# *An investigation into recent phreatic and phreatomagmatic eruptions of Ruapehu Volcano, New Zealand: the causes and local/regional effects of the September 2007 eruption, and current and postulated mitigation strategies against future similar eruptions*

---

A Report submitted as the examined component
of the Project Module SXG390

**Rebecca Elizabeth Lesley Corlett PI:U069108X**

**Date of Submission: September 15th 2013**

**Word Count: 5310**

# Abstract

**(Word count: 298)**

## Introduction

This report comprises a literature review of the 25th September 2007 eruption of the volcano Ruapehu, New Zealand. It details the eruption causes and effects, and describes mitigation strategies against future eruptions.

This eruption was a northward-directed moderate-sized phreatic to phreatomagmatic eruption, with Volcanic Explosivity Index 1, from Ruapehu's smaller Northern vent underneath Crater Lake. It posed unexpected hazards as it occurred without warning during a period of quiescence.

## Results

Monitoring systems employed by GeoNet recorded continuous GPS, seismic and barometric data for the eruption; supporting data (e.g. gas, visual and tephra analysis) was gathered afterwards.

The eruption most likely resulted from the failure of a hydrothermal seal, which caused a vapour-static gas column (released from passively degassing magma) to interact with lake water explosively. This lack of magmatic activity meant that the earliest recorded precursor was anomalous seismic activity 10 minutes before onset.

The eruption duration was brief, lasting approximately 3-4 minutes, with 20-30 seconds explosive activity. It generated a steam column to c.2000m above the Crater Lake, launched ballistics which reached 2km north of the vent, and generated surtseyan and radial jets. Ice-slurry and snow-slurry lahars were generated in the Whangaehu and Whakapapa catchments, requiring evacuation from these areas.

Explosive activity was directed primarily northwards towards the Whakapapa ski field, with ballistics and lahars reaching the upper slopes. The ski-field is the focus of a public education campaign to improve awareness of (and response to) volcanic hazards, such as tephra and lahars.

## Conclusion

Recent improvements to the eruption detection system (EDS) may improve resolution and sensitivity, and detect anomalous activity earlier; however, this theory has not yet been tested by subsequent eruptions.

Sudden phreatic eruptions pose unusual hazards on Ruapehu, which cannot be reliably predicted with current technology. Further work is needed to improve understanding.

# Contents List

## List of abbreviations

- cGPS: Continuous GPS monitoring.
- COSPEC: Correlation Spectrometer.
- DoC: Department of Conservation (of New Zealand).
- EDS: Eruption Detection System.
- ERLAWS: Eastern Ruapehu Lahar Warning System.
- IRCCASN: Interferometry on Retrieved Cross-Correlation Function from Ambient Seismic Noise.
- MT: Magnetotelluric.
- TVZ: Taupo Volcanic Zone
- SOM: Self-organizing models.
- TVC: Tongariro Volcanic Centre
- VEI: Volcanic Explosivity Index
- VLP: Very Long Pulse
- VT: Volcano-tectonic

## Numbered list of tables

## Numbered list of figures

# Chapter 1 Introduction

## 1.1 Overview

This report is a literature review of the geohazards from the September 25th 2007 eruption of Ruapehu Volcano, New Zealand. Understanding Ruapehu's volcanic activity and hazards is crucial, because it is one of the most active mainland New Zealand volcanoes, is located close to primary road and rail routes, and contains three large ski-fields (Leonard et al., 2010).

The purpose of this report is to understand why this eruption occurred, how it affected the surrounding regions, to assess the likelihood of similar future eruptions, and explain how these risks are mitigated.

## 1.2 Objectives

1. Investigate the processes and factors involved in phreatic eruptions of Ruapehu; describe which were significant for the September 2007 eruption.
2. Investigate the timescale of events of the 2007 eruption; describe why existing warning systems did not predict the eruption.
3. Investigate the hazards posed by ice slurry lahars, explosions, and tephra fallout during and immediately after the eruption: describe their duration, their spatial scale and the effects on infrastructure and nearby populations.
4. Assess the likelihood of future sudden eruptions of Ruapehu and their severity.
5. Describe the public education and evacuation strategies to reduce the risks from eruptions and lahars in the Whakapapa ski area.
6. Describe the lahar and eruption prediction systems currently deployed and assess the potential for improvements to predict sudden explosions.

## 1.3 Scope

This report presents the findings of a literature review of sudden phreatic eruptions of Ruapehu during periods of low volcanic activity; the 2007 eruption is used as a case study.

Subaqueous phreatic (gas-driven) eruptions provide a distinct set of hazards, as they often lack useful precursors (warning signs). As such, phreatomagmatic/magmatic eruptions are out of scope (except insofar as they provide data about the volcanic structure and processes).

This report is limited to the effects on the summit area and the adjacent Whakapapa ski-field, since this contains the main population affected by phreatic eruptions. Multiple geohazards affecting this area are studied, including lahars, tephra, jets, and explosions. Hazards posed by volcanic gases and plumes are out of scope, as are lahars in the Whangaehu catchment.

Previous eruptions are included in the review where they help predict the likely scale and hazards of future similar eruptions.

Current mitigation strategies are covered, including evacuation, education and monitoring strategies. Potential improvements in instrumentation resolution and analytical techniques are assessed.

## 1.4 Methodology

Relevant literature was gathered using *One Stop Search*, *Google Scholar* and the databases *Sciverse Scopus*, *Web of Science* and *Science Direct*. Search terms included "Ruapehu 2007", "Ruapehu hazard", "Ruapehu phreat*", "Ruapehu monitoring". Searches were limited to peer-reviewed articles to improve credibility, with a focus on material with a high number of citations. Additional literature was obtained from an iterative analysis of the bibliographies.

Inclusion and exclusion criteria were based on PROMPT criteria to ensure the bulk of the literature was relevant, objective and recent.

Other supporting literature was obtained from citation alerts from key papers, and from websites of the organisations monitoring Ruapehu, including GNS Science, GeoNet and the New Zealand Department of Conservation.

# Chapter 2 Geological setting of Ruapehu volcano

## 2.1 Geographical location

Mount Ruapehu, New Zealand (as shown in Figure 2.1), is an active 250 ka andesitic volcano located within the Tongariro Volcanic Centre (TVC), part of the Taupo Volcanic Zone (TVZ), a continental back-arc region. It has an acidic crater lake, below which are the larger, central vent and a smaller, northern vent (Christenson et al., 2010).

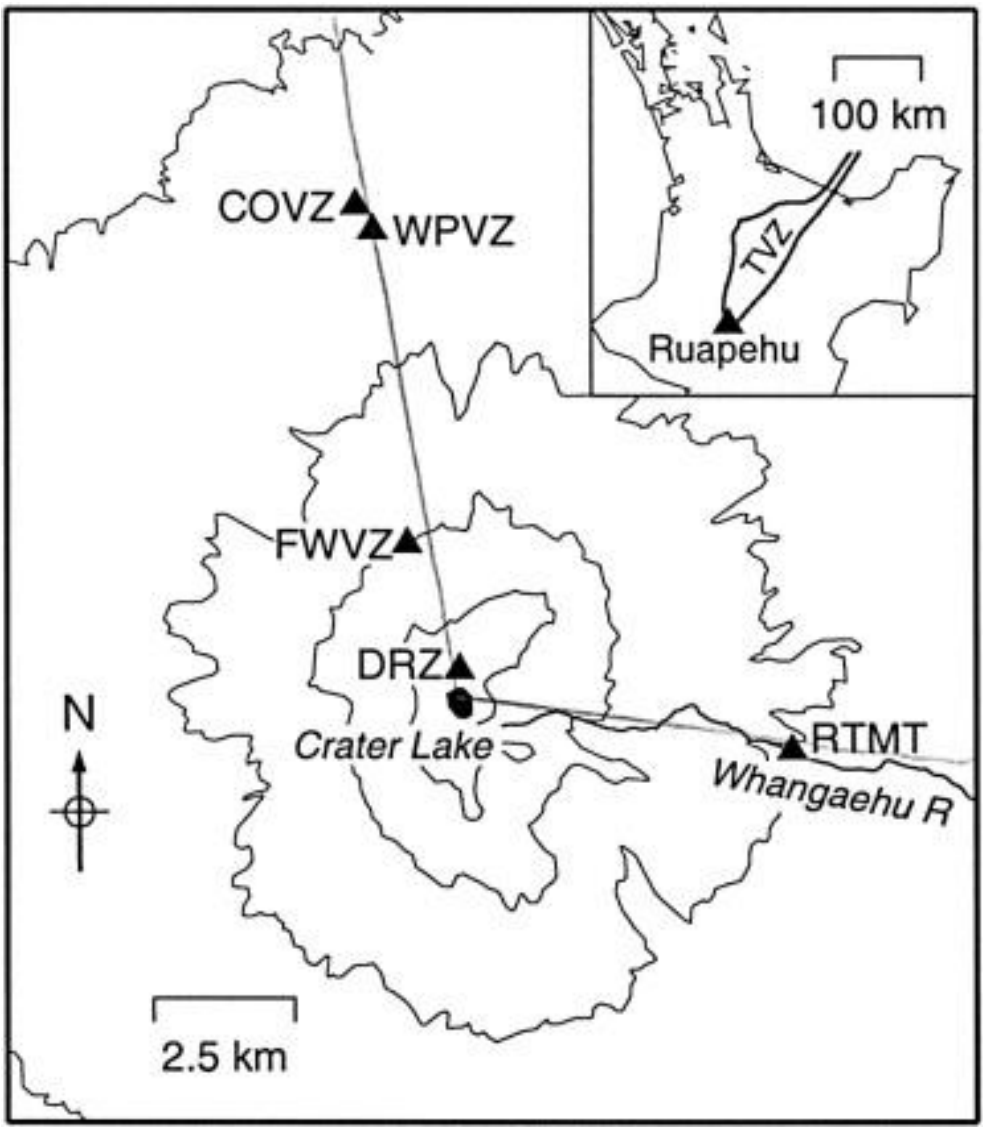


Figure 2.1 : Map showing location of Ruapehu within New Zealand.

(Taken from Jolly et al., 2010)

## 2.2 Eruption frequency

Table 2.1 summarises the frequency with which Ruapehu experiences significant (medium or larger) eruptions. The 25th September 2007 eruption was a medium-sized eruption that began as phreatic (gas-driven), then progressed to phreatomagmatic (i.e. had some magmatic involvement).

**Table 2.1: A summary of the historical frequency of moderate or larger eruptions at Ruapehu.**

**(Smithsonian Institution, 2013; Leonard et al., 2010)**

| Eruption size | Typical eruption style | Typical Volcanic Explosivity Index (VEI) | Eruption Volume ($10^5$ $m^3$) | Number of years between eruptions of this size |
|---|---|---|---|---|
| Medium | Phreatic | 1 | 1 | ~10 |
| Large | Phreatic-phreatomagmatic | 2 | 10 | 20 – 30 |
| Very Large | Phreatic-phreatomagmatic and Phreatomagmatic-magmatic | 3 | 100 | 50 – 100 |

This eruptive style has changed over time. Before c.10ka, eruptions with a Volcanic Explosivity Index (VEI) of five or greater (Plinian eruptions) dominated (Pardo et al., 2012).

Historical eruption styles have been controlled by the presence of the Crater Lake and associated hydrothermal system, resulting in frequent smaller phreatic eruptions. When the Crater Lake empties (as it last did in 1996), the eruption style shifts from phreatomagmatic to magmatic activity (Gamble et al., 2003; Bryan and Sherburn, 1999).

## 2.3 Recent eruption history

Table 2.2 collates a fifty year eruptive history of Ruapehu, with key similarities to the 2007 eruption marked in bold.

**Table 2.2 : A summary of eruption styles and sizes at Ruapehu over the past 50 years**

**NB: For clarity and brevity, this table shows only tephra-generating eruptions and eruptions during low apparent volcanic activity.**

**(Smithsonian Institute, 2013; Christenson et al., 2010; Mordret et al., 2010; Barberi et al., 1992)**

| Year | Notes | Approximate crater lake temperature at time of eruption ($^{o}$C)<br><br>(Christenson et al., 2010) | Estimated tephra volume, if known<br><br>(x $10^5$ $m^3$)<br><br>(Smithsonian Institute, 2013) | VEI |
|---|---|---|---|---|
| *2007* | Phreatic or phreatic to phreatomagmatic<br><br>Powered by gases from passive magmatic degassing<br><br>Low heat flow (apparent quiescence)<br><br>No useful seismic precursors | 17 | 2.6 | 1 |
| **2006** | **Low heat flow (quiescence)** | 19 | (Not tephra-generating) | 1 |
| 1996 | Major phreatomagmatic-magmatic eruption | >60 | 40 | 3 |

| **Year** | **Notes** | **Approximate crater lake temperature at time of eruption (°C)** **(Christenson et al., 2010)** | **Estimated tephra volume, if known** **(x $10^5$ $m^3$)** **(Smithsonian Institute, 2013)** | **VEI** |
|---|---|---|---|---|
| 1995 | Major phreatic-phreatomagmatic eruption<br>Pyroclastic flow | 50-60 | 300 ± 200 | 3 |
| **1988** | Phreatic eruption, similar to 2007<br>**Low heat flow (quiescence)**<br>**May have lacked useful precursors? (Mordret et al., but not Barberi et al.)** | 9 | No data | 1 |
| **1980** | Small phreatic eruption<br>**Low heat flow (quiescence)**<br>No useful precursors (Barberi et al.) (Mordret et al. only reported on larger eruptions) | 17 | (Not tephra-generating) | 1 |
| 1977 | Pyroclastic flow | 30-50 | 5.5 ± 5.0 | 2 |

| Year | Notes | Approximate crater lake temperature at time of eruption ($^{0}C$)<br><br>(Christenson et al., 2010) | Estimated tephra volume, if known<br><br>(x $10^5$ $m^3$)<br><br>(Smithsonian Institute, 2013) | VEI |
|---|---|---|---|---|
| 1975 | Phreatic explosions; pyroclastic flow<br><br>**May have lacked useful precursors? (Mordret et al., but not Barberi et al.)** | 45 | No data | 2 |
| 1971 | Phreatic explosion | 30-40 | >10 | 2 |
| 1969 | Phreatic explosions, pyroclastic flow<br><br>**May have lacked useful precursors? (Mordret et al., but not Barberi et al.)** | 30-40 | No data | 2 |
| 1968 | Phreatic explosion | 30-40 | No data | 2 |
| 1966 | Phreatic explosion; lava flows | 54 | No data | 1 |

## 2.4 Discussion

### 2.4.1 Eruptions without precursor activity

The threshold for useful precursor activity varies between authors. Comparing the results for eruptions from 1965-1990, Mordret et al. (2010) identified three additional eruptions (1969, 1975, and 1988) to be lacking precursors than Barberi et al. (1992) did.

A worldwide study of 115 phreatic eruptions by Barberi et al. reported that c.15% of such eruptions do not produce measurable precursors, even with extensive monitoring.

I applied Barberi's 15% estimate to the 10-year recurrence interval for medium phreatic eruptions of Ruapehu (from Table 2.1). This gives a conservative estimate of the recurrence interval for significant unpredicted eruptions of Ruapehu of c.70 years (1 s.f.). See Appendix 1 for calculations.

(NB: This calculation only applies to phreatic eruptions. Larger eruptions are typically phreatomagmatic or magmatic, so are excluded from this estimate. Also, phreatomagmatic and magmatic eruptions would usually show detectable precursor activity).

### 2.4.2 Historic activity

Eruptions in 2006, 1988 and 1980 were similar to 2007: they occurred during periods of apparent quiescence, and may have lacked useful precursors. Of these four eruptions, 2007 was the largest and the only tephra-generating eruption.

I used this historic frequency (4 eruptions of interest in 50 years) to predict the future likelihood of similar sudden phreatic eruptions at Ruapehu. This gives a recurrence interval of c.10 years (1s.f.). See Appendix 1 for calculations.

## 2.5 Summary

The history of sudden eruptions of Ruapehu during periods of apparent quiescence makes future recurrences extremely likely, although from past records, it is expected the majority of events will be smaller than in 2007. I estimate a recurrence interval of c. 10 years for small eruptions of this type, and c.70 years for sudden medium eruptions.

# Chapter 3 Ruapehu: Eruption processes, sources and factors

## 3.1 Vent and hydrothermal systems

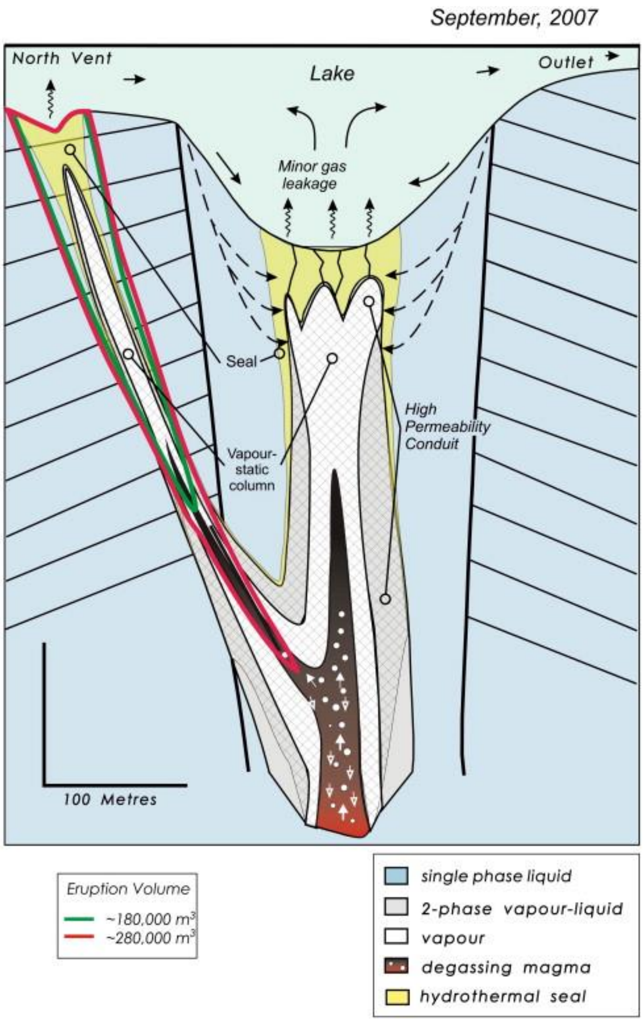


**Figure 3.1: Cross-sectional view of the shallow vent structure at Ruapehu.**

**(Taken from Christenson et al., 2010)**

Figure 3.1 depicts a model of the shallow vent structure and hydrothermal system, shown here immediately before the 2007 eruption. This is the topmost section of an open vent system where magma movement is unhindered (Christenson et al., 2010).

The impermeable partial hydrothermal seal (shown in yellow) formed from sulphur being ad- and absorbed by andesitic vent rocks over a period of c. 10 years. This restricts the gas flow, allowing a vapour-static column to pressurise the base of the seal (Christenson et al., 2010).

### 3.1.1 Geochemical Data

Geochemical analysis of magma compositions from historic eruptions shows Ruapehu has an open vent system with magmatic composition dominated by AFC (crustal assimilation and fractional crystallisation) (Price et al, 2007).

### 3.1.2 Hydrothermal system

Magnetotelluric (MT) surveys (which use electrical resistance measurements to infer subsurface structure) show that hydrothermal circulation operates for at least several hundred metres beneath the lake. This circulation alters the surrounding rocks and scrubs (removes) sulphur-containing gases.

Regions of high temperature alteration are consistent with a heat pipe operating between the base of Crater Lake and the top of the magma column. A heat pipe is a convecting regime which transfers gas and heat, without magma advection. The convective heat pipe contains a single-phase liquid, a gas-liquid phase (near the magma) and a vapour phase (within the conduit) (Jones et al., 2008; Hurst et al., 1991).

Ruapehu exhibits cyclical variations of lake temperatures (between 10-60$^{o}$C) and gas flux ($CO_2$ and $SO_2$), with a period of 4-16 months, suggesting a variation either in magma supply or of magmatic degassing rates. Gas flux continues during periods of quiescence, demonstrating a counterexample to the assumption that gas plumes during periods of quiescence were rare (Varekamp, 2000).

The gas discharge and heat flow cycles are correlated (suggesting a common source process), but partially decoupled (peaks in $CO_2$ come earlier). $SO_2$ and $CO_2$ fluxes have complex variations due to hydrothermal scrubbing of S-gases. The correlation between $CO_2$ and temperature suggests a variation in magmatic degassing (Christenson et al., 2010).

## 3.2 Deeper structures

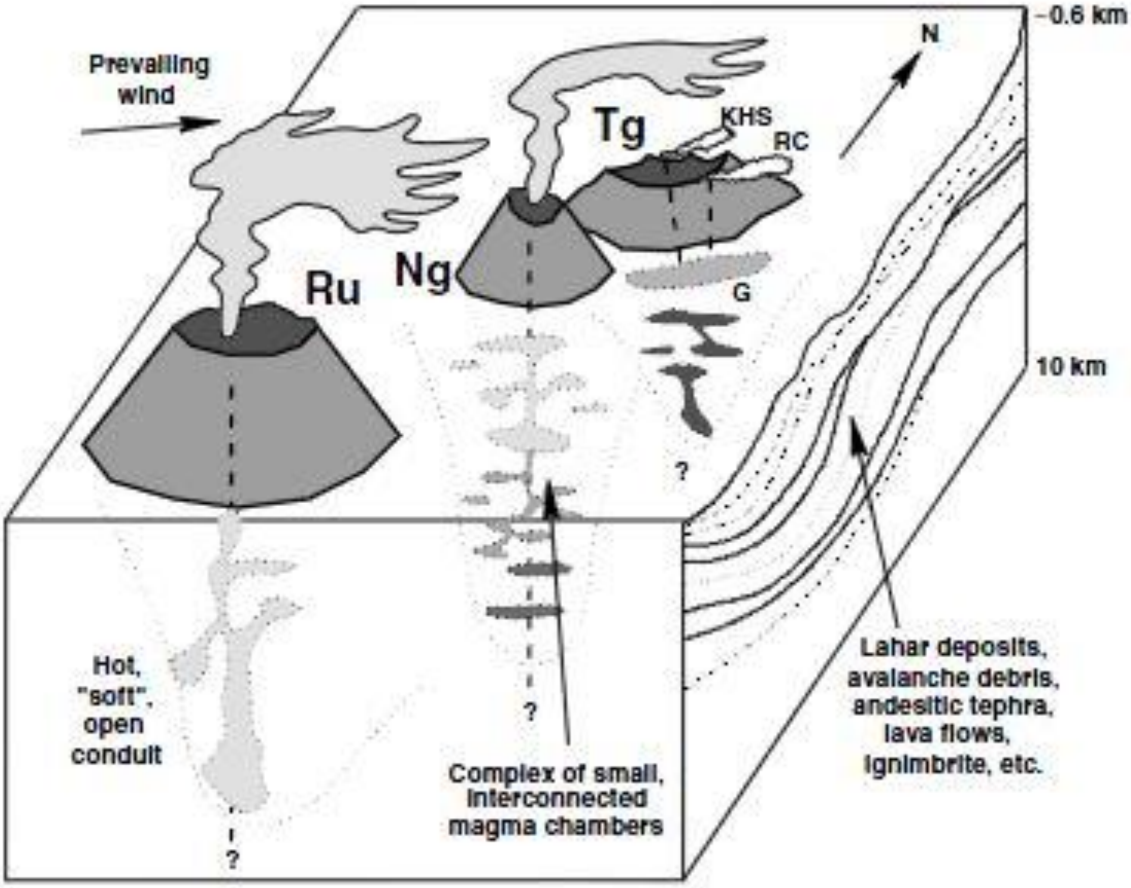


**Figure 3.2: Interpretation of the deeper structures and conduits beneath the Tongariro Volcanic Centre as derived from seismic tomography.**

**(Taken from Rowlands et al., 2005)**

Seismic tomography allows inferences of deeper structures to be made from inversion of P- and S-wave data. These show Ruapehu sits atop an aseismic, low-velocity region. This is best explained by a hot, soft (crystal mush), open conduit as seen in Figure 3.2. However, low seismic resolution, limits the model's accuracy, and restricts our understanding of deeper processes (Rowlands et al., 2005).

## 3.3 Seismic signals

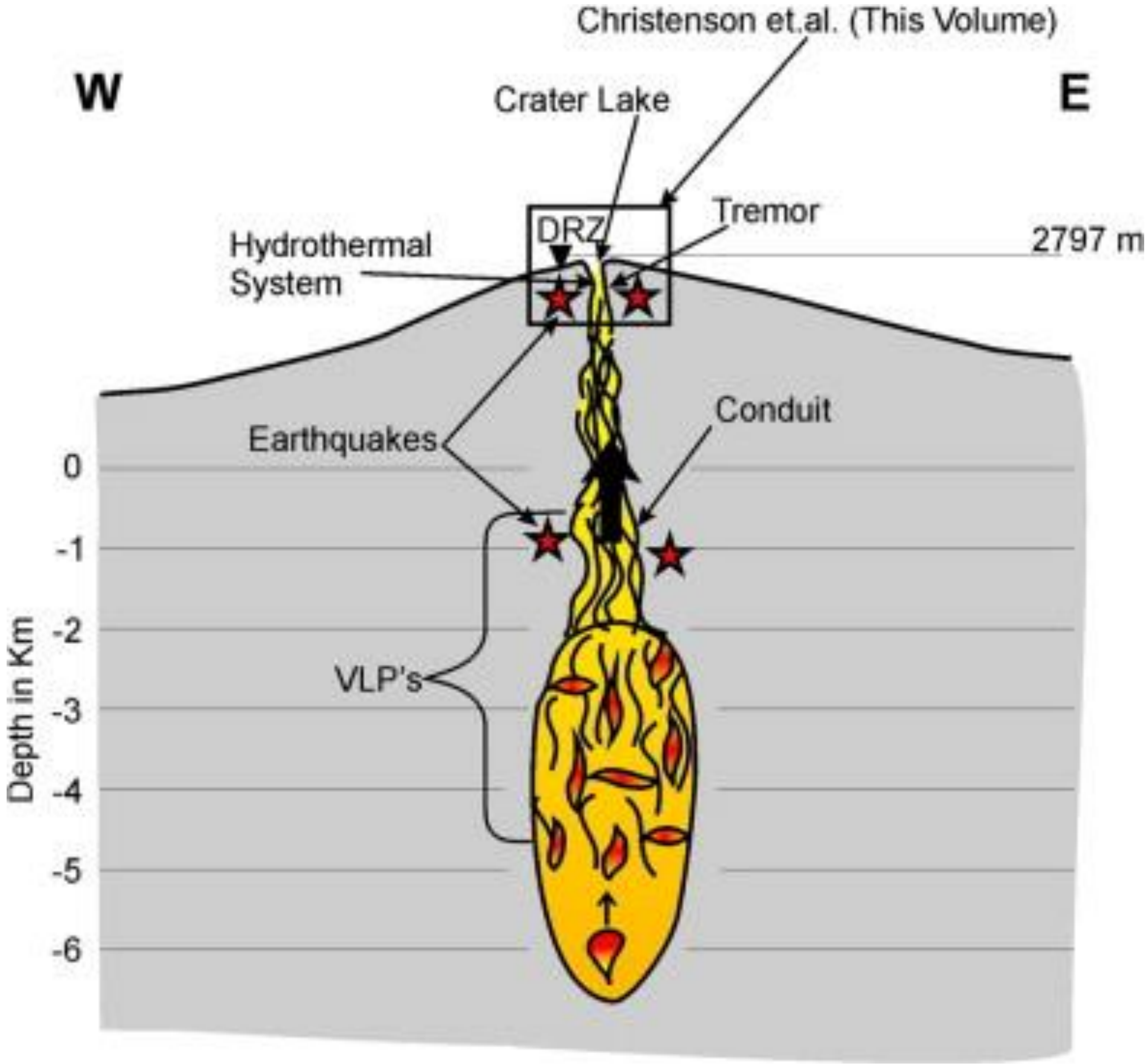


**Figure 3.3: A vertical cross-section of Ruapehu showing the location of pre-eruption seismic activity. NB: Vertical and horizontal scales are the same.**

**(Taken from Jolly et al., 2010)**

Figure 3.3 summarises the seismic source locations of the 2007 eruption. Seismic spectral analysis reveals multiple signals pre- and syn-eruption, associated with distinct source processes.

Harmonic tremor (known at Ruapehu as 2Hz tremor after its dominant frequency) is also present during periods without eruptive activity. It is shallow-sourced, quasicontinuous with a narrow-peaked spectrum, which varies with temperature and pressure. Increases in frequency are correlated with magmatic activity. The source process is uncertain but may be either harmonic resonance of the vapour-phase of Figure 3.1 (Hurst and Sherburn, 1993), or resonances in the magma column (magma wagging) (Jellinek et al., 2011).

VT (Volcano-tectonic) earthquakes are tectonic processes operating within the volcano. These generate shallow-sourced discrete seismic events corresponding to brittle failure of the crust (Sherburn et al., 1999; Werner et al., 2006).

VLP (Very Long Pulse) signals involve deeper magmatic processes, such as magma injection or movement. Source locations are approximate, because the long wavelengths of VLP signal limit resolution (Lokmer and Bean, 2010).

## 3.4 Discussion

### 3.4.1 Model limitations

The models presented in this chapter have limitations: these are ill-posed inverse problems: a type of mathematical problems with more than one possible numerical solution (Sneider and Trampert, 1999). These models represent the best fit for the data, but not the only possible interpretation.

Unique analytical solutions are not possible because data is incomplete, noisy, and often based on infrequent discrete eruption events. Numerical solutions require use of simplifying approximations, regularisation techniques, and must be constrained using the author's a-priori domain expertise.

### 3.4.2 Model Confidence

The shallow-vent model from Figure 3.1 is supported by multiple data sets, including geochemical, seismic, magnetotelluric, lake composition, heat flow, and gas flux. This means we can have confidence that it is a good model of Ruapehu's shallow systems.

Seal formation processes are currently poorly understood, and may be improved by sorption studies to model the ad- and absorption of sulphur into andesite, and subsequent gas flows.

The deeper processes and structures only use seismic data and constraints from shallow processes. This means they are much less well understood, poorly constrained and suffer from inherent resolution limitations. Further research with improved data resolution is needed.

## 3.5 Summary

The hydrothermal system of Ruapehu is driven by the interaction of a shallow, degassing magma column and acidic Crater Lake waters in the vent rocks. These models are well understood and supported by multiple geophysical data sets.

Deeper processes are poorly understood, but are thought to involve a partially molten magma chamber, with composition dominated by AFC processes.

# Chapter 4 2007 eruption data

## 4.1 Pre-eruption

Vent output decreased in the eight months before the eruption, as summarised in Table 4.1. Reduced heat flow and emissions in the months before the eruption can be evidence of either reduced magmatic degassing, or vent obstruction.

**Table 4.1: A summary of the decrease in vent output at Ruapehu in the eight months before the 2007 eruption.**

**(Christenson et al., 2010)**

| Measurement | January 2007 | August 2007 | Notes / Interpretation |
|---|---|---|---|
| Lake temperature | 27°C | 13°C | Decrease in heat flow between January and August |
| $CO_2$ emissions | 662t/d | 178t/d | Gas flow reduced between January and August due to vent obstruction. |
| $SO_2$ emissions | 19t/d | 13t/d | |

## 4.2 Eruption chronology

Eruption chronology and observation data are presented and interpreted in Table 4.2-Table 4.4. Small differences in data are presented as ranges. These most likely represent differences in precision and rounding.

**Table 4.2: Timescale of 2007 eruption of Ruapehu.**

**(Christenson et al., 2010 (source C); Jolly et al., 2010 (source J); Kilgour et al, 2010; Mordret et al., 2010; Lube et al., 2009)**

| Start time (NZST on 25th September 2007) | Observation | Notes |
|---|---|---|
| 20:17 | Small VT earthquake, tremor | Earliest activity |
| | Small VLP event | 5km deep |
| 20:25 | Second small VLP and tremor | |
| 20:26:20 | Eruption onset | |
| | Positive pressure acoustic signal (explosion) | Duration c.20-30s<br>Velocity c.320 m/s |
| | VLP pulse (period of 2-25s) | Simultaneous to acoustic signal<br><br>Surface waves<br><br>Interpretation: explosive phase |
| c.20:26 | Dome shelter (refuge on summit of Ruapehu) door blown open by blast | 3-4s after rumbling started |
| c.20:26-20:27 | Dome shelter fills with water and debris | Seconds after door blew open<br><br>Water is the base surge |
| c.20:27 | Eyewitnesses report the eruption stops | c.30s-1min after the start |
| After 20:26 | High amplitude tremor | Duration c.3-4 min (C, J) |

**Table 4.3: Timescale of post-eruption events.**

**(Christenson et al., 2010)**

| Date and time | Observation | Notes |
|---|---|---|
| 25th (after 20:26) – 27th September 2007 | Low amplitude tremor | Tremor declined in intensity over 48h |
| Morning of 26th September | Convective upwelling over Northern Vent | |
| After 26th September | Strong gas ebullition from Northern vent | Continued vent clearing |
| 23:05 29th September | Tremor/volcanic activity | |
| 1st October | Upwelling over central vent | Central vent clearing |

## 4.3 Eruption evidence

2007 eruption data resulted in four key papers from 2010, with lead authors at GNS Science (a major geoscience research organisation in New Zealand) analysing complementary data sets.

Christenson et al. (labelled C in the tables) analyses cyclicity in shallow system processes, Kilgour et al. (K) considers petrographic data, Jolly et al. (J) analyses seismic data, and Mordret et al. (M) analyses IRCCASN data (seismic interferometry).

Table 4.4-Table 4.6 summarise the eruption data and interpretations thereof, noting similarities and differences in opinion between authors, including a fifth paper (Car) by Carniel et al. (2013).

**Table 4.4: Interpretations of petrographical evidence from the 2007 eruption of Ruapehu.**

**(Carniel et al., 2013 (source Car); Christenson et al., 2010 (source C); Jolly et al., 2010 (source J); Kilgour et al., 2010 (source K); Mordret et al., 2010 (source M)).**

| Observation | Interpretation | Source | Notes |
|---|---|---|---|
| Elemental sulphur and sulphate minerals in rock pores and voids of ejecta | Sulphur minerals form hydrothermal seal | C | Hydrothermal seal theory is supported by all authors. |
| Strongly asymmetric distribution of ash and ballistic deposits | Focussed blast and jet (both strongly directional) from the north vent. | K; J | |
| Dense andesitic ballistic blocks with similar trace element composition to 1995-6 lava. | Degassed portions of 1995/6 magmas | K | |
| Juvenile material in ejecta | Explosive expansion of pressurised vapour in shallow hydrothermal system intersected magma column | C; J; K | Significant difference in interpretations |
| | Pressurisation from conduit injected magma into eruption | J | |
| | Brought with slug of gas from deep magma system | Car; M | |
| Geochemistry of juvenile magma similar to 1996 magmatic eruption | Similar magmatic supplies | C; K; | |

**Table 4.5: Interpretations of seismic data from the 2007 eruption of Ruapehu. (Carniel et al., 2013; Christenson et al., 2010; Jolly et al., 2010; Mordret et al., 2010).**

| Observation | Interpretation | Source | Notes |
|---|---|---|---|
| Deep (3-7km) VLP and volcano-tectonic seismicity starting 10 minutes before eruption | Failure of magma carapace in deep magma chamber<br><br>Emission of slug of gas from magma chamber<br><br>Introduction of fresh magma to deep magma chamber/magmatic advance | J; M; Car; C; K | Poor VLP localisation makes process hard to identify.<br><br>All authors support the presence of deep activity and present multiple options |
| c.150s between volcano-tectonic pulse and eruption for both 2006/2007 eruptions | Slug of gas/liquid released from magma reservoir, travels up vent. | M | Similarities in timing implies similar processes |
| Poorly localised VT tremor | Failure of hydrothermal seal | J; K | Two potential plausible solutions |
| | Failure of magma carapace | J; K | |
| Eruption occurring 30s after a VLP pulse | Open, convecting vent allows rapid ascent of gases<br><br>Or magma column pushed upwards (c.f. hosepipe) | J | Supports the model presented in Figure 3.1 |
| Shallow tremor | Failure of hydrothermal seal | C; J | |
| | Rise of gas slug | M | |

| Observation | Interpretation | Source | Notes |
|---|---|---|---|
| Shallow VLP | Shallow explosion | J; K | |
| Main VLP pulse acted in southward and downward direction | Northward-directed jet | J | |
| Increased frequency of tremor before eruption | Pressurisation of vapour phase in shallow vent | Car | |

**Table 4.6: Interpretations of physical and chemical evidence from the 2007 eruption of Ruapehu.**

**(Christenson et al., 2010; Kilgour et al., 2010).**

| Observation | Interpretation | Source |
|---|---|---|
| Reduced gas emissions in months before eruption | Hydrothermal seal development prevented some gas reaching lake | C |
| Reduced lake temperature at time of eruption | Hydrothermal seal development prevented heat being advected to lake | C |
| Gas emissions did not cease before eruption | Seal was only partial | C |
| Eruption occurred from north vent | Seal on north vent ruptured due to lower confining hydrostatic pressures (Kilgour et al., 2010) | C; K |
| Subsequent upwelling over central vent and gas ebullience | Non-explosive seal clearing of central vent | C |

## 4.4 Analysis

There is broad agreement that the 2007 eruption of Ruapehu was a VEI 1 subaqueous phreatic explosion. The eruption most likely resulted from the catastrophic failure of a partial hydrothermal seal blocking the north vent. Seal failure resulted from deeper magmatic activity which may have been a rapidly ascending slug of gas or liquid into a pressurised conduit. (Carniel et al., 2013; Christenson et al., 2010; Jolly et al., 2010; Kilgour et al., 2010; Mordret et al., 2010).

All five authors agreed that deeper activity was involved, and hydrothermal seal failure occurred. However, opinion is divided as to whether the explosive decompression associated with the eruption progressed from the seal downwards or from failure of the carapace of the magma chamber upwards (rupturing the seal).

### 4.4.1 Top-downwards explosion

Christenson et al. (2010) supports the top-down eruption theory, whereby catastrophic seal failure causes a shallow explosion to proceed down the vent and intersect the top of the magma column. Geochemical evidence for this includes the presence of juvenile material in the ejecta.

Seismic analysis of shallow VLP and tremor data by Jolly et al. (2010) identified a shallow (1.5km) southward-plunging directed single force concurrent with a positive pressure (i.e. explosive) acoustic wave. This downward-directed force is interpreted as a reactive force from the explosive generation of a northward-directed jet and ballistics (witnessed by two climbers).

Kilgour et al. (2010) also present the surtseyan jet as evidence of shallow explosive depressurisation caused by seal fracturing. The cause of the seal failure is identified as over-pressurisation from gases released from deeper processes. The eruption involved only the shallower north vent because it has a lower confining hydrostatic pressure than the central vent.

This scenario is consistent with deeper process involvement, such as the injection of new magma into a deeper magma chamber, or the release of a gas slug, or increased magmatic degassing. These processes increased the pressure beneath the seal, and therefore the stresses on the seal, eventually causing rupture to occur (Christenson et al., 2010).

### 4.4.2 Upwards-directed explosion

Carniel et al. (2013) also presents a second possible explanation: the seal fractured as a result of bottom-upwards decompression after deeper rupturing of a magma carapace (rigid outer surface).

In this theory, the juvenile material was brought with a rapidly-ascending gas slug (Carniel et al., 2013, Mordret et al, 2010).

The poorly-localised deep VLP pulse was explained as the gas slug release (Carniel et al., 2013; Mordret et al., 2010) or the fracture of a magma carapace, which caused depressurisation (Jolly et al., 2010; Kilgour et al., 2010); the syn-eruption VLP and shallow tremor are surface expressions of the ascent of the gas slug.

This second explanation does not explain why there was no central vent eruption, nor the syn-eruptive VLP evidence of a shallow downward-directed single force, nor the subsequent central vent clearing episode some days later.

### 4.4.3 Summary

From the evidence presented in these papers, the top-down explosive decompression is a better explanation, since it has no contradicting evidence, nor any unexplained observations.

## 4.5 Discussion

Phreatic eruptions are notoriously difficult to predict, since they are gas-driven, so may not necessarily be associated with increased magmatic activity.

The 2007 eruption could not be predicted by then-current detection methods, due to the (apparent) lack of both volcanic activity and seismic precursors. The apparent quiescence was an artefact of the progressive restriction of gas and heat from the vent by a hydrothermal seal. In effect, this masked the volcanic activity, making it harder to detect.

Seal formation creates a second problem: it permits a potentially hazardous pressurised gas column to form beneath the seal. If this is suddenly released, it may lead to an explosive vent clearing episode (e.g. this eruption).

However, the seals can also clear non-explosively (e.g. the central vent clearing episode one week post-eruption). Further research is needed to understand what circumstances promote explosive vent clearing.

### 4.5.1 Alternative explanations

There is an unusual level of agreement in interpretations between the authors, who are analysing very different data. This usually indicates robustness and consistency of the models.

This agreement may be an consequence of the extensive collaboration and co-authorship: e.g. Jolly and Kilgour are each listed as co-author on the other's paper, Jolly is second author on Mordret et al. (2010) and Carniel et al. (2013), and four of the five lead authors are associated with GNS Science.

Any inconsistencies may be hard to identify, as the data sets are very different – similar to comparing apples and oranges. As the seismic data is so poorly resolved, significant variations in data might be possible without introducing a direct contradiction or inconsistency with the other data. Furthermore, errors in one model which was used to constrain another may lead to associated errors in the derived model.

## Chapter 5 Geohazards of the 2007 eruption

Moderate phreatic eruptions of Ruapehu (such as in 2007) mainly affect the summit area, and lahar catchment areas. Figure 5.1 shows the region affected by ash, ballistics and lahars. The affected area includes a major ski-field at Whakapapa.

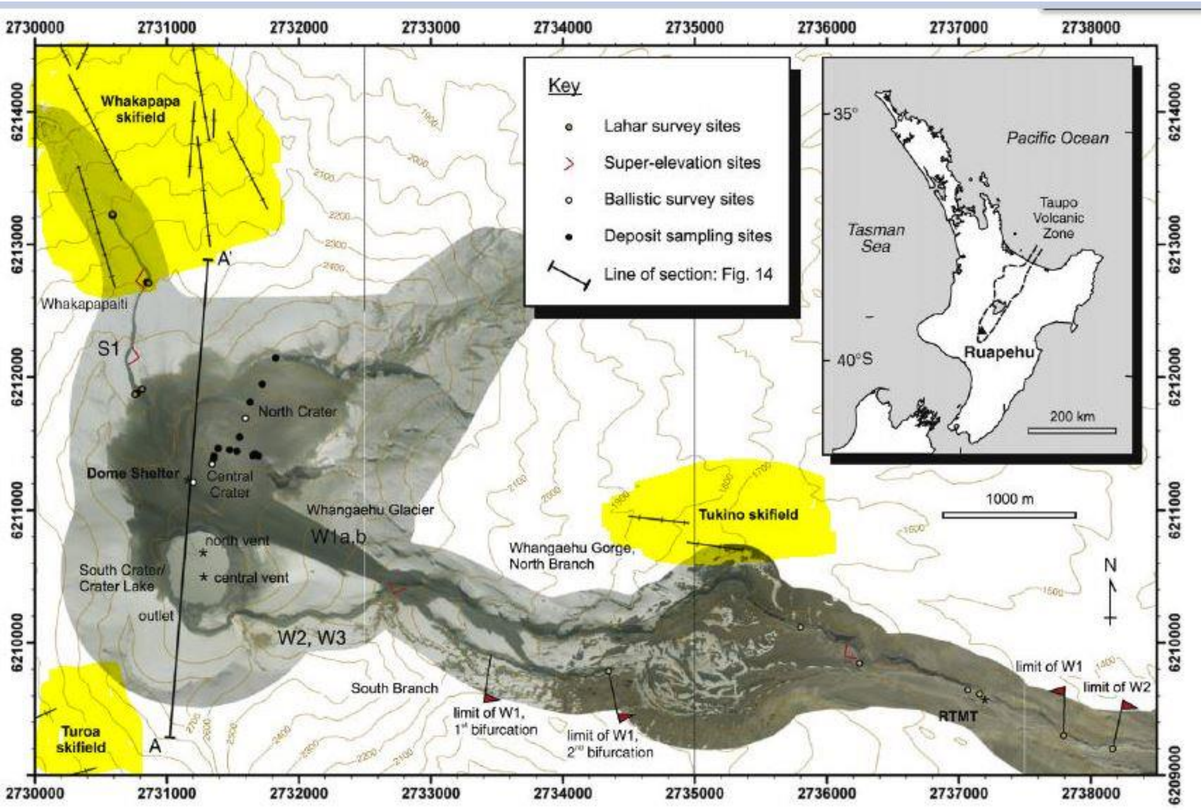


**Figure 5.1: Map showing the geographical extent of the eruption.**

**Ski-fields are highlighted in yellow. (Adapted from fig. 14 of Kilgour et al., 2010)**

## 5.1 Explosion

A reconstruction of the explosive phase of the eruption is shown in Figure 5.2. This is reconstructed from microbarograph and seismic data and eyewitness reports. Eyewitnesses report the shockwave reached the dome shelter c.3-4 seconds after a low rumbling; the hut filled with water seconds later (Kilgour et al., 2010).

The explosion lasted c.0.5-1 minute, with estimated magnitude of c.$1.2 \times 10^{12}$ kJ, with moment magnitude 4.0 $M_w$ and local magnitude 3.2$M_L$. It generated a single shockwave, launched a northward-directed surtseyan jet (a mixture of water, gases and solid debris) and ballistics, generated radial and vertical jets, and created a steam plume reaching c.4500 masl (metres above sea level) (Kilgour et al., 2010).

The explosion effects are similar to those predicted by Morrisey et al. (2010) using SAGE models of subaqueous eruptions of Ruapehu. In these models, the explosive force is powered by the sudden expansion of volatiles within the vent, followed by collapse of a transient gas cavity. The angle of the vent and the bathymetry focus the blast).

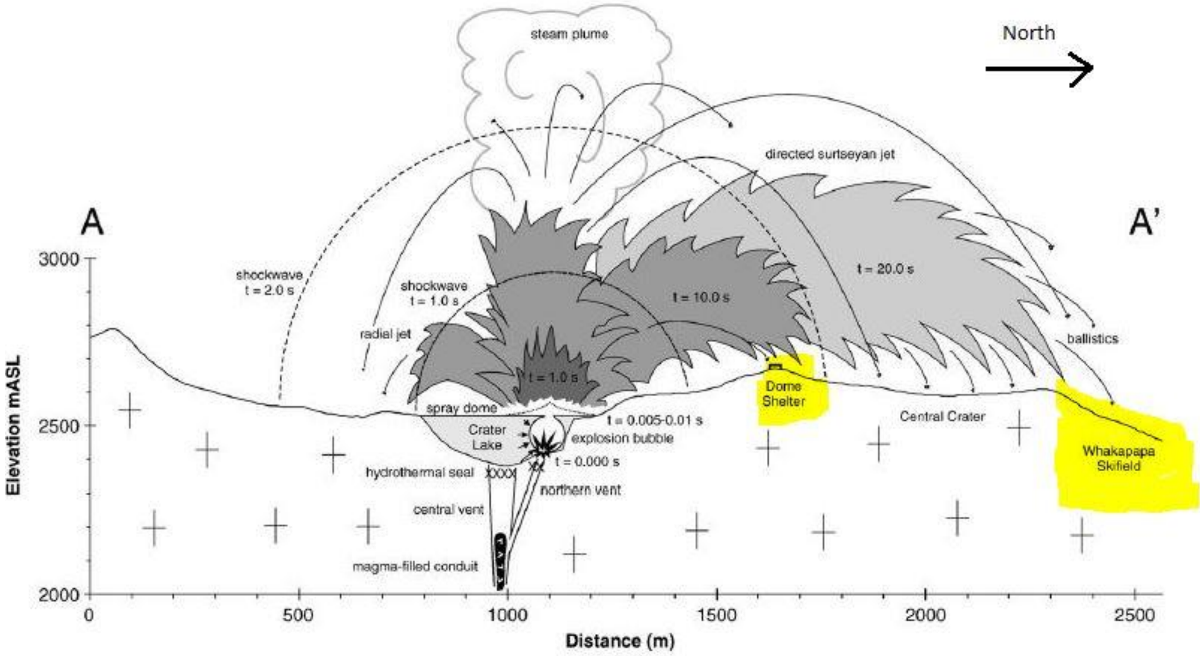


**Figure 5.2: A cross-sectional view of the explosive eruption sequence. (Adapted from fig. 14 Kilgour et al., 2010)**

## 5.2 Lahars

Ice and snow-slurry lahars are a four-phase mixture of ice, snow, water and rocks. These form when the base surge interacts with snow/ice. They are the most mobile type of mass flow, are nearly invisible, and are extremely destructive, with the capability of burying or sweeping away people, and even destroying or burying buildings, ski-lifts and bridges. In 1953, the Tangiwai rail bridge was destroyed by a lahar in the Whangaehu catchment, leading to the deaths of 151 people (Leonard et al., 2010; Lube et al., 2009).

Regions labelled W1 (in the Whakapapaiti catchment) and E1/E2 (in the Whangaehu catchment) in Figure 5.3 show the area affected by ice- and snow-slurry lahars following the eruption.

Lahar W1 was syn-eruptive, travelled 2.2km in 4 minutes and reached the upper slopes of the Whakapapa ski field. Peak velocity is estimated as 11.5m/s and flux 450-650$m^3$/s, with overall volume 3.0-6.0x$10^4 m^3$. Lahar E1 lasted c.180s, was syn-eruptive, reaching 8.5km with average speed of 13.5m/s. E2 was post-eruptive (20:42), lasted 1-2 minutes, with average speed 7.5m/s. A later lahar, coincident with E2 began at 21:40, lasting 1.5h (Kilgour et al., 2010).

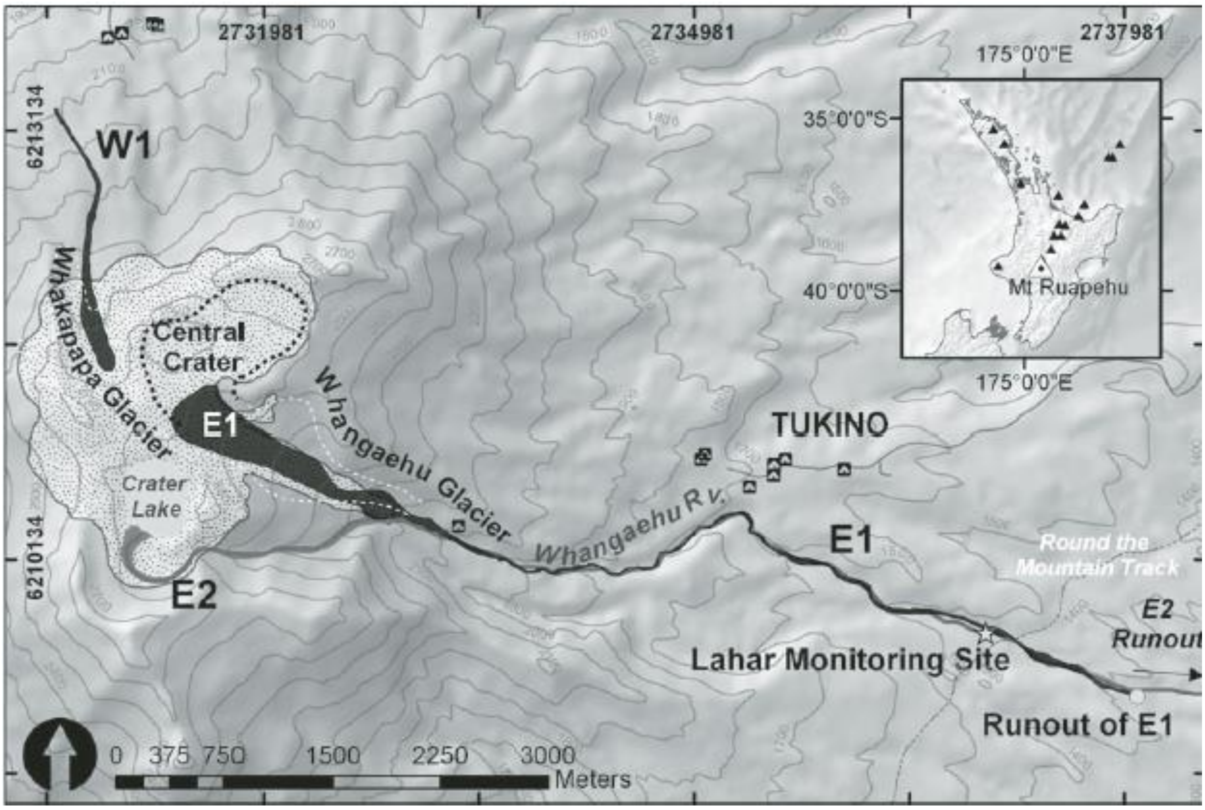


**Figure 5.3: Map showing the lahar paths of the 2007 eruption.**

**(Taken from Lube et al., 2010)**

## 5.3 Directed ballistics and jets

Ejecta distribution patterns (shown in Figure 5.4) are consistent with a low angled northward-directed blast, forming an apron approximately 40° wide. Jet deposits and ballistics were launched during the explosive phase of the eruption (duration 0.5-1 minute), with an initial velocity of 137 $ms^{-1}$. Tephra reached 2km from the vent, with blocks up to 2m in size. In spite of the southerly winds, the fallout distribution was not shifted to the south (Kilgour et al., 2010).

Ejecta composition included andesitic lava and breccias, lacustrine sediments, vent fill, and small amounts of juvenile glass. Andesitic samples showed extensive hydrothermal alteration, with sulphur-containing minerals filling the pores. Pore exudations of molten elemental sulphur place a minimum temperature at the top of the vent of 119°C. Geochemical analysis shows that the andesitic lavas were degassed remnants from the 1995-6 eruptions (Christenson et al., 2010; Kilgour et al., 2010).

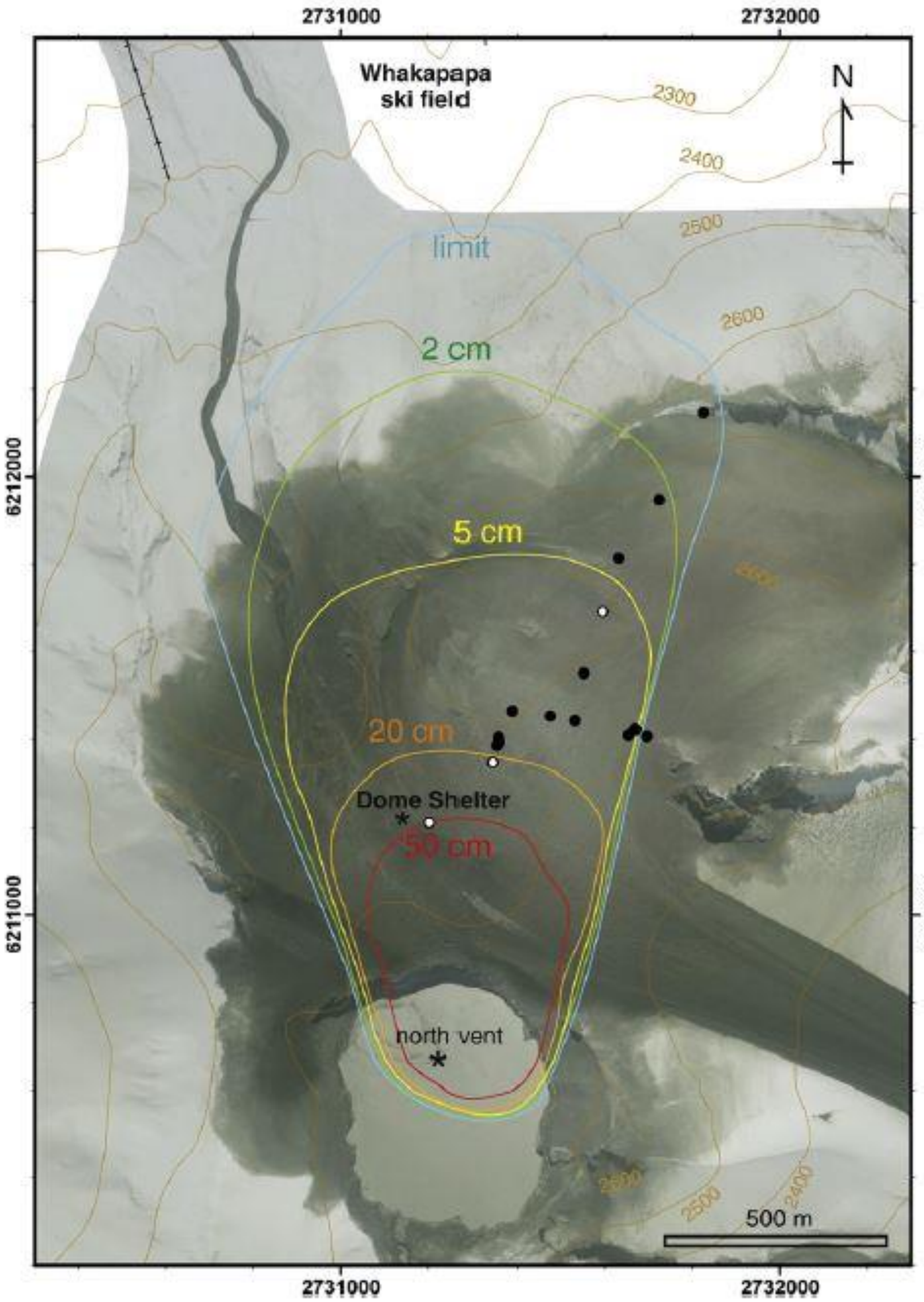


**Figure 5.4: Map of North Ruapehu immediately following the eruption, showing the ash coverage and ballistic sizes.**

**(Taken from Kilgour et al., 2010)**

## 5.4 Discussion

Volcanic risks result from human exposure to geohazards, and are a measure of how likely particular geohazards will cause harm or damage.

Two high-risk areas of Ruapehu are the immediate summit area and, during winter months, the upper slopes of the Whakapapa ski resort, albeit for different reasons. The summit area is more hazardous to individuals, but the ski-field also has a high risk of casualties because of its larger population.

As seen in this chapter, individuals at the summit are at high risk of death or serious injury from eruptive geohazards including explosions, shockwaves, water jets and ballistics.

A further risk factor affecting the Whakapapa ski field is the directed nature of the north-vent eruptions. The inclined vent and topography direct jets and debris directly towards the ski-field, making this area significantly more dangerous during an eruption than either the Turoa or Tukino ski-fields (on the south-western and eastern flanks of the volcano respectively).

Away from the immediate summit area, lahars pose the biggest risk to people. During lahar simulation drills at Whakapapa, skiers in the upper slopes took 4 minutes to reach high ground, compared to the 1.5 minutes a typical lahar would have taken to arrive at the top of the ski area (Leonard et al., 2010).

# Chapter 6 Mitigating against future eruptions

## 6.1 Probability of recurrences

Ruapehu has not erupted since 2007. However, between November 2012 and March 2013, Ruapehu was raised by GNS Science to volcanic alert 1 and aviation alert yellow (increased risk of eruption). Reduced lake temperatures and gas flow (conditions similar to August 2007) raised fears of a hydrothermal seal reforming; normal conditions resumed in March, and the risk was downgraded (Scott, 2012; Miller, 2013).

Based on historical record, future sudden modest eruptions similar to the 2007 eruption are inevitable; the lack of (significant) magmatic involvement limits their size, but would still pose a significant threat to hikers, skiers and scientists near the summit.

## 6.2 Dome shelter

Dome Shelter was a summit refuge hut for use when eruption alarms sounded. It has been rebuilt since its destruction in the 2007 eruption. Two climbers (who were inside the hut when it was destroyed) received serious injuries, but survived thanks to the shelter’s protection.

## 6.3 Monitoring and eruption detection systems

Prediction of phreatic eruptions is problematic because eruptions without significant magmatic activity may not show useful precursor activity.

Ruapehu is monitored by an automated Eruption Detection System (EDS) owned by the Department of Conservation (DoC), and operated by the GeoNet project, a collaboration between GNS Science and the DoC.

The EDS is a three-part system comprising instrumentation (summarised in Table 6.1), a computer system to quickly identify anomalous events from instrumentation data, and a warning system that alerts the emergency service and sounds alarms in the affected areas (GeoNet, 2013a; Sherburn, 2011; Neal et al., 2010; Sherburn and Bryan, 1999).

**Table 6.1: Ruapehu's Eruption Detection System.**

**(Summary of data from GeoNet, 2013a)**

| **Instruments/measurements** | **Frequency of measurements** | **Notes** |
|---|---|---|
| Six seismographs | Continuous | Main method of eruption detection |
| Microbarographs | Continuous | Detect air pressure changes |
| Continuous GPS: 8 stations | Continuous | Detects deformations from magma volume changes |
| Surveying | Regular | |
| Visual monitoring: 2 cameras | Continuous | |
| Chemical sampling of Crater Lake | Regular | Detects changes in composition: • Magnesium – fresh magma near surface • Chloride – steam input • pH – indicates volcanic activity |
| Temperature of crater lake | Regular | Heat flow |
| Water level and overflow | Regular | Risk of lahars, may indicate activity |
| Gas plume analysis (COSPEC, LICOR) | Regular | Measures concentration of $SO_2$, and shape/extent of plume. Elevated $SO_2$ is correlated with increased volcanic activity |

The EDS has been upgraded since 2007. Figure 6.1 shows the current cGPS and seismograph sites, with new sites (since 2007) shown in yellow (GeoNet, 2013a).

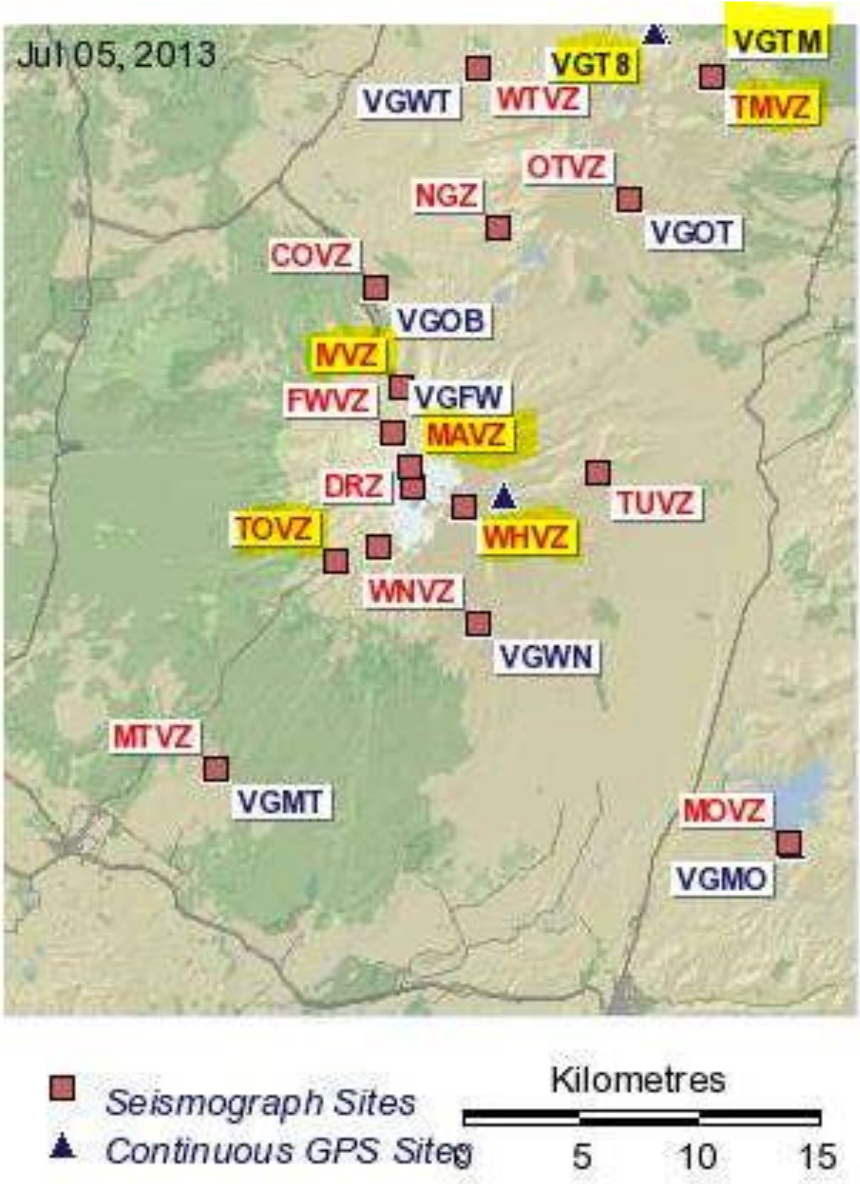


**Figure 6.1: A map showing the locations of seismic and cGPS monitoring sites near Ruapehu.**

**Highlighted sites are new since September 2007. (GeoNet, 2013b)**

A second monitoring system, ERLAWS (Eastern Ruapehu Lahar Warning System) monitors the Whangaehu River against lahars, and automatically closes road and rail connections 40km away. This system performed successfully in both the September 2007 eruption, and a March 2007 breakout lahar (Leonard et al., 2010).

## 6.4 Analytical methods and instrument improvements

### 6.4.1 cGPS

Resolution limitations meant that no surface deformation was detected for the 2007 eruption; this places an upper limit of new magma entering the magma chamber of ~$1.7 \times 10^6 m^3$ (Mordret et al., 2010).

Estimates of resolution from two GPS receivers are a near-real-time detection of 40-70mm vertical displacement (equivalent to a small, shallow source eruption) (Miller et al., 2003).

Further research is needed to see if additional cGPS sites on the flanks of the volcano may improve this resolution and detect off-centre deformations.

### 6.4.2 Seismic monitoring

In 2007, seismic interferometry (IRCCASN) data resolution was insufficient to detect magma chamber pressurisation (Mordret et al., 2010).

With only three broadband seismic stations, VLP inversion was impossible. This restricted seismic modelling of the 2007 eruption to an evaluation of which plausible models (created by the author using their domain expertise) fitted the recorded data (Jolly et al., 2010).

Additional broadband seismographs spaced over a baseline comparable to the size of Ruapehu might improve the resolution of the VLP pulses, and permit VLP inversion.

Four additional seismographs sites have been added since the 2007 eruption (GeoNet, 2013b). These additional instruments will help to increase the overall seismic resolution. Further research is needed into noise reduction methods using cross-correlated data from different sites (Mordret et al., 2010). This should help reduce the effect on the seismic data from local traffic, weather and snow grooming.

#### *6.4.2.1 New analytical techniques*

Carniel et al. (2013) showed that self-organising-models (SOM) trained with seismic data from an earlier eruption (2006) can recognise the onset of the 2007 eruption using similar transitions in seismic behaviour. This is a promising area of near-real-time numerical modelling requiring further research.

## 6.5 Education and evacuation strategies


**Figure 6.2: A public awareness poster from the Whakapapa ski resort detailing what to do in the event of an eruption.**

**(GNS Science, 2008)**

The main population at risk from eruptions are the transient winter population of 10,000 people at Whakapapa ski-field, who are not familiar with volcanic risks (Kilgour et al., 2010).

Educational posters such as Figure 6.2 explain the correct behaviour if an alarm is sounded. Drills show human behaviour is a major risk: during one simulation, dozens of people ignored alarms or left safe areas (Page, 2012; Leonard et al., 2010).

A five step early-warning model has been developed to mitigate the eruption risks. This model uses the EDS and drills to help with planning, education, and staff training. Efforts are co-ordinated by a consortium of government agencies (including the DoC), scientific organisations (including GeoNet and GNS Science), emergency services and the media (Leonard et al., 2010).

## 6.6 Discussion

Deaths and injuries from the eruption may have been reduced by its night-time occurrence, when few people were on the summit or ski slopes. The seriously injured climbers were probably saved by being in the shelter.

Mitigation strategies for volcanic eruptions fall into two categories: improvements to prediction/early-warning systems, and improving the human response to minimise the risk posed to populations by the geohazards.

### 6.6.1 Improved prediction

In both the September 2007 eruption and a breakout lahar in March 2007, the ERLAWS successfully detected and reacted to lahars by closing road and rail bridges approximately 40km away (Leonard et al., 2010).

Nearer the summit, however, there was insufficient time to evacuate: the proximity of the Whakapapa ski-field to the north vent meant lahars reached the field only 1.5 minutes after eruption onset. Improving the warning systems at Whakapapa would therefore require earlier precursor detection (Leonard et al., 2010).

That “earlier precursor detection” would improve eruption prediction presumes that undetected earlier precursor stages did in fact exist but were not detected. This reframes the problem as an issue of detecting signals below the resolution limits of current instrumentation.

Increased resolution brings an increase in susceptibility to noise, artefacts and signal processing problems, and a potentially increased risk of false positives. Such false alarms may lead to increases in people ignoring real alarms. Artefacts due to snowfield grooming during the eruption prevented the recording of useful seismic data at the FWZT (Far West T-bar) seismic site (Jolly et al., 2010).

Decorrelations of seismic signals were recorded in March 2006 and September 2007 due to severe storms, which would have prevented any eruption detection (Mordret et al., 2006).

### 6.6.2 Risk minimisation

The rebuilt dome shelter (destroyed in the 2007 eruption) offers some protection to climbers at the summit area. Earlier warning, or additional shelters would be needed to further reduce risk in this area.

An effective way of minimising volcanic risk would be not to locate a ski resort on an active volcano, particularly not in a major lahar catchment.

Socioeconomic reasons make this solution implausible. Mitigation strategies to reduce risky behaviour via people-focussed solutions are more socially acceptable and practical.

Historic lahar path studies show that the upper slopes of the Whakapapa ski-field are more likely to be affected by lahars and debris (Palmer, 1991).

Restricting access to the upper slopes (e.g. via permits or lift closures) during periods of unusual activity (including conditions consistent with seal formation) could further reduce casualties. Lower slopes have additional time to respond to any emergency, making evacuation easier.

# Chapter 7 Conclusions

## 7.1 Summary

The 2007 eruption of Ruapehu is a case study of an unusual eruption style that characterises a subset of eruptions of this volcano. These eruptions have sudden onset, without seismic precursors or other signs of increased volcanic activity.

### 7.1.1 Timescales

The September 25$^{th}$ 2007 eruption of Ruapehu was a short-lived (3-4 minutes) phreatic to phreatomagmatic eruption of sudden onset (10 minute warning) during a period of low apparent volcanic activity.

The lack of useful seismic precursor activity before the eruption, together with apparently low levels of volcanic activity made the event impossible to predict using current methods, even with extensive monitoring.

Based on previous similar eruptions, an estimation of the recurrence interval for sudden eruptions during periods of quiescence is 10-20 years for small eruptions and 60-70 years for medium eruptions.

### 7.1.2 Processes

The shallow processes and structures of Ruapehu are well-understood, due to decades of seismic, chemical and gas-plume data, and recent magnetotelluric studies. The volcano has an open vent system, which transfers heat and gases from a shallow magma column to the Crater Lake, via a convecting heat pipe and a shallow hydrothermal system operating beneath the Crater Lake.

However, the deeper structures and processes are much less well understood. These are derived from poorly-resolved VLP data, and constraints derived from and heat flow budgets and cGPS data.

### 7.1.3 EDS limitations and improvements

The resolution available in 2007 from cGPS and seismic monitoring was not sufficient to detect any pressurisation before the eruption. EDS improvements since 2007 will help improve resolution which may (together with cross-correlation and SOM modelling methods) lead to earlier precursor detection and improve the understanding of volcanic structure and processes.

### 7.1.4 Geohazards

The summit area was affected by explosions, tephra and northward-directed jets, seriously injuring two climbers.

Northward-directed tephra fallout reached 2km north of the vent, falling on the summit areas and the upper slopes of the Whakapapa ski-field.

Both the Whangaehu and Whakapapaiti catchments experienced ice and snow-slurry lahars. The Whakapapaiti lahar breached the upper slopes of the ski-field less than four minutes after the eruption. The major road and rail routes in this area pass through the Whangaehu catchment, but were not damaged by this eruption.

### 7.1.5 Mitigation

Mitigation strategies at the volcano are generally effective outside the summit area: early-warning systems are able to detect lahars before they would reach road and rail networks. The summit area is, however, extremely hazardous and cannot quickly be evacuated, but the dome shelter offers some protection.

The upper slopes of Whakapapa ski-field are hazardous to individuals with poor volcanic risk knowledge. Due to the high seasonal population, this area remains a high-risk area for casualties.

## 7.2 Recommendations

VLP data from this eruption show involvement of poorly-resolved and poorly-understood deeper processes and structures.

Further research to improve understanding the deeper structure and processes of the volcano is needed. This understanding would be assisted by additional cGPS sites on the flanks of the volcano, and additional broadband seismographs, to increase the number and the aperture of the seismograph array.

Further study to improve the understanding of hydrothermal seal formation is also recommended, e.g. numerical sorption simulations to investigate how sulphur-containing minerals are ad- and absorbed onto/into the voids in andesitic rocks, and how this will affect gas flow.

## 7.3 Objectives

This project meets the Objectives set in chapter 1, covering the causes and effects of the 2007 eruption of Ruapehu and mitigation strategies against similar future events.

Each objective has been investigated in detail and answered to the best of current knowledge. One area where understanding is lacking or insufficient (the deep processes and structures of Ruapehu) was identified and this report recommends further research with improved instrumentation.

A summary of links to report sections where the objectives are met is provided in Table 7.1.

**Table 7.1: : A summary of where objectives have been met**

| Objective | Description | Section of report |
|---|---|---|
| 1 | Processes and factors | Chapter 3: Ruapehu: Eruption processes, sources and factors |
| 2 | Eruption timescale | Chapter 4: Eruption chronology<br><br>Chapter 4L Discussion |
| 3 | Eruptive geohazards | Chapter 5: Geohazards of the 2007 eruption |
| 4 | Future eruption | Chapter 2: Summary |
| 5 | Public education strategy | Chapter 6: Education and evacuation strategies |
| 6 | Eruption Detection System | Chapter 6: Monitoring and eruption detection systems |

## References

Barberi, F., Bertagnini, A., Landi, P. and Principe, C. (1992) 'A review on phreatic eruptions and their precursors', *Journal of Volcanology and Geothermal Research,* vol. 52, no. 4, pp. 231 [Online], DOI: 10.1016/0377-0273(92)90046-G" (Accessed 20th May 2013).

Bryan, C, & Sherburn, S. (1999), 'Eruption-induced modifications to volcanic seismicity at Ruapehu, New Zealand, and its implications for eruption forecasting', *Bulletin of Volcanology*, vol. 65, no.1, pp. 30-42 [Online], DOI: 10.1007/s00445-002-0236-z (Accessed 20th Feb 2013).

Carniel, R., Jolly, A.D. and Barbui, L. (2013) 'Analysis of phreatic events at Ruapehu volcano, New Zealand using a new SOM approach', *Journal of Volcanology and Geothermal Research,* vol. 254, pp. 69-79 [Online],DOI: 10.1016/j.jvolgeores.2012.12.026 (Accessed 20th April 2013).

Christenson, B.W., Reyes, A.G., Young, R., Moebis, A., Sherburn, S., Cole-Baker, J. and Britten, K. (2010) 'Cyclic processes and factors leading to phreatic eruption events: Insights from the 25 September 2007 eruption through Ruapehu Crater Lake, New Zealand', *Journal of Volcanology and Geothermal Research,* vol. 191, no. 1, pp. 15-32. [Online], DOI: 10.1016/S0377-0273(96)00064-9 (Accessed 20th Feb 2013).

Gamble, J.A., Wood, C.P., Price, R.C., Smith, I., Stewart, R.B. and Waight, T. (1999) 'A fifty year perspective of magmatic evolution on Ruapehu Volcano, New Zealand: verification of open system behaviour in an arc volcano', *Earth and Planetary Science Letters*, vol. 170, Issue 3, pp.301-314 [Online], DOI: 10.1016/S0012-821X(99)00106-5 (Accessed 1st July, 2013).

GeoNet (2013a) 'Monitoring Methods' [Online], Available at http://info.geonet.org.nz/display/volc/Monitoring+Methods (Accessed 14th July 2013).

Geonet (2013b) 'Ruapehu Network Map' [Figure]. Available at http://images.geonet.org.nz/maps/networks/volcanic-ruapehu.jpg (Accessed 18th Feb 2013).

GNS Science (2013a) 'Monitoring volcanic unrest' [Online], Available at http://gns.cri.nz/Home/Learning/Science-Topics/Volcanoes/New-Zealand-Volcanoes/Ruapehu/Monitoring-volcanic-unrest (Accessed 10th April 2013).

GNS Science (n.d.) 'Volcano Fact Sheet – Mount Ruapehu Volcano' [Online], Available at http://gns.cri.nz/content/download/6186/33930/file/VolcanoFactSheets%20Ruapehu.pdf (Accessed 22nd February 2013).

GNS Science, Department of Conservation, Mt Ruapehu (2008) 'Volcanic hazards at Whakapapa, Mt Ruapehu' [Online], Available at http://www.doc.govt.nz/Documents/parks-and-recreation/tracks-and-walks/tongariro-taupo/whakapapa-poster_a4.pdf (Accessed 10th April, 2013).

Hurst, A.W., Bibby, H.M., Scott, B.J., McGuinness, M.J. (1991) 'The heat source of Ruapehu crater lake; deductions from the energy and mass balances', *Journal of Volcanology and Geothermal Research*, vol.46, no.1–2, pp.1–20 [Online], DOI: 10.1016/0377-0273(91)90072-8 (Accessed 20th April, 2013).

Hurst, A. W., Sherburn, S. (1993) 'Volcanic tremor at Ruapehu: Characteristics and implications for the resonant source', *New Zealand Journal of Geology and Geophysics*, 36:4, 475-485 [Online], 10.1080/00288306.1993.9514593 (Accessed 20th May 2013).

Jellinek, A.M. and Bercovici, D. (2011) 'Seismic tremors and magma wagging during explosive volcanism', *Nature,* vol. 470, no. 7335, pp. 522-525 [Online], DOI: 10.1038/nature09828 (Accessed 18th Feb 2013).

Jolly, A.D., Sherburn, S., Jousset, P. & Kilgour, G. 2010, 'Eruption source processes derived from seismic and acoustic observations of the 25 September 2007 Ruapehu eruption—North Island, New Zealand', *Journal of Volcanology and Geothermal Research,* vol. 191, no. 1, pp. 33-45. [Online], DOI: 10.1016/j.jvolgeores.2010.01.009 (Accessed 18th Feb 2013).

Jones, K.A., Ingham, M.R. and Bibby, H.M. (2008) 'The hydrothermal vent system of Mount Ruapehu, New Zealand - a high frequency MT survey of the summit plateau', *Journal of Volcanology and Geothermal Research,* vol. 176, no. 4, pp. 591-600 [Online], DOI: 10.1016/j.jvolgeores.2008.05.006 (Accessed 15th May 2013).

Kilgour, G., Manville, V., Della Pasqua, F., Graettinger, A., Hodgson, K.A. and Jolly, G.E. (2010) 'The 25 September 2007 eruption of Mount Ruapehu, New Zealand: Directed ballistics, surtseyan jets, and ice-slurry lahars', *Journal of Volcanology and Geothermal Research,* vol. 191, no. 1-2, pp. 1-14 [Online], DOI: 10.1016/j.jvolgeores.2009.10.015 (Accessed 20th Feb 2013).

Leonard, G.S., Johnston, D.M., Paton, D., Christianson, A., Becker, J. and Keys, H. (2008) 'Developing effective warning systems: Ongoing research at Ruapehu volcano, New Zealand', *Journal of Volcanology and Geothermal Research; Volcanic risk perception and beyond,* vol. 172, no. 3, pp. 199-215. [Online], DOI: 10.1016/j.jvolgeores.2007.12.008 (Accessed 20th Feb 2013).

Lokmer, I. and Bean, C.J. (2010) 'Properties of the near-field term and its effect on polarisation analysis and source locations of long-period (LP) and very-long-period (VLP) seismic events at volcanoes', *Journal of Volcanology and Geothermal Research*, vol.192, no.1–2, pp.35-47. [Online], DOI: 10.1016/j.jvolgeores.2010.02.008 (Accessed 20th April, 2013).

Lube, G., Cronin, S.J. and Procter, J.N. (2009) 'Explaining the extreme mobility of volcanic ice-slurry flows, Ruapehu volcano, New Zealand', *Geology,* vol. 37, no. 1, pp. 15-18 [Online], DOI: 10.1130/G25352A.1 (Accessed 20th April 2013).

Miller, C. (2013a) 'Volcanic Alert Bulletin RUA-2013/02 - Ruapehu Volcano' [Online], http://info.geonet.org.nz/pages/viewpage.action?pageId=4292767 (Accessed 4th July 2013).

Miller, V., Hurst, T. and Beavan, J. (2003) 'Feasibility study for geodetic monitoring of Mt Ruapehu volcano, New Zealand, using GPS', *New Zealand Journal Geology and Geophysics,* 2003, 46, 1, 41-46 [Online], DOI: 10.1080/00288306.2003.9514994 (Accessed 20th June 2013).

Mordret, A., Jolly, A.D., Duputel, Z. and Fournier, N. (2010) 'Monitoring of phreatic eruptions using Interferometry on Retrieved Cross-Correlation Function from Ambient Seismic Noise: Results from Mt. Ruapehu, New Zealand', *Journal of Volcanology and Geothermal Research,* vol. 191, no. 1-2, pp. 46-59 [Online], DOI: 10.1016/j.jvolgeores.2010.01.010

(Accessed 19th Feb 2013).

Morrissey, M., Gisler, G., Weaver, R. and Gittings, M. (2010) ‘Numerical model of crater lake eruptions’, *Bulletin of Volcanology*, vol. 72, issue 10 , pp. 1169-1178 [Online], DOI: 10.1007/s00445-010-0392-5 (Accessed 1st May 2013).

Neal, V.E., Houghton, B.F., Cronin, S.J., Donoghue, S.L., Hodgson, K.A., Johnston, D.M. Lecointre, J.A., Mitchel A.R. (2010) ‘Ruapehu Geology’ [Online], Available at http://www.gns.cri.nz/Home/Learning/Science-Topics/Volcanoes/New-Zealand-Volcanoes/Volcano-Geology-and-Hazards/Ruapehu-Geology (Accessed 20th Feb, 2010).

Page, S., (2012) ‘Eruption Hazards at Mt Ruapehu’ [Online], Available at http://gns.cri.nz/content/download/8868/47905/file/Ruapehu_Hazards_poster_A3.pdf (Accessed 22nd February 2013).

Palmer, B.A. (1991) 'Holocene lahar deposits in the Whakapapa catchment, northwestern ring plain, Ruapehu volcano (North Island, New Zealand)', *New Zealand Journal of Geology and Geophysics*, vol. 34, p.177–190 [Online], DOI: 10.1080/00288306.1991.9514455 (Accessed 20th February 2013).

Pardo, N., Cronin, S., Palmer, A., Procter, J. and Smith, I. (2012) 'Andesitic Plinian eruptions at Mt. Ruapehu: Quantifying the uppermost limits of eruptive parameters', *Bulletin of Volcanology*, vol. 74, no. 5, pp. 1161-1185 [Online], DOI: 10.1007/s00445-012-0588-y (Accessed on 20th February, 2013).

Price, R.C., George, R., Gamble, J.A., Turner, S., Smith, I.E.M., Cook, C., Hobden, B. and Dosseto, A. (2007) 'U–Th–Ra fractionation during crustal-level andesite formation at Ruapehu volcano, New Zealand', *Chemical Geology*, vol. 244, no. 3–4, pp. 437–451 [Online], DOI: 10.1016/j.chemgeo.2007.07.001 (Accessed 20th Feb 2013).

Rowlands, D.P., White, R.S. and Haines, A.J. (2005) 'Seismic tomography of the Tongariro Volcanic Centre, New Zealand', *Geophysical Journal International,* vol. 163, no. 3, pp. 1180-1194 [Online], DOI: 10.1111/j.1365-246X.2005.02716.x (Accessed 20th April, 2013).

Sherburn, S. (2011) 'Mitigating eruption risks – GeoNet and the Mt Ruapehu eruption', *GeoNet News*, Issue 14 [Online], Available at http://info.geonet.org.nz/download/attachments/951214/GeoNet_News_14.pdf (Accessed July 10th 2013).

Sherburn, S. and Bryan, C.J. (1999) 'The Eruption Detection System: Mt. Ruapehu, New Zealand', *Seismological Research Letters*, vol. 70, no. 5, pp. 505-511 [Online], DOI: 10.1785/gssrl.70.5.505 (Accessed July 3rd 2013).

Smithsonian Institute (n.d.) 'Global Volcanism Program – Ruapehu' [Online], Available at http://www.volcano.si.edu/world/volcano.cfm?vnum=0401-10=&volpage=erupt (Accessed 22nd February 2013).

Snieder, R.K., Trampert, J., (1999) 'Inverse problems in geophysics' In: Wirgin, A. (Ed.), *Wavefield Inversion*, Springer, New York, pp. 119–190 [Online], Available at http://samizdat.mines.edu (Accessed 10th July 2013).

Symonds, R.B., Gerlach, T.M. and Reed, M.H. (2001) 'Magmatic gas scrubbing: implications for volcano monitoring', *Journal of Volcanology and Geothermal Research,* vol. 108, no. 1-4, pp. 303 [Online], DOI: 10.1016/S0377-0273(00)00292-4 (Accessed 20th May 2013).

Varekamp, J.C., Pasternack, G.B. and Rowe, G.L. (2000) 'Volcanic lake systematics II. Chemical constraints', *Journal of Volcanology and Geothermal Research*, vol. 97, no. 161–pp179 [Online], DOI: 10.1016/S0377-0273(99)00182-1 (Accessed 10th July 2013).

Werner, C., Christenson, B.W., Hagerty, M. and Britten, K. (2006) 'Variability of volcanic gas emissions during a crater lake heating cycle at Ruapehu Volcano, New Zealand', *Journal of Volcanology and Geothermal Research,* vol. 154, no. 3, pp. 291-302 [Online], DOI: 10.1016/j.jvolgeores.2006.03.017 (Accessed 20th April, 2013).

## Acknowledgements

I would like to acknowledge all the helpful advice by my tutor, Mick Wright, in particular the guidelines on how to select a good project. Thanks also go to the course tutors for answering all students' questions.

Thanks also to Marion and Stuart for proof-reading this document.

# Appendix 1

## Recurrence interval based on historic frequency

The past 50 years of eruption data (Table 2.2), show that four relevant eruptions (sudden phreatic eruptions without precursor activity) occurred in 50 years. This gives a future recurrence interval based on the past history:

$$Recurrence\ interval,\ I_1 = \frac{Number\ of\ years}{Number\ of\ relevant\ eruptions} = \frac{50\ years}{4} = 12.5\ yr$$

$$\therefore\ I_1 = 10\ yr\ (1\ s.f.)$$

## Medium-sized sudden phreatic eruptions

Given a recurrence interval for all medium eruption of ~10 years (Table 2.1), and Barberi's estimate that 15% of all phreatic eruptions lack precursors (Barberi et al., 1992):

$$Yearly\ probability\ of\ a\ medium\ phreatic\ eruption,\ P_1 = \frac{1}{10} \times 100\ \%\ yr^{-1} = 10\%\ yr^{-1}$$

$$Yearly\ probability\ of\ a\ medium\ phreatic\ eruption\ without\ precursors,\ P_2 = 0.15\ \times P_1$$

$$= 0.15 \times \frac{10}{100}\ yr^{-1}$$

$$= 1.5\%\ yr^{-1}$$

$$\therefore\ Recurrence\ interval\ for\ medium\ phreatic\ eruption\ without\ precursors\ I_2 = \frac{1}{P_2}\ years$$

$$I_2 = \frac{1}{0.015}\ yr = 66.7\ yr = 70\ yr\ (1\ s.f.)$$