Lake in the foreground to Mount Tarawera in the background. The 1886 eruption, like many that have occurred in the Taupo Volcanic Zone, was from numerous vents along a fissure, which creates problems for volcanologists trying to define hazard zones on our volcanoes. Where vents emerged on Mount Tarawera itself, basaltic scoria was ejected, but the vents in the foreground and middle distance opened up through an existing hydrothermal field, causing massive steam explosions. The geothermal system is currently re-establishing itself below Waimangu.

(a) Volcanic Fields

Northland and Auckland

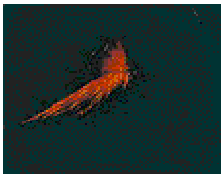
Three volcanic fields occur in Northland and Auckland, where small individual eruptions occur at intervals of hundreds to thousands of years. The best known of these is the Auckland field, where over 60 small volcanoes have formed, Rangitoto being the youngest (700 years old). The magma is basaltic in composition, and eruptions tend to be small (typically 0.1-1.0 km3), and the areas affected are, at most, a few tens of km2; therefore hazards are very localised. However, the growth of New Zealand's biggest commercial centre almost exactly on top of one of these fields has led to much greater awareness of the risks posed by a potential renewal of activity in this area.

(b) Cone volcanoes

Egmont

The modern cone of Egmont is only the latest in a series of cone volcanoes that stretches back in time for 1.7 million years. The older cones (1.7-0.13 million years) have now been eroded down to relicts which form the Pouakai and Kaitake Ranges, and the Sugarloaf Rocks at New Plymouth. The main Egmont cone is about 130,000 years old, and has a complex history of multiple cone **building** episodes followed by cone **collapse** episodes when much of the cone was destroyed by huge debris avalanches. Most of the actual mountain that we see today is only about 10,000 years old and has rapidly built up since the last major collapse. The latest eruption where magma reached the surface is thought to have occurred in 1755 AD, so the volcano is considered to be dormant. Eruptive products of Egmont are andesitic to dacitic in composition. They form domes and lava flows that, together with some pyroclastic material, have built up the modern cone itself, together with comparable volumes of pumice, scoria and ash that have spread as thin pyroclastic fall and flow deposits beyond the cone.

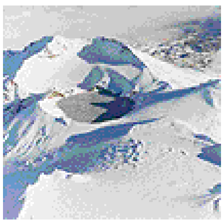
Tongariro/Ngauruhoe



Ngauruhoe at night
A night shot of Ngauruhoe erupting in 1974. The red-hot pyroclasts are being ejected from the vent and tumbling down the steep slopes of the cone. The white irregular streaks are lightning.

Tongariro is a large (100 km3) cone volcano of which the youngest cone, Ngauruhoe, is the main active centre. Tongariro, like Egmont, has been both built up by eruptions of lava flows and pyroclastic material as well as partially destroyed on occasions in the past. However, the main destructive force at Tongariro does not appear to have been cone collapse, so much as erosion by ice during glacial periods. The oldest lavas from Tongariro are at least 340,000 years old, and occur in places that imply there was a substantial 'Mt. Tongariro' at that time. New work is showing that the modern cone has grown since 275,000 years ago, with intervals of cone building occupying a few thousand to tens of thousands of years (Ngauruhoe is only 2,500 years old). These cone-building periods are separated by times when either most activity was expressed as widespread pyroclastic deposits (which did not contribute much to cone building) or the volcano was much less active. In most eruptions the magma was andesite, but minor amounts of dacite and basalt are also known here. The most prominent vent, Ngauruhoe, has been frequently active in recorded times, but has not erupted since 1975 and is now undergoing its longest break from activity in recorded history.

Ruapehu



Ruapehu Crater Lake (before the 1995 eruption)
The grey, steaming crater lake of Ruapehu is kept heated by gases streaming up the throat of the volcano from magma which is stored at depth beneath the cone. The abundance of snow and ice around the hot lake means that mudflows are a common product in even small eruptions. The Whakapapa skifield is at high risk from mudflows, which flow from the summit plateau through the notch seen at the bottom right corner of the photo.

Ruapehu is New Zealand's largest cone volcano and, like Tongariro and Egmont, has been built up and partially destroyed on several occasions during its history. The oldest dated lavas are 230,000 years old, but there has probably been a 'Ruapehu volcano' for at least 0.5 million years. Destructive influences at Ruapehu include both cone collapse and glacial erosion, the latter continuing to the present day. Like Tongariro, Ruapehu has erupted mostly andesite, and only minor amounts of basalt and dacite have been found. Ruapehu is unusual among the cone volcanoes in having a crater lake which, in historic times, has greatly modified eruptive behaviour such that even small eruptions are accompanied by potentially dangerous mudflows or lahars. With the exception of the 1945 eruption, the lake has acted as a trap for magmatic heat an volatiles, so making it warm and highly acidic. Ejection of lake water leads to the formation of lahars, one of which in 1953 led to New Zealand's worst volcanic disaster at Tangiwai. Only in 1945 was the lake displaced, and lava extruded at the surface during the largest volcanic eruption in New Zealand this century.

White Island

White Island
White Island, New Zealand's most active cone volcano has been in a state of near-continuous eruption since December 1976. The eruptions are mostly small, which means that hazard zones are limited to the island itself, but dustings of tephra occasionally fall on the mainland. The white clouds are highly acidic because of the presence of abundant HCl and SO2 in the gases given off by the volcano.

White Island is the 320 m high emergent tip of a 17 km wide, 750 m high cone volcano largely submerged beneath the Bay of Plenty. It is unusual in being one of the very few privately owned volcanoes in the world. White Island is currently New Zealand's most active volcano with three long cycles of eruption recorded between 1976 and 1994. Our knowledge of the earlier history of the volcano is severely limited by a lack of data on the age of prehistoric eruptions. This early history includes two major episodes of cone growth with both extrusion of lava flows and explosive eruptions. There are no recognisable products of primeval or historic activity preserved on the mainland. Historic activity included a small collapse of the west wall of the main crater in 1914, forming a debris avalanche which killed 11 sulphur miners. All subsequent events have been small explosive eruptions, linked to the formation of collapse craters through the 1914 deposits. Since 1976, White Island has erupted low-silica andesitic magma, whereas most earlier activity involved higher-silica andesite or dacite.

Kermadec Islands

Many oceanic volcanoes occur along a line from the North Island, tending north-northeast towards and including Tonga, and the Kermadec Islands which represent points where some of these volcanoes have constructed cones above the surface of the sea (Fig. 1). Although shaped like their mainland counterparts, the three major cone volcanoes in the Kermadecs (Raoul, Macauley and Curtis) differ in two respects.

The first respect is that they have erupted substantial amounts of both dacite and basalt, rather than andesite.

The second is that the main processe causing destruction of the cones are marine erosion, and caldera collapse, the latter accompanying dacite eruptions. Many details of the volcanic histories of the Kermadec volcanoes are unknown, as the oldest rocks available on the islands are only a few thousand years old, whereas by analogue with similar-sized volcanoes on the mainland, the individual volcanoes would have taken several hundred thousand years to be constructed. Raoul Island has experienced several historic eruptions, the most recent in 1964. The size range of eruptions at the Kermadec volcanoes is higher than that usually considered the norm for cone volcanoes, and pyroclastic deposits (including ignimbrites) are prominent features of the young eruptive records.

(c) Caldera volcanoes

Taupo

Taupo is a large caldera volcano, whose shape reflects collapse following two large eruptions about 26,500 and 1,800 years ago, although the volcano itself first began erupting about 300,000 years ago. The modern Lake Taupo partly infills this caldera structure. Taupo has erupted mostly rhyolite, with only minor amounts of basalt, andesite and dacite, and is the most frequently active and productive rhyolite caldera in the world. The eruptions are notable for varying enormously in size, from <0.01 km3, up to the largest (26,500 years ago) which ejected about 800 km3 of pumice and ash (if expressed as dense rock, this would be similar to the volume of Ruapehu). There have been 28 eruptions at Taupo since 26,500 years ago, of very different sizes and spaced at very different intervals. The variability in the sizes and repose periods makes it impossible to predict when the next eruption will occur and how big it will be. The latest major eruption from Taupo caldera volcano about 1,800 years ago was the most violent volcanic eruption in the world for the past 5,000 years and has left marks on the landscape and vegetation patterns which are still visible today.

Okataina

Okataina is a large caldera volcano which has been erupting over a similar time span to Taupo, at similar rates of production, and involving the same types and proportions of magma (that is, almost entirely rhyolite). However, the superficial appearance of the volcano and the styles of recent eruptions at Okataina are different. The last caldera collapse occurred about 64,000 years ago, and the many eruptions since then have largely infilled the hole left behind by the collapse. These young eruptions at Okataina have been fewer in number than at Taupo, but more uniform in size, so that the smallest rhyolite eruptions at Okataina were bigger than all but the four or five largest eruptions at Taupo in the same time period. Many eruptions at Okataina have produced large volumes of rhyolite lava; this lava has piled up over the vent areas to produce two large massifs, Haroharo and Tarawera. However, Okataina has also produced some unusual eruptions such as the basaltic eruption of Tarawera in 1886 AD which is not only New Zealand's largest historic eruption, but also the largest basaltic eruption known in the entire 1.6 million-year history of the Taupo Volcanic Zone.

Mayor Island

Mayor Island
A view of Mayor Island, the smallest caldera volcano in New Zealand. The youngest caldera on the island formed about 6300 years ago, and is seen as the square depression forming the field of view in the middle of the island. The caldera has been partly infilled by younger lava flows to produce rounded hills. Coastal cliffs show many layers of pyroclastic deposits and lava flows, which have been dated and used to establish the 130,000 year volcanic history of the island.

Mayor Island (Tuhua) is the emergent summit, 4 km in diameter and 350 m high, of a caldera volcano which is roughly 15 km across and 750m high. Our present understanding of the history of the volcano is therefore limited to what we can see on the island, the oldest portion of which is about 130,000 years old. Although Mayor Island erupts almost entirely rhyolite magma, this rhyolite is unusual in containing higher amounts of sodium and potassium than the more 'normal' rhyolites at Okataina or Taupo, reducing the magma viscosity and therefore the degree of explosivity of many eruptions. The volcano has produced many explosive and effusive eruptions during its history above the water surface, punctuated by at least 3 occasions when caldera collapse occurred. The latest of these occurred about 6,300 years ago, following the largest eruption known in the history of the volcano, and later lavas have only partly filled in this caldera. The eruption 6,300 years ago was so large that substantial amounts of fall material fell on the North Island, and large pyroclastic flows entered the sea, building up fans that (temporarily) roughly doubled the area of the island.

Conclusions

New Zealand's young volcanoes represent a cross section of most of the types of volcanoes documented elsewhere in the world, the only type missing being an example of a modern basaltic shield volcano such as Kilauea or Mauna Loa in Hawai'i. In two respects, New Zealand's volcanoes are world-beaters: our cone volcanoes at Ruapehu, Ngauruhoe and White Island are among the most frequently active examples known; and Taupo and Okataina are the most productive and frequently active rhyolite caldera volcanoes on Earth. The short time span for which the eruptive histories of New Zealand's volcanoes have been observed is inadequate to show the full extent of eruption.

Civil Defence, New Zealand
TEPHRA Vol 14 No 2 *October 1995*

SURVEILLANCE OF NEW ZEALAND'S VOLCANOES

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Introduction

In New Zealand's recorded history, volcanoes have claimed more lives than any other form of natural disaster. Coupled with the economic development of the country, this means that any future eruptive activity has to be watched for so that the sizes and styles of any eruptions, and their consequent threats to lives and property, can be forecasted. Studies of the deposits laid down by volcanoes are used to assess the hazards posed by past eruptive activity (both historic and prehistoric), as a guide to what might be expected in the future. Surveillance of New Zealand's volcanoes is carried out in order to provide warning of any impending eruptive activity so that appropriate steps can be taken to reduce the risk to lives and property. Surveillance has to be linked with hazards studies, as any warning of an impending eruption is not very useful unless the size and type of eruption can be estimated.

Volcanic hazards

Volcanic hazards are quite different to those posed by almost any other kind of natural or man-made phenomenon, which makes their assessment in future eruptions very challenging. Volcanologists refer to a 'volcanic crisis' as the whole realm of events concerned with the awakening of a volcano, the build-up to an eruption (or closely-spaced sequence of eruptions) and the aftermath as the environment recovers. A unique feature of volcanic crises when compared to other kinds of natural hazards is each eruption has a far wider range of possible outcomes, each in turn with a characteristic range of threats to life and property. Volcanic crises have several major differences when compared to other regional or national natural disasters (Table 1).

TABLE 1: Comparison of volcanic crises with selected other natural hazards.

	Volcanic Activity	Earthquakes	Flooding
Duration of hazards	days to decades	seconds to minutes	hours to weeks
Areas affected	local to national	local to regional	local to regional
Warning time	days to months	none	hours
Predictable?	to some extent	no	no

The onset of large volcanic eruptions are predictable, because earthquakes, ground deformation and unusual outputs of volcanic gases can all be used to infer that an eruption is imminent, and thus some degree of site-specific planning or mitigation is possible. However, once an eruption has started, then significant hazards can be present for much longer period than with any other natural event, and threats may be posed for even decades after the onset of the eruption.

TABLE 2: Summary of the effects and extent of the main volcanic hazards

Hazard	Threat to life	Threat to property	Areas affected
Ash and pumice fall	generally low, except close to vent	variable, depends on thickness	local to regional
Ash and pumice currents	extremely high	extremely high	local to regional
Lava flows	low	extremely high	local
Lahars/flooding	moderate	high	local to regional
Gases/acid rain	low	moderate	local to regional

The major types of volcanic hazard are listed in Table 2. The scale of the hazard and the likelihood of it happening are inversely related; small events are very likely within the lifetime of anyone reading this article, while the probability of a major eruption is much lower. Volcanism on a small scale is likely to cause disruption over an area the size of a district every few years to decades (for example, Ngauruhoe 1949, 1954, 1974-75). In turn, events which will cause disruption and damage on a regional scale might be expected once every few decades (e.g. Ruapehu 1945). Some larger events which would adversely affect the entire national economy only occur every few centuries to thousands of years (for example, Tarawera 700 years ago, Taupo 1,800 years ago).

Another aspect of volcanic, as opposed to many other natural hazards, is that eruptions leave behind substantial quantities of material (for example, 2 km3 in the case of Tarawera 1886). This material accumulates to depths of several metres, with serious implications for the post-eruptive recovery of affected areas.

In any given area, the nature of volcanic hazards will vary with:

- the size of the eruption (which cannot be pre-determined, except within broad limits);
- the eruption type or style (for example, lava flow, fire-fountaining, steam explosions) which can vary both in time and scale;
- the distance from the volcano; and
- proximity to any waterway draining the volcanic area, that might act as a pathway for flooding or lahars.

Volcanic Surveillance

Volcanic surveillance is based on the assumption that movement of molten rock or magma beneath a volcano will occur before any large eruption can start. Volcanologists primarily use three kinds of techniques to detect magma and monitor its movements.

- Monitoring of volcanic earthquakes.
  Any movement of the magma requires it to push its way past the rocks of the earth's crust. This causes cracking of rock, and movement along faults, resulting in earthquakes that can be detected at the earth's surface.

- Monitoring of ground deformation.
  As the magma approaches the surface of the earth, and moves into the conduit below the vent of a volcano, the pushing aside of the surrounding rocks to make way for the magma causes the ground surface to move and the volcano to swell. This rising or swelling can then be used to assess the depth of the magma body and often give some idea of its volume.

- Monitoring of the chemistry of volcanic gases and crater lakes.
  Magma deep in the earth contains gases dissolved in it. As the magma rises to shallow levels, these gases are released and, because they are so mobile when compared to the sluggish liquid magma, they rise to the surface and are discharged through gas vents as fumaroles. The temperatures and absolute amounts of the gases and for the relative proportions of different gases give information on the state of the magma and how close to the surface it is. In some cases,notably Ruapehu, these gases emerge under a lake, and the chemistry of the lake water is then used to work out how much volcanic gas is being released into it.

The rationale for doing surveillance work at as many of New Zealand's volcanoes as possible is the need to know what is normal, that is, the 'background' levels of seismicity, ground movement and gas flux at the volcano. In addition, to be of any real use in planning for a future volcanic eruption, this surveillance has to be done essentially in 'real-time', that is, analysed and interpreted immediately and automatically.

History of Surveillance

Although Mt Tarawera had claimed more than 108 lives in 1886, Waimangu 4 in 1903 and 2 more in 1917, and a further 10? died at White Island in 1914, no formal volcanology group was established in New Zealand until the late James Healy was appointed Government Volcanologist in 1947. This surveillance continues now under the mantle of the Institute of Geological and Nuclear Sciences (GNS). Surveillance of New Zealand's volcanoes first began 50 years ago at Ruapehu during the 1945 eruption, which has proved to be the largest and most damaging

eruption in New Zealand so far this century. However, recognition of the need for a more detailed and coordinated approach to surveillance was brought about by the tragic events of 1953 when the rail bridge at Tangiwai was destroyed by a lahar from the re-formed Ruapehu Crater Lake and 151 lives were lost when the Wellington to Auckland express plunged into the Whangaehu River. Regular surveys of the Crater Lake area were initiated after this disaster. The first seismometer was installed in 1952, to record earthquakes beneath the Tongariro Volcanic Centre, and the Chateau Observatory was established at Whakapapa Village in 1954 to observe ongoing lava eruptions at nearby Ngauruhoe. Slowly over the past three decades monitoring has been expanded to cover the Taupo and Okataina (Tarawera) volcanic centres, White Island, Egmont, Auckland and the Kermadecs (Raoul Island).
Further eruptions at Ruapehu in 1969 and 1975 both produced moderate lahars, causing damage to the Whakapapa ski field. Fortunately these occurred at night and no lives were lost. Owing to the obvious risk that exists on the mountain, the then Department of Scientific and Industrial Research (DSIR) developed the Ruapehu Lahar Warning System which was commissioned in 1984. It is designed to detect eruptions that are likely to produce lahars and provide a warning to those in paths of potential lahars on the northern slopes of the volcano.

Geodetic monitoring commenced at White Island in 1967 and 1970 at Ruapehu with other centres following. New Zealand's first fully integrated volcano-seismic network including a computerised automatic location system, with the capability to locate earthquakes essentially as they happen, was completed for Bay of Plenty/White Island in 1992. Similar systems are now operating for Taupo, Tongariro National Park and Egmont. A volcano-seismic network is currently being developed in Auckland.

Volcano Surveillance Today

Two scales of monitoring are required for active volcanoes.

The first is background monitoring between crises using a limited number of fixed instruments or sampling points. The key here is to strike a balance between cost and the need for accurate and reliable data. GNS currently spends $620 000 per annum on volcanic surveillance.

The second scale is the monitoring during a crisis. This requires a much greater deployment of monitoring equipment and personnel, but for a finite time.

Monitoring of volcanic earthquakes

Background monitoring

Earthquakes commonly provide the first indication of volcanic unrest. Today there are five volcano-seismic networks in operation around New Zealand's volcanoes.

Three are operated by GNS in the Taupo Volcanic Zone. The Taranaki and Auckland networks are operated by their respective regional councils in conjunction with GNS and the University of

Auckland. Raoul Island, New Zealand's most northern and one of the most active volcanoes, has one seismograph on it. Four of these networks have dedicated computer-based automatic location systems attached to them. These take data directly from the digital seismic recorders, process it and print a result about 50-60 seconds after an earthquake occurs. Computer-based analysis systems have also been developed by GNS to look at volcanic tremor signals from the volcanoes. They are installed at Chateau Observatory and Wairakei Research Centre.

Crisis response

The networks installed to provide the background data also have some capabilities to record seismic activity associated with eruptive activity. However, there are trade-offs between the requirements to acquire background data and those needed for crisis assessment. Once a volcanic crisis is identified GNS would look to supplementing the already installed base with additional equipment. Most of this equipment would be portable digital seismometers.

Monitoring of ground deformation

Background monitoring

Geodetic measurements are used to monitor changes in the shape of the ground-surface caused by the movement of magma within a volcano. Techniques used by GNS include measuring distances with electric distance measuring equipment (EDM), while ground tilting measurements are made by precise levelling and using some of the volcanic lakes as large scale natural spirit levels. Lake levelling is conducted in one of the lakes on Raoul Island, and at lakes Tarawera, Rotorua and Taupo. At White Island a precise levelling network was established in 1966 on the floor of Main Crater to measure changes in crater height.

More recently detailed horizontal control surveys have been repeated across the Taupo Fault Belt, both north of Taupo and south of Rotorua, using traditional triangulation and trilateration techniques, and since 1991 we have used global positioning systems (GPS) technology. Regular surveys of the Ruapehu Crater Lake geodetic network are carried out to ascertain the diameter of the crater containing the lake.

Crisis response

Following the identification of a crisis situation, the existing ground deformation systems would be intensified. This would involve both the frequency of surveys and the style. If a robust survey network already existed, GNS would just increase the frequency of surveys. If the network was weak, additional sites would be established to enhance it. Unfortunately, ground deformation surveying often involves people working close to the active vents. However, as the rates of deformation increase it becomes possible to use remotely operated equipment, hence reducing the hazards to the survey team.

Monitoring the chemistry of volcanic gases and crater lakes

Background monitoring

Changes in volcanic gas chemistry, the rate of gas emissions (for example, SO2) from craters and the chemistry of crater lake and thermal spring waters are used to detect changes in the behaviour of the volcanoes and their associated geothermal systems. Geochemical surveys include sampling of volcanic gases from selected fumaroles at White Island; fumaroles on Mount Tarawera (Okataina Volcanic Centre); Red Crater, Central Crater, and Ketetahi on Mount Tongariro; and the summit crater of Ngauruhoe. During regular visits to Ruapehu's Crater Lake samples of water are collected (Fig. 3). More recently GNS has purchased a correlation spectrometer (COSPEC) to enable it to monitor accurately the gas emitted from New Zealand's volcanoes. Changes in groundwater, lake levels, rates of stream flow and the temperatures of such waters often give evidence of unrest within a volcano. Crater lakes in particular are valuable indicators of the status of volcanic systems. At Raoul Island weekly measurements of the levels and temperature of Blue and Green lakes are taken along with regular ground temperature measurements and water sampling. The water level of Green Lake rose more than six metres before the 1964 eruption started. Within the Okataina Volcanic Centre, heat flow from the large crater lakes at Waimangu has been continually monitored since 1970 by recording the temperature, level and rate of discharge of the lakes. A satellite based monitoring system (ARGOS) which is linked to a computer database in France has been used to monitor the temperature of Ruapehu's Crater Lake. Unfortunately, eruptions in June 1995 destroyed this installation. At White Island, magnetic and gravity measurements are made by staff of the Geology Department, Victoria University of Wellington in conjunction with regular GNS visits.

Crisis response

As a volcanic system approaches a major eruption the volumes and sometimes types of gases being discharged will change. Regular COSPEC monitoring becomes a key tool in predicting the onset of dangerous activity. Unfortunately, volcanic gases are usually only given off in close proximity to active areas that are likely to be destroyed by eruptive events. Because crater gas emanations present difficulties of either access or maintenance of equipment due to corrosion by acid gases, attention has been recently devoted to soil gas from the flanks of active volcanoes and to groundwater that circulates inside the volcanic edifice and come into contact with the magmatic fluids.

Scientific Alerts

As part of the National Civil Defence Plan 1994, the GNS volcanology programme is responsible for monitoring and assessing the state of New Zealand's volcanoes and issuing scientific alerts. The scientific alerts range through six levels (Table 3).

Table 3: Scientific Alert Levels

Scientific Alert Level	Phenomena Observed	Scientific Interpretation (Volcano Status)
0	Typical background surface activity; seismicity, deformation and heat flow at low levels.	Usual dormant, intra-eruption or quiescent state.
1	Departure from typical background surface activity.Apparent seismic, geodetic thermal or other unrest indicators	Minor phreatic activity. Signs of volcano unrest. No significant eruption threat.
2	Increase from low level of eruptive activity accompanied by changes to monitored indicators. Increase in seismicity, deformation, heat flow and/or other unrest indicators.	Significant change in level or style of ongoing eruptive activity. Indications of intrusive processes. Local eruption threat.
3	Increased vigour of ongoing activity and monitored indicators. Commencement of minor eruptions at reawakened vent(s). Relatively high and increasing trends shown by unrest indicators.	Significant local eruption in progress. Increasing intrusive trends indicate real possibility of hazardous eruptions.
4	Significant change to ongoing activity and monitored indicators. Establishment of magmatic activity at reawakening vent(s), with acceleration of unrest indicators.	Hazardous local eruption in progress. Large scale eruption now appears imminent.
5	Hazardous large volcanic eruption in progress.	Destruction within the Permanent Danger (red) Zone. Significant risk over wider areas.

Note:
The frequently active cone volcanoes (White Island, Ngauruhoe, Ruapehu) require definitions different from all other volcano systems, hence the subdivisions of Stages 1, 2, 3 and 4. The upper portion relates to the frequently active volcanoes, while the lower to the other systems (Auckland, Taranaki, Taupo, Okataina etc).

Once GNS recognises a 'volcanic crisis' exists, it issues a scientific alert (that is, defines the status of the volcano), and this information goes to the Ministry of Civil Defence and the affected regional councils. At this stage the affected authorities (regional and district councils) will initiate responses according to their respective volcano contingency plans. In some areas (for example, Auckland and Taranaki) scientific advisory groups have been established to assist authorities in interpreting the consequences of changing alert levels. Unfortunately, very few regional or district councils have formulated operative contingency plans to date.

Dissemination of Information

In intervals between volcanic crises, 'Immediate Reports' are issued by GNS following routine surveillance visits to volcanic centres. The reports are distributed to other scientists, civil defence organisations, the Department of Conservation (DoC), police and various international groups. Data presented in these reports, along with more detailed studies are presented annually in the New Zealand Volcanological Record, which summarises the results of volcano surveillance in New Zealand.

The New Zealand Volcano Database, maintained by the volcanology programme of GNS, has 'national importance' status from the Foundation for Research Science and Technology. This database was initiated in 1945 and provides the authoritative, quantitative basis for GNS advice to civil authorities and the general public.

Details of volcanic hazards at specific volcanoes are addressed in the Civil Defence "Yellow Book" series. The aim of the series is to publish the facts about particular volcanoes into a concise and readable form in order to raise awareness of volcanic hazards. To date, volumes have been published about White Island, Egmont, Mayor Island, Okataina Volcanic Centre, Auckland, and the Kermadecs and submarine volcanoes.

Results of long term detailed volcanological investigations are published by university and GNS scientists in both local and international scientific journals. These published works can include summaries of volcanic eruptions, eruption histories and hazard analyses.

Looking to the Future

The 1990s have been designated by the United Nations as the International Decade for Natural Disaster Reduction. Around the world there is increasing recognition of how poorly understood many volcanoes are, and increasing realization of the amount of devastation a large volcanic eruption can cause, often for time periods of years to even decades (for example, Rabaul in Papua New Guinea; and Pinatubo in the Philippines). New Zealand is better placed than most other countries to minimise the problems associated with volcanism because of:

- the huge amount of work that has been and is continuing to be put into understanding the histories of New Zealand's volcanoes;
- the broad recognition of volcanic hazards by scientists, civil defence, and the public;
- the unified national approach to civil emergencies; and
- the extensive and comprehensive surveillance programme that is in place

The keys to minimising economic and social losses from future volcanic activity lies in the continued research of volcanic processes to enhance our knowledge so that realistic volcano hazard assessments can be made, and ultimately successful eruption predictions. Our scientists also face the challenge of communicating the scientific results in a way that can be used by communities which face volcanic hazards.

Civil Defence, New Zealand
TEPHRA Vol 14 No 2 *October 1995*

THE POTENTIAL VOLCANIC THREAT AT RUAPEHU

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The threat from future volcanic activity at Ruapehu to lives and infrastructure is highlighted this year with the 50th anniversary of Ruapehu's 1945 eruptions, the largest in New Zealand this century. But why is it that we treat this threat so seriously? There are other volcanoes of this type in New Zealand, but none are ranked so highly dangerous from a civil defence standpoint. There are at least four reasons for this.

First, Ruapehu is an active volcano, which has periodically erupted in most years since 1969. Many have been minor steam eruptions that have splashed water and mud to a few hundred metres around the lake. Others have been major ash eruptions with the ejection of lake waters into the Mangaturuturu, Whakapapa and Whangaehu catchments creating substantial lahars. Were it not for these latter events occurring at night there would have almost certainly been some loss of life.

Second, Ruapehu has a crater lake, containing 7 million cubic metres of acid water at 2,540 m altitude (Fig. 1) ready to accelerate downhill whenever the barrier enclosing it should rupture.

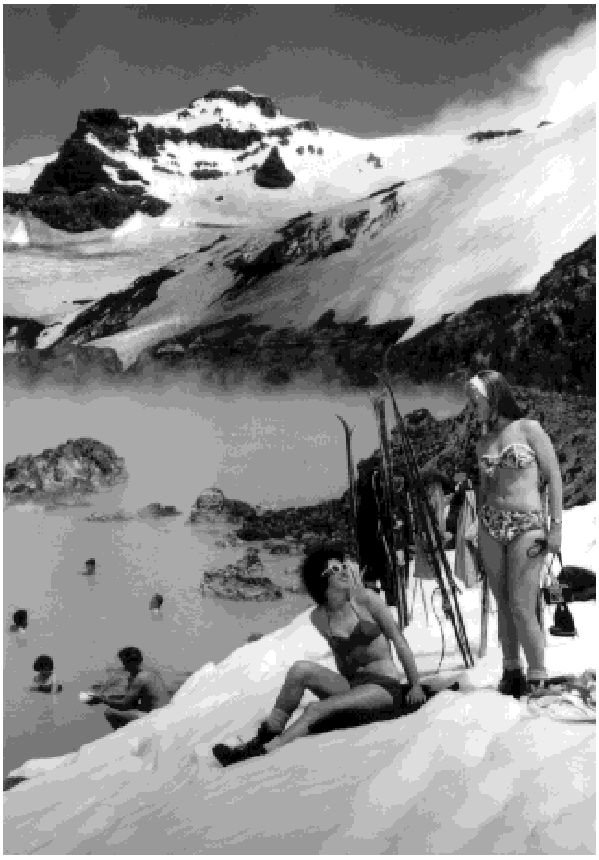


Figure1
Contrary to popular belief in the 1960s, the waters of Crater Lake are now sufficiently acid to attack skin, let alone bikinis! Photo: National Archives

The second largest volcanic disaster in New Zealand was associated with such an event when on 24 December 1953 the barrier partially collapsed allowing a surge of water down the Whangaehu River catchment. On reaching the Rangipo Desert the waters fanned out entraining sediment before re-amalgamating in the southward-flowing main channel of the river that parallels the Desert Road. The released water had now formed a lahar which reached Tangiwai just before the Wellington #173;Auckland railway express was about to cross the railway bridge. The weight of the engine combined with the force of the lahar on the bridge piers led to the bridge collapsing as the train plunged into the muddy lahar below. New Zealand's worst railway disaster claimed 151 lives. Later lahars in 1969 and 1975 (Fig. 2) serve as timely reminders of the potential risk from such hazards at Ruapehu.

The Staircase Kiosk at Whakapapa skifield was structurally damaged by the June1969 lahar and was later removed. Note how the rear wall was stoved in, part of the roof collapsed and later portions of the lahar washed up onto the fallen roof.
Photo by V.E. Neall

Third, Ruapehu has a long history of volcanic activity extending back over the last 240,000 years and most of the eruptions occurred from the same general summit area of the massif. This implies that for the next century future eruptions are likely to emanate from the same general area rather than from a totally new volcano nearby. It also suggests that volcanic activity is likely to continue at frequent intervals as it has been doing for thousands of years. Our job is to record, date and map the deposits of these past volcanic events and by interpreting their mode of origin, plot the past distribution and frequency of each volcanic hazard. This can then form the basis of assessing volcanic risk to visitors, residents and property in areas affected by these hazards in the geological past.

Fourth, Ruapehu has become the mecca for North Island skiing as well as a major tourist destination with arterial railway, air, road and electricity routes close by. Should another major eruption occur, there is considerable potential for loss of life and disruption to these major services.

So what could realistically happen at Ruapehu in any future eruption?

An important point to consider in answer to this question is the past volcanic behaviour of Ruapehu. If we consider the number of larger-sized eruptions (technically named plinian and sub-plinian eruptions), as recognised by their pumiceous tephra beds on the adjoining ring plain, then four distinct periods can be identified (Fig. 3).

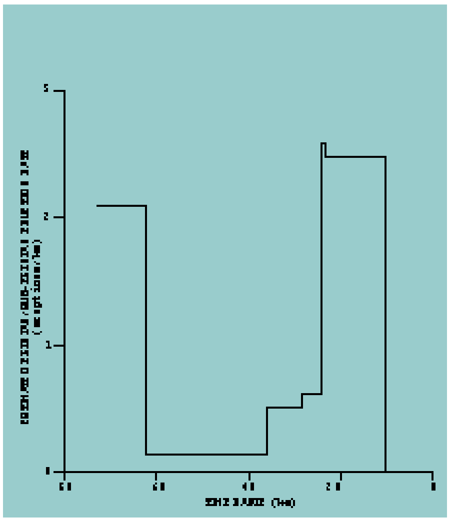


Figure 3.

Estimated eruption rate of plinian/sub-plinian eruptions over the last 75,000 years at Ruapehu. ka = thousands of years.

Expressed as a rate per 1,000 years, these eruption styles were high prior to 65,000 years ago, and between 25,000 and 10,000 years ago. In contrast, between 65,000 and 35,000 years ago the plinian / sub-plinian eruption rate was low and since 10,000 years ago it has been zero. This is surprising when one considers how active Ruapehu is today, but it can be explained by Ruapehu now being in a different stage and style of activity.

Since at least 2,000 years ago, hydrovolcanic (combined magma-steam) eruptions through the crater lake have resulted in non-pumiceous grey- or black-coloured ashes being frequently locally distributed, with the expulsion of lake waters forming lahars; quite different to the period immediately prior to 10,000 years ago. Were this eruptive style to suddenly change, the risk from a different set of volcanic hazards would increase.

There are two great threats.

First, hydrovolcanic eruptions, which are rapidly expanding steam explosions that surge radially outwards from the crater lake, destroying all in their path (Fig. 4). Fortunately, in historical time these have been localised to within one kilometre of the lakeshore.

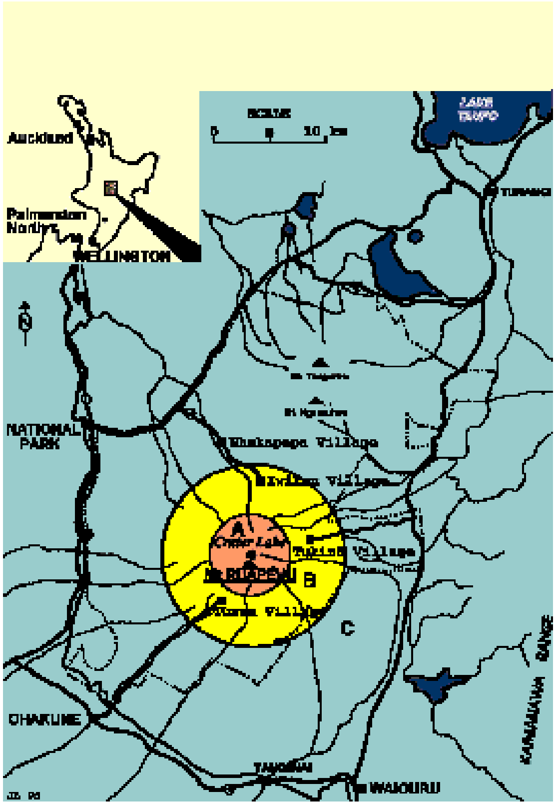
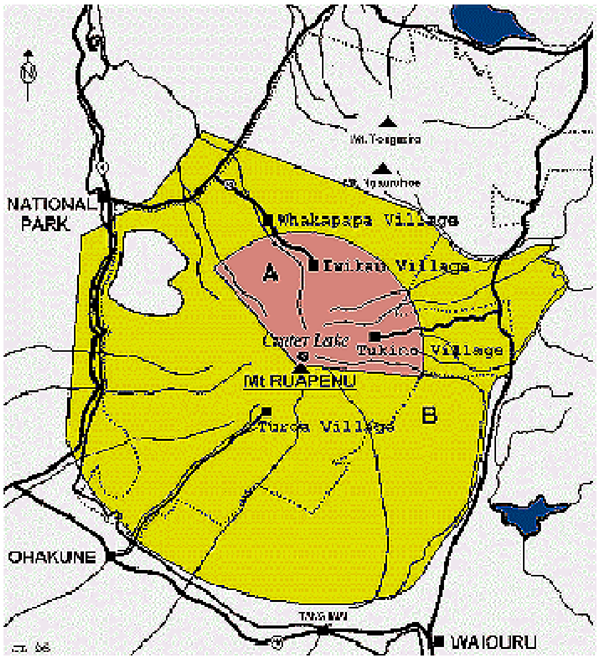


Figure 4.

Zones of risk associated with hydrovolcanic eruptions through Crater Lake at Ruapehu, for eruptions with return periods of: (red) 1-3 years; (yellow) 10-30 years; and (blue) up to 100 years (source: Houghton et al. 1987).

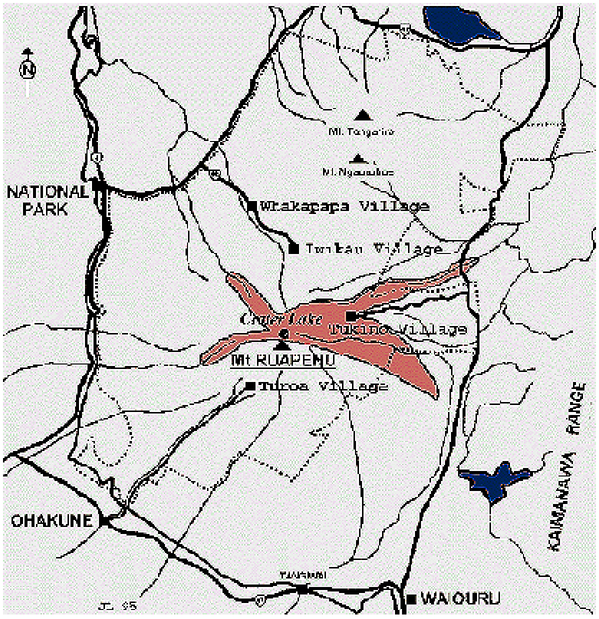
The second threat is the sudden ejection of lake waters into catchments draining the summit area. These waters incorporate boulders and sand as they descend the mountain to bulk up into lahars with considerable potential to remove road and rail bridges in their channels (Fig. 5).



Areas of highest risk from lahars (red), based on distribution of <10,000 year old lahar deposits at Ruapehu.

Since 1860 there have been 18 lahars generated in the Whangaehu catchment, on average one every seven years. The biggest historical lahar was in 1861 when an estimated six million m3 descended. In contrast, the 1975 lahar was an estimated 1.8 million m3 and for comparison, occupied about one third of the cross-sectional area beneath the present Colliers Bridge. Yet on the western approaches to the bridge are deposits of four prehistoric lahars (younger than the Taupo Pumice 1,800 years ago) clearly greater in size than the 1861 event, at a point 84 km downstream from source.

Of moderate threat is the extrusion of lava flows from the crater. All lava flows less than 10,000 years old occur in the northwest to east sector within 10 km from source (Fig. 6).



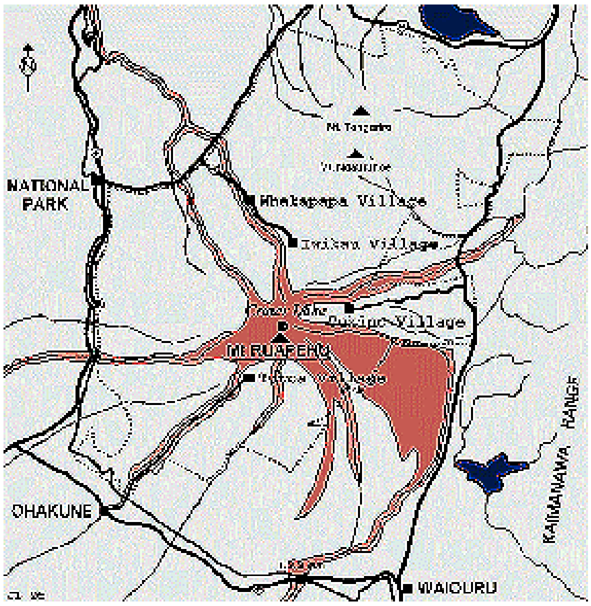
Areas of high risk (red) and moderate to low risk (yellow) from lava flows, based on distribution of <10,000 year old and >10,000 year old lavas at Ruapehu.

Older lavas extend up to 20 km distance near Ohakune, Tangiwai and across the Desert Road. Being in a national park there is not an immediate danger from such flows, but should these be voluminous or should they burst from a satellite vent on the flanks of the volcano, there is the potential for them to destroy ski field equipment and huts. Probably of greatest concern would be the likelihood of hot lava melting snow and ice to generate further lahars.

Should the mountain shift back into a plinian / sub-plinian eruptive episode there would be a considerably greater hazard from thicker and more widely distributed pumice tephra. Depending upon the wind direction at the time (usually westerly), pumice lapilli falling to the ground would likely close the ski fields on the mountain; close the Desert Road; severely disrupt the electricity supply along the same route; pose numerous problems for the Tongariro Power Scheme intakes, tunnels and equipment; disrupt the New Zealand Army's activities and equipment based at Waiouru; and ruin the trout fishing in the region thus impacting on our tourist visitor numbers. Should the wind direction change to the north, tephra fall could destroy much of the market gardening produce in the Ohakune-Raetihi district and render the main Auckland-Wellington Main Trunk Railway impassable. This would have a major detrimental economic and social impact on the local communities, as well as impacting on our national infrastructure.

Of infrequent occurrence, but also hazardous is new evidence for pumiceous pyroclastic flows from Ruapehu during some plinian / sub-plinian eruptions (Fig. 7).

Areas of highest risk (red) from pyroclastic flows based on distribution of <10,000 year old pyroclastic flow deposits at Ruapehu.



Not only do these events destroy all life and property in their path, but they also are renowned on high snow-covered peaks such as Ruapehu, for melting large volumes of snow and ice to form large accompanying lahars. The last time this happened on Ruapehu was about 9,000 years ago at the end of its particularly active series of pumice eruptions throughout the Last Glacial Maximum (between 25,000 and 10,000 years ago).

Also of infrequent occurrence are major rock landslides and avalanches caused by collapse of weak sections of the volcanic edifice. At least two of these have been identified in the last 10,000 years at Ruapehu, directed to the northwest and the east, both caused by sector collapse of the upper parts of the volcanic cone. Hydrothermal alteration of the source rocks to clays may have contributed to these collapses. The trigger for such events may include earthquakes or magma intrusion.

Where to from here?

There are two critical advances that we can take to being prepared for the next hazardous eruption of Ruapehu.

The first is to gather as much information as is possible about Ruapehu's past volcanic history so that we can understand what are the events and hazards likely to ensue when Ruapehu next erupts. Mapping the deposits associated with such volcanic events and interpreting their emplacement mechanisms allows us to reconstruct the past extent and frequency of volcanic hazards from Ruapehu. Since most of the summit region is mantled in snow and glaciers, is steep, highly eroded and is capped by young lava flows, this hazard record is only preserved in the many streams and rivers on the surrounding volcanic ring plain. This is where our studies have been concentrated to reconstruct Ruapehu's prehistoric volcanic record. Within the next six months we hope to complete a 1:50 000 map of Ruapehu catchments showing the former distribution of lahars and an interpretative lahar hazard map for civil defence purposes.

The second advance is to continuously monitor the volcano for any advanced signs of impending eruption. Volcanic monitoring at Ruapehu is conducted by the Institute of Geological and Nuclear Sciences (GNS) who constantly record earthquake activity, monitor lake temperature and acoustic sounds when the lake is quiet, and periodically survey the summit for deformation and gather samples for lake water chemistry. By monitoring the volcano, it is hoped that we will be able to gather the earliest warning signs of magma making its way towards the surface. In the event of such a sign, the lahar warning scheme in the ski fields is designed to warn skiers immediately and give them sufficient time to move to the protection of nearby ridges away from potential lahar paths.

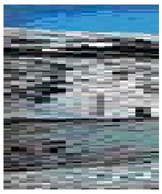
Volcanoes have a certain fascination to all of us. We may be overawed by the immense powe and visual spectacle created by eruptions that we can watch on television and film, yet seldom see in reality. Their products form the basis of the highest food-producing soils in the world. Yet their myriad of eruptive styles can form the most frightening and hazardous events on our planet, leaving behind a swath of destruction and human misery. Ask anyone who survived Mt Pinatubo about their impressions of what happened and there is usually a tragic tale to tell. Hopefully, New Zealand's efforts to understand and predict volcanic hazards will keep our losses to a minimum.

Civil Defence, New Zealand
TEPHRA Vol 14 No 2 *October 1995*

LIVING WITH VOLCANOES

David Johnston (Department of Soil Science ,Massey University) and Bruce F. Houghton (Institute of Geological and Nuclear Sciences, Wairakei Centre)

Introduction



The North Island of New Zealand contains a number of active and potentially active volcanoes. Although the probability of a damaging eruption affecting a significant portion of the North Island is relatively low in any one year, the probability of one occurring in the future is high.

The potential impacts of a large eruption are significant and the risk cannot be ignored. The timing of the next eruption of a volcano cannot yet be determined but its probable effects can reasonably be assessed. Recent eruptions overseas, such as Mount Unzen from 1991-1995, Mount Pinatubo in 1991, and Rabaul in 1994, have demonstrated the devastating impact of volcanic activity on nearby landscapes and communities. Volcanic crises need to be planned for using a comprehensive emergency management approach, linking mitigation, preparedness, education, response and recovery.

Impacts of Volcanic Hazards

Typically, a number of types of hazards will result from a volcanic eruption. Each hazard poses different risks affecting different areas. This is the key difference between eruptions and the other principal natural hazards, floods and earthquakes. The most threatening hazards include pyroclastic falls, pyroclastic flows and surges, lava extrusions (flows and domes), lahars, debris avalanches and volcanic gases.

Pyroclastic falls

Pyroclastic fall deposits consist of material which rains out from an eruption column (Fig. 2).

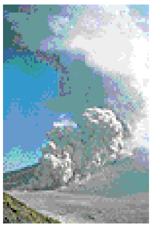


Figure 2
Contrast between pyroclastic fall and pyroclastic flow mechanisms, operating simultaneously at Mt St Helens in 1980. The fall deposits are associated with the high eruption column at the right of the photograph, while the denser billows of ash and gas to the left are part of the ground-hugging pyroclastic flow.
Photo: U.S. Geological Survey.

Large fragments (blocks and bombs) follow ballistic trajectories and are highly damaging. These fragments rarely land more than two kilometres from the vent. Finer material (ash and lapilli) is convected upwards in the eruption column before settling out downwind to form pyroclastic fall deposits. Fine ash can be deposited hundreds to thousands of kilometres from its source, and volcanic ash is the product most likely to affect the largest area and the most people during an eruption. These particles commonly have sharp broken edges and volcanic ash is therefore highly abrasive. Volcanic ash clouds will block out sunlight and total darkness may result where moderate to heavy falls of ash occur.

The impact of ash falls on people, structures and equipment depends largely on its thickness (Fig. 3). Pyroclastic falls will not initially result in fatalities unless the fall is extremely heavy. Falling ash is not toxic but will act as an irritant affecting eyes and throats. Deaths and injuries are more likely to result from secondary effects such as roof or veranda collapse, falling branches, or traffic accidents.

Figure 3(a)
World Airways DC-10 aircraft at Manilla airport, settled on its tail due to the weight of the ash erupted from Pinatubo.
Photo by Roger, US Navy.

A community's infrastructure provides the services and linkages which allow society to function. These 'lifelines', such as electricity, water, sewerage and roads are vulnerable to damage from ash falls. Falls of volcanic ash, for example, have the potential to disrupt electricity supply. Loss of supply commonly occurs when ash is wet, as a result of rain during or immediately after the ash fall.

Figure 3(b)
Ash from Pinatubo covering vehicles at Clark Air Force Base
Photo by RP Hoblitt, US Geological Survey.

Contamination of open water supplies occurs, even in relatively small ash falls. Both turbidity (suspended material) and acidity are the most common problems affecting water supplies but they will usually return to normal levels within a few hours or days unless ash falls are prolonged. Hazardous chemicals from ash can mix with small volumes of water such as roof-fed water tanks, stock water troughs and shallow surface water bodies, causing chemical contamination above safe guidelines for drinking water. Volcanic ash falls can cause severe damage to sewage and stormwater systems. Ash is easily washed off impervious surfaces, such as roads, carparks and buildings, into these systems.

Volcanic ash falling on roads is extremely disruptive to transportation, reducing visibility. The ash is easily raised in clouds by passing vehicles and this presents an ongoing visibility hazard. Wet ash can turn into mud, causing further problems with vehicle traction. Fine ash causes clogging of air filters resulting in cars overheating. Vehicle brakes are susceptible to damage and ash may also enter the engine causing wear on moving parts, which reduces vehicle life. Even minor ash fall (<1mm) will close airports.

Ash has damaging affects on other electrical or mechanical systems.

Pyroclastic flows and surges

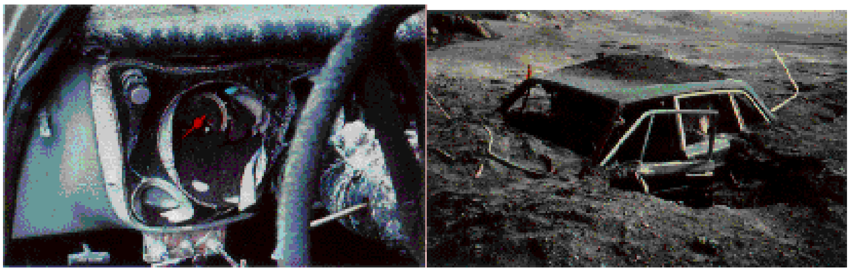


Figure 4
Views of (a) interior and (b) exterior of a car devastated by a pyroclastic flow at Mt Helens, 1980.

The collapse of all or part of an eruption column into a descending fountain of rocks and gas produces pyroclastic flows and surges (Fig. 2). Flows and surges travel across the landscape, often at speeds of more than 200 km/h and cause widespread destruction (Fig. 4). Surges are dilute, turbulent, and widespread in their effects. Flows are more concentrated and are topographically controlled. Pyroclastic flows are usually very hot (several hundred °C) and can start fires. Pyroclastic flows and surges have been produced by many eruptions from New Zealand volcanoes and represent one of the most destructive manifestations of volcanic activity.

People caught in the direct path of pyroclastic flows and surges are most unlikely to survive and any survivors will probably receive severe injuries. Buildings offer limited protection on the periphery of the flow but will not guarantee survival as they may be destroyed or severely damaged. The best protection is to evacuate the area prior to the event. Pyroclastic flows and surges will cause destruction of vegetation in their path, often removing the forest cover by uprooting and stripping foliage, branches and bark. Heat damage to plants may also occur.

Lava flows

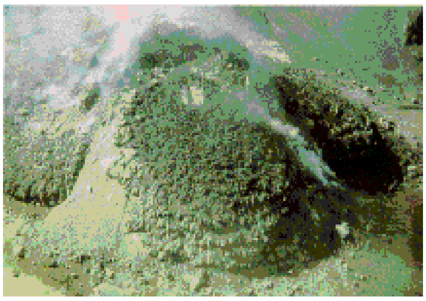


Figure 5(a) Growing dacite lava dome at Mt St Helens, September 1981. Note the contrast in shape to the more fluid lava flow in Figure 5(b).
Photo: U.S. Geological Survey.

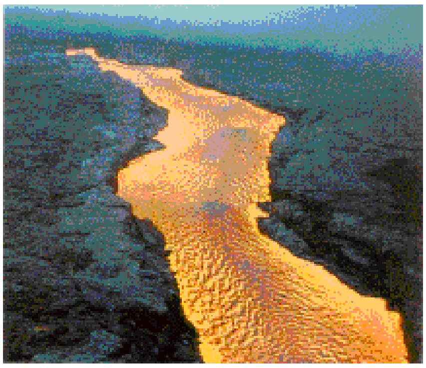


Figure 5(b)
Basaltic lava flow, Kilauea East rift, Hawaii. The moving flow is restricted to a narrow channel, but can travel for many kilometres.
Photo: U.S. Geological Survey. eruption rate, eruption volume, steepness of the slope, topography and obstructions in the flow path.

Basalt flows have low viscosity (flow easily) and have been recorded to travel more than 50 km from a volcano, although they usually only flow 5-10 km. Andesite flows are more viscous and rarely travel more than 5 km. Dacite and rhyolite lavas have high viscosity and typically form short, thick flows or domes. Lava flows will seldom threaten human life because of their slow rate of movement. An associated hazard is that the steep fronts of flows may become unstable and can collapse, causing small pyroclastic flows. Lava flows will cause total destruction of buildings, bridges and other structures in their path.

Debris avalanches

A debris avalanche is a sudden and rapid movement of rock and other material due to gravity. Flowage can be wet, dry or both. If the avalanche contains a large amount of water it may continue to flow downhill as a lahar once the larger blocks have settled out. Debris avalanches usually occur on larger, over-steepened volcanoes like Mt Egmont, and are one of the most hazardous but least common of volcanic events. Failure of a portion of a volcanic cone may result from one or more causes: intrusion of magma, earthquake shaking, gradual weakening due to hydrothermal alteration, or heavy rain which may saturate and weaken parts of the cone. Debris avalanches can travel a considerable distance from the source area, but are generally confined to one sector of the volcano.

Debris avalanches destroy everything in their path. As they can occur with little or no warning and can travel at moderate speeds, prior evacuation is the only safe option for areas where an avalanche is anticipated.

Volcanic gases

Volcanic gases consist predominately of steam (H2O), followed in abundance by carbon dioxide, chlorine and sulphur compounds. Minor amounts of carbon monoxide, fluorine and other compounds are also released. Volcanic gas emissions can be harmful within about 10 km of a volcano under certain circumstances. Acids, ammonia, and other compounds in volcanic gases can affect eyes and respiration and can corrode metals and other materials. Heavier-than-air gases such as carbon dioxide can collect in depressions and suffocate people and animals. Concentrations of gases will dilute rapidly away from a volcano and pose little threat to communities more than a few kilometres from the active vent.

Lahars

Lahars are mudflows formed by the mixing of volcanic particles and water (Fig. 6).

Figure 6

Arial view of flooding associated with the eruption of the Pinatubo volcano, 1991. Note how the village of Santa Rita de Concepcion has been isolated by flooding.

They can be generated by the collapse or overtopping of a volcanic barrier impounding a lake or river, or heavy rain washing unconsolidated volcanic material from slopes. Lahars can also form directly from pyroclastic flows or debris avalanches. The threat from lahars may last for years after the close of an eruption.

People caught in the path of a lahar have a high risk of death from severe crush injuries, drowning or asphyxiation. Lahar events will cause destruction of buildings, installations and vegetation caught in their path. Depending on their densities and flow velocities, lahars may destroy structures, or bury them. People have survived lahars by climbing onto the roofs of houses which have remained intact despite inundation by the lahar.

Coexisting with Volcanoes

Most volcanoes have long intervals between damaging eruptions, ranging from years to many centuries. The management of volcanic hazards can therefore be divided into two distinct time frames. Non-eruptive or quiescent times represent the most common situation and afford the best opportunity to develop mitigation strategies and prepare society for an eruption. A volcanic crisis is the time during which a volcano shows signs of unrest, frequently leading to an eruption. At this time public interest will be at its height but little time is available for public education and consultation.

The mitigation of all natural hazards in New Zealand is covered by the Resource Management Act (1991) which seeks to provide a structure for natural hazard management that focuses responsibilities and requires the adoption of effective means of control. Implementation of this new regime is carried out by regional and territorial authorities through regional policy statements, regional plans, district plans and resource consents. Civil defence in New Zealand operates under the Civil Defence Act (1983), its subsequent amendments and the National Civil Defence Plan. These regulations bind the Crown, local government and state-owned organisations. Regional councils and territorial authorities have a responsibility to perform a number of functions, including the preparation of civil defence plans which outline hazards, warning systems, response systems and disaster recovery matters. The adoption of an 'all hazards' Comprehensive Emergency Management (CEM) approach allows natural hazards to be incorporated into an integrated emergency management system, linking hazard mitigation, community preparedness and recovery.

Preparedness

Preparing for disasters is deemed to be the responsibility of every New Zealander. The Civil Defence Act (1983) requires all Regional Councils to prepare Regional Civil Defence Plans and establish civil defence organisations. Territorial Authorities must also undertake such actions or contract this function to Regional Councils. Volcanic hazards should be considered within an 'all-hazards' approach. The National Civil Defence Plan includes general guidelines on planning a response to a volcanic crisis. A need still exists for specific contingency plans to be developed for individual volcanoes. An example of this kind of planning is the Taranaki Regional Council's response plan for Mt Egmont.

Being aware of volcanic hazards is the key to effective preparedness. Being involved in a volcanic eruption is a frightening, alien and demoralising experience. Awareness and knowledge shorten reaction time and improve the quality of the decisions made during a crisis. There is much empirical evidence showing that hazard knowledge greatly improves risk perception, warning compliance, planning and recovery behaviour. Schools play a vital role in natural hazards education, with volcanic hazards awareness included in the science and geography curriculums. The Ministry of Civil Defence has produced a range of resource material on volcanic hazards. These include *Civil Defence Education Kits* for primary and secondary schools, information brochures and the *Volcanic Hazard Information Series* (as listed in the Bibliography on page).

Mitigation

Mitigation strategies are aimed at reducing risk.

To be effective, the risk from volcanic hazards must first be identified. Volcanic hazard analysis is based primarily on assessments of past eruptions. By studying the geological record, observing eruptions, and monitoring background levels of activity, an understanding of the likely future hazards can be gained.

Risk analysis involves assessing the risks to the population and infrastructure from specific hazards and can be undertaken at various levels. The production of hazard maps is a first step in assessing risk from active volcanoes. Hazard maps can be used to produce risk maps by combining them with social data such as population densities, locations of critical facilities (for example, schools, hospitals, transport routes and the location of infrastructure lifelines of water, sewerage and electricity systems).

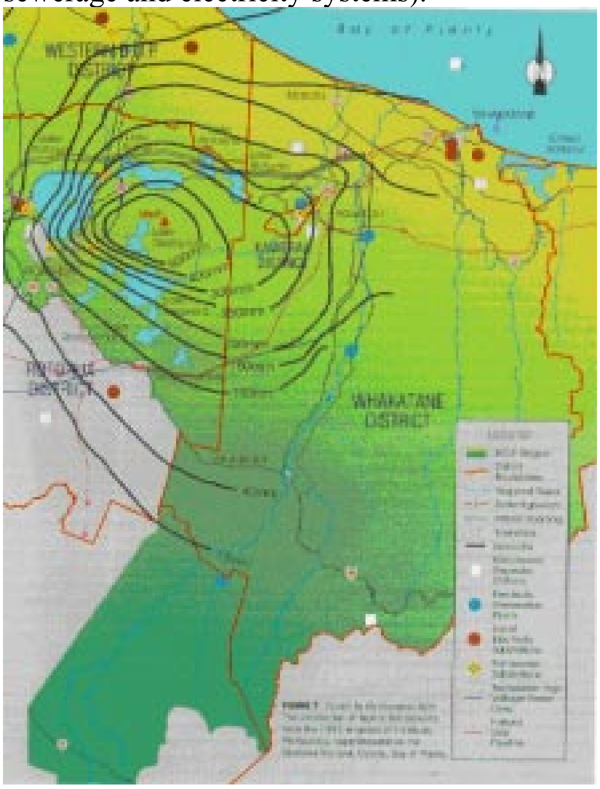


Figure 7.

Another method is the use of eruption scenarios which provide a way of illustrating the types of impacts that might realistically be expected from a volcanic eruption. Land-use planning and regulation can be employed to prevent development in high risk locations.

Physical protection against damage from thick pyroclastic falls, lahars, pyroclastic flows or surges is almost impossible and relocation is the only fail-safe protection. However, moderate to light ash falls are the most widespread effect of eruptions, and properly constructed buildings offer good protection. Windows, doors and other openings can be sealed, if possible, to prevent ash entering buildings. Steep roof lines offer the best chance of building survival.

Crisis Management

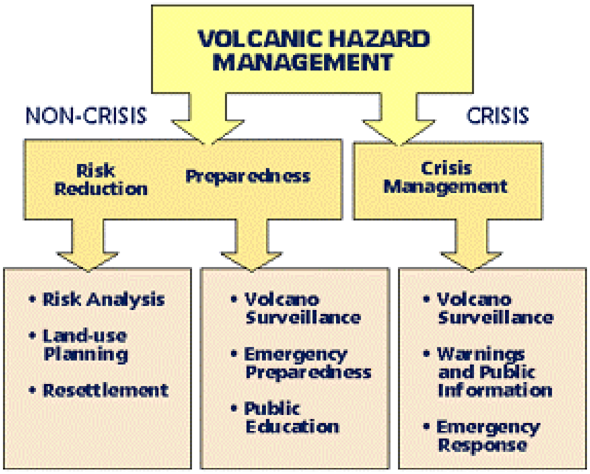


Figure 8

The distribition of tephra fall deposits from the 1991 eruption of Pinatubo, Philippines, superimposed on the Okataina Volcanic Centre, Bay of Plenty.
Picture by Environment BOP.

A volcanic crisis is the total period during which a significant risk occurs at a volcano. It may be an extended time interval, which begins when precursory activity is first observed, and extends through the eruption and often for a period of months to years afterwards. The response is highly dependent on which volcano is involved, as hazard types and levels differ between volcanoes.

In the event of volcanic activity that could threaten people and property, or could develop into such a situation, warnings need to be given.

The National Civil Defence Plan assigns the responsibility for scientific advice for government to the Institute of Geological & Nuclear Sciences (GNS). The procedure and responsibility for issuing warnings is outlined in the article by Scott et al. on page . A declaration of a state of Civil Defence Emergency will be made in the event of an incident occurring on a scale too great to be dealt with by normal emergency services. Since large volcanic eruptions have the capacity to affect large areas it is probable that a regional or national declaration would be necessary.

People living within high risk areas may need to be evacuated, and should be aware of this fact and be willing to move away if advised to. Evacuations from areas near vents must be completed before an eruption, as lahars and ash falls may effectively cut transport routes. The higher the population density, the earlier evacuation must begin in order to cope with the logistics of moving a large number of people quickly. New Zealanders' experience of large scale evacuations is minimal, and the logistical and social problems associated with such an action would be substantial.

Recovery

The time required for a community to recover from a volcanic eruption depends on the extent of the impacts and the amount of assistance available. Recovery planning can reduce this period and minimize ongoing social and economic effects. Communities receiving less than 10 cm of volcanic ash should be able to restore essential services (electricity, water, sewage and transport) within weeks of an eruption if they are not subject to additional ash falls. In areas affected by pyroclastic flows, lahars, surges, lava flows or heavy ash falls, where severe damage has occurred, recovery becomes a much greater problem. Lahars may continue to affect flood-prone communities for years following an eruption, as material is washed off the volcano.

Individuals are covered by the Earthquake Commission (EQC) and are insured against loss or damage to their homes, their personal possessions and land. Currently EQC cover limits are set at $100,000 for homes and $20,000 for personal possessions. Local authorities are responsible for dealing with the impacts to their own facilities such as roading, water and sewerage, but will receive central government assistance in severe cases. Where the magnitude of impacts are such that recovery requires central government help the Civil Defence Act (1983) allows for the appointment of a Disaster Recovery Coordinator to coordinate assistance and provide a means of communicating the needs of a community to the government.

Conclusion

A number of destructive hazards exist close to an erupting volcano and evacuation may be required to protect inhabitants from them. Ash falls are the most likely hazard to affect communities at a distance from a volcano. In most cases they will be disruptive not destructive, affecting services such as water, sewerage, electricity and transport. For volcanic hazard management strategies to be effective the hazards posed by the various volcanoes of New Zealand must be well understood. Careful prior scientific analysis will provide the vital information needed for thorough preliminary planning and minimise the unexpected. Signs of unrest must be recognised before the eruption, and additional temporary monitoring equipment must be installed. The public must be clearly, concisely and rapidly informed. Civil defence, emergency services and other relevant organisations must understand the significance of information received and identify the appropriate response.

Civil Defence, New Zealand
TEPHRA Vol 14 No 2 *October 1995*

LESSONS FROM RABAUL

Summarised Results of a Fact-Finding Visit

By E.T. Finnimore and B.S. Low from the Ministry of Civil Defence; R.J. Martin, Environment BOP; P. Karam, Taupo District Council; and Dr I.A. Nairn and B.J. Scott of the Institute of Geological & Nuclear Sciences.

Introduction

From 9 to 19 May 1995, a New Zealand fact-finding team visited Papua New Guinea. This team consisted of Ministry of Civil Defence personnel, regional and local civil defence officers, and two volcanologists from the Institute of Geological and Nuclear Sciences. The visit had two objectives. Firstly, to identify contingency planning, emergency management and response issues relating to the September 1994 volcanic eruption in Rabaul, and secondly, to examine how these would apply to New Zealand.

Team members visited areas of relevance to their individual research interests, and interviewed key people involved in the management of the emergency. This report focuses on the outcomes of this research and discusses the lessons which can be applied to civil defence, emergency management and related scientific issues in New Zealand.

Background

Rabaul, located on the north-eastern tip of New Britain Island, Papua New Guinea, is the provincial capital of East New Britain Province and lies within a vast volcanic caldera. The caldera forms a natural protected harbour for the town of Rabaul, which since its establishment in 1910, has grown around the foreshores. Volcanic eruptions have affected Rabaul in recent history. For example, the eruption of Mounts Tavurvur and Vulcan in 1937 caused serious damage and loss of life. between 1983 and 1985, an episode of intense seismicity and ground deformation occurred within the caldera. A volcanic eruption was expected but did not occur. Nevertheless, this experience led to the development of a comprehensive volcanic response plan for Rabaul.

Early in the morning of 19 September 1994, the Rabaul caldera volcanoes, Tavurvur and Vulcan, began erupting almost simultaneously, causing extensive damage within the town of Rabaul and its surrounding area. Such an eruption had been anticipated since the major episode in 1983-85. What was not anticipated, however, was the speed of its onset, signalled by 27 hours of intense seismic activity and the massive uplift of parts of the caldera floor. Warnings of the impending eruption from the Rabaul Volcanological Observatory, a volcano-aware local population, and practised emergency response procedures allowed the smooth evacuation of more than 30,000 people, in the 12 hours before the eruption. Only five fatalities were attributed to the eruption, in great contrast to the more than 500 deaths caused by the very similar eruptions in 1937.

Figure 1
Ash fall on the road to Rabaul

The 1994 Rabaul eruption provides many lessons in the prediction and management of damaging volcanic events, and offers an insight into their social, economic and environmental consequences. These lessons are relevant to the active volcanic regions of New Zealand.

The1994 Rabaul eruption is significant to New Zealand in that it occurred where substantial population centres and infrastructures have developed near active volcanic centres.

The hazard mitigation, response and recovery procedures followed at Rabaul, highlight many lessons for dealing with a major volcanic crisis in New Zealand. The procedures adopted in the Ministry of Civil Defence National Civil Defence Plan, Parts One and Three, can be evaluated against the real-life situation at Rabaul.

Lessons and Observations

The lessons learned, and observations made, from the pre-event, event and recovery phases of the Rabaul eruption are summarised below:

Pre-Event Phase

Past experiences should be scrutinised - they are essential for mitigation planning. Clear identification and public awareness of the threat is vital. Specific planning at central and local government level is needed for potentially major events. A disaster plan must cover all aspects, including land-use planning, mitigation measures and recovery. It must not focus predominantly on the response phase.

The role of emergency response managers and all emergency staff needs to be identified, and organisational responsibilities clearly defined. Procedures for the relocation of emergency control centres need to be established and tested in areas where relocation may be necessary.

Practical response drills are invaluable in ensuring the correct public actions when a crisis occurs. Commercial organisations should also be encouraged to establish contingency plans.

The Rabaul Event Phase

A unified management structure, operating under one controlling system, applied throughout. It is vital that each level of government clearly understand its respective role.

The Disaster Plan prescribed alert levels based on likely volcanic sequences over specific periods of time. In the event however, the acceleration of volcanic activity occurred so rapidly that the alert levels were overtaken by events. Alert systems must not be time-dependent. They would be better based on specific threat levels.

The provincial government's Disaster Plan had been rehearsed several times. This probably accounts for the smooth evacuation of Rabaul and the remarkably limited loss of life. The ability of the population to follow appropriate procedures during a crisis, when time is limited, highlights the importance of an active public education programme supported by timely and accurate public information. Many people found evacuation routes unexpectedly blocked or about to be blocked by ash-fall. Therefore the need to plan for 360 degree plume effects is an important factor. The Rabaul Volcanological Observatory was not available for official comment in the first 12 hours. Early media liaison would have prevented the spread of many rumours and stories without factual substance or authority. Radio stations should remain open in an emergency and be provided with accurate and up-to-date information to be broadcast to the public.

Figure 2
Ash fall on the road to Rabaul

The Recovery Phase

Post-eruption effects can continue for a long time and lead to social and other effects worse than the original eruption. These need to be taken into account in recovery planning. An agency responsible for overall recovery planning, co-ordination and implementation must be identified well before the event. Ad hoc response plans and recovery tasks can be avoided by having well-prepared recovery plans made by the individual agencies responsible for their implementation. Relief personnel and other key staff must be provided for emergency management. Recovery planning must include consideration of relief supply needs, and specify the relief agencies responsible for procuring and delivering supplies. Recovery planning must also include procedures for co-ordinating aid requirements.

An early return to clean the buildings that housed essential services, and indeed private dwellings, would have lessened the extent of damage, reduced looting, and more importantly, restored some of the key facilities, such as the telephone exchange. Where an early return was made, structural damage was limited and in some cases prevented.

It was noted that high-pitched roofs survived ash deposits, whereas the compacted layers that formed on the standard flat-roofed buildings contributed to building collapse. Site selection for telephone exchanges, hospitals and other potentially threatened key buildings is essential. Where the site is dictated by purpose, design should ensure survivability. Emergency radio communications systems should be sited away from high-risk areas, and all communications systems must have reliable back-up. Recovery planning should take into account likely post-event land-use changes.

Lessons for New Zealand

The prime lesson to be learned from our researches is the need for a National Volcanic Contingency Plan, as an extension of the National Civil Defence Plan. This plan must specify mitigation, preparation, response and recovery policies, during the pre-event, event, and post-event phases. It must also identify and allocate central and local government responsibilities in planning for and implementing those policies. A national policy on rehabilitation and resettlement of perhaps thousands of people is required, together with a national policy on financial support and insurance . Extending from the principal plan should be subordinate plans describing objectives and planning factors associated with specific volcanic threats. These would enable detailed planning to meet particular contingencies. Each volcanically threatened region has its own hazard characteristics and the effects of these on population, industry and commerce will differ from one area to another.

The plans relating to each volcanic region must contain:

- a clear description of the possible extent and magnitude of the threat;
- overall organisational responsibilities;
- established policies and responsibilities for management of the crisis;
- logistic support needs and responsibilities;
- medical and health issues;
- arrangements for public education and public information including media liaison;
- a public warning system following the protocols of the National Civil Defence Plan;
- clearly defined protocols linking scientific threat assessments to the public information and warning system.

The media must be part of the planning and response process. Liaison arrangements need to be established, including links between scientific advisors, emergency management and the media. Guidelines for the dissemination of information must be established, including the protocols for maintaining up-to-date information to public radio and TV.

Planning for each specific volcanic threat must take into account such aspects as:

- transporting, sheltering, feeding and clothing displaced people in very large numbers, as well as seeing to their health and hygiene needs;
- the need for stress counselling;
- security, law and order; and
- the need for on-going monitoring of the threat, as well as the provision of scientific advice.

Figure 3
Effects of ash fall on Rabaul

Recommendations

The consequences of the volcanic events in the Rabaul area in September 1994 highlighted many issues, not the least of which were the disruption and hardships suffered by the community. There is however one lesson that stands out: the simple fact that East New Britain province had a disaster plan. The plan had been practiced and, when the test came, it worked - as witnessed by the successful evacuation of approximately 30,000 people with minimal loss of life. It is recommended that Annex C to Part One, National Civil Defence Plan be reviewed in terms of the lessons learned and observations listed and be replaced by a National Volcanic Contingency Plan. It is also recommended that regional councils of volcanically threatened regions be charged with the production of specific volcanic contingency plans, according to the guidelines contained in the National Volcanic Contingency Plan.

Figure 4
Effects of ash fall on Rabaul.

This article is a summary of *Contingency Planning for and Emergency Management of the 1994 Rabaul Volcanic Eruption, Papua New Guinea*.
Published by the Ministry of Civil Defence, May 1995.

Civil Defence, New Zealand
TEPHRA Vol 14 No 2 *October 1995*

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