Blue-sky eruptions, do they exist? Implications for monitoring New Zealand's volcanoes.

A thesis

submitted in partial fulfilment

of the requirements for the Degree

of

Master of Science in Disaster and Hazard Management

at the

University of Canterbury

by

Angela Louise Doherty

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

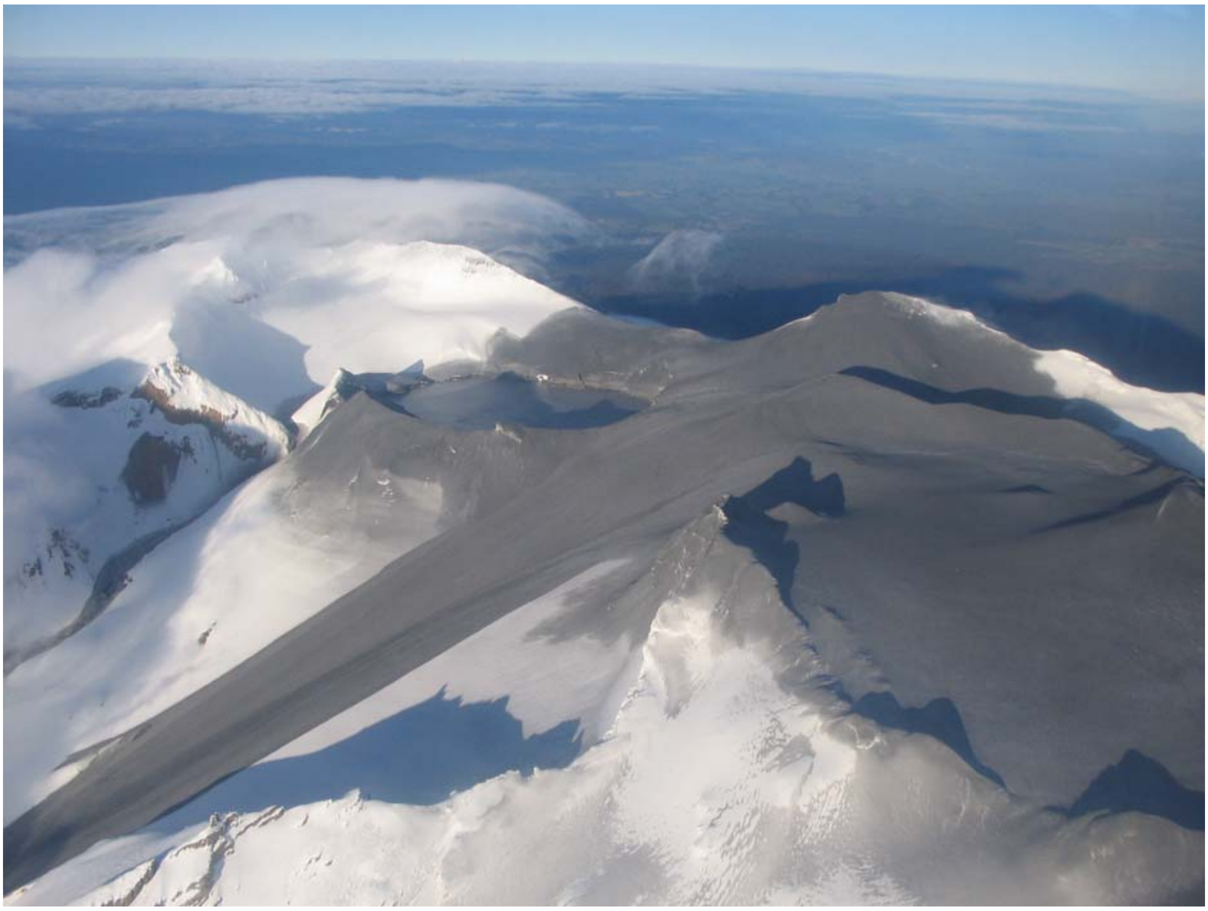
University of Canterbury

2009

Frontispiece

"What are the odds, right?"
"Before it happened it would have said slim, but since it did happen I would say 100%..."

Dr Ray Langston replying to Catherine Willows (played by Lawrence Fishburne and Marg Helgenberger – CSI: Crime Scene Investigation).



Lahar following the September 2007 eruption of Ruapehu (photo: GNS Science).

Abstract

The term "blue-sky eruption" (BSE) can be used to describe eruptions which are unexpected or have no detected precursory activity. Case study analyses indicate that they have a diverse range of characteristics and magnitudes, providing both direct and indirect hazards and occur in both under-developed and developed countries. BSEs can be a result of physical triggers (e.g. the lack of physically detectable precursors or a lack of understanding of the eruption model of the volcano), social triggers (such as an inadequate monitoring network), or a combination of the two. As the science of eruption forecasting is still relatively young, and the variations between individual volcanoes and individual eruptions are so great, there is no effective general model and none should be applied in the absence of a site-specific model. Similarly, as methods vary between monitoring agencies, there are no monitoring benchmarks for effective BSE forecasting. However a combination of seismic and gas emission monitoring may be the most effective. The United States began a hazard and monitoring review of their volcanoes in 2005. While the general principles of their review would be beneficial in a monitoring review of New Zealand's volcanoes, differences in styles of volcanism, geographic setting and activity levels mean changes would need to be review to fully appreciate the risk posed by New Zealand's volcanoes. Similarly, the monitoring benchmarks provided in the U.S. review may not be fully applicable in New Zealand. While advances in technology may ultimately allow the effective forecasting of some BSEs, the immediate threat posed by unexpected eruptions means that effective management and mitigation measures may be the only tools currently at our disposal to reduce the risks from BSEs.

Acknowledgements

It takes a village to raise a baby, and apparently, to complete a Master's thesis. Firstly I would like to acknowledge all the support and guidance I received from my super-visory team, Tim Davies, Jim Cole and Gill Jolly. You were a dream team and I thank you for helping steer me in the right direction and not laughing too much at my penchant for 5 line sentences. I'd also like to sincerely thank the crew at GNS Science in Wairakei for their assistance and advice, especially Brad Scott and Craig Miller. Thank you my friends and ex-colleagues at the Hawaii Volcano Observatory, especially Kelly, Jeff and Jim for the email research and to Florian Schwandner for your insights into the principles of volcano monitoring. I'd also like to thank William Pike for taking the time to give me a phone interview which gave a valuable insight into the 2007 eruption of Ruapehu and made the dangers of this style of eruption tangible. Thanks go to the Mason Trust for their financial support and to the entire UoC Geology Department for their expertise and assistance.

To my fellow students, especially Elke, Hanna and Danni, thank you for your positivity, support and listening to my occasional rants. Thank you to those who read over things, gave advice, support and made me laugh (there are so many of you but especially Cooksey and the Facebook editorial squad). And finally, thank you my parents, Terry and Heather. Thank you for always believing in me and knowing it was worth a second shot. I could not have done this without you.

Table of Contents

List of Figures

List of Tables

Abbreviations

AVF – Auckland Volcanic Field

BSE – Blue Sky Eruption

CUSVO – Consortium of United States Volcano Observatories

DoC – Department of Conservation

OVC – Okataina Volcanic Centre

ERLAWS – Eastern Ruapehu Lahar Alarm and Warning System

GNS – Geological and Nuclear Sciences

GVO – Goma Volcano Observatory

LOLE – Loss of Life Event

MCDEM – Ministry of Civil Defence and Emergency Management

MVO – Montserrat Volcano Observatory

PDC – Pyroclastic Density Current

NOAA – National

NVEWS – National Volcano Early Warning System

TVZ – Taupo Volcanic Zone

UNDRO – United Nations Disaster Relief Organisation

USGS – United States Geological Survey

WOVO – World Organisation of Volcano Observatories

1

Introduction

Volcanoes have always been the sirens of the natural world, enticing people to explore and to understand them. They are responsible for some of the most terrifying and beautiful displays in nature. Their slopes provide fertile soils for growth, their vistas entice development and they encourage exploration by both the adventurous and the scientifically curious. However, as with the sirens of the Greek epics, volcanoes are responsible (both directly and indirectly) for innumerable deaths throughout the course of human history.

While in historical times, the natural forces of our planet were explained by angry gods and the actions of the world's inhabitants, the last two centuries have seen huge advances in our scientific understanding and exploration of the earth's interior. Since the first dedicated volcano observatory, the *Osservatorio Vesuviano*, began systematically monitoring Mt. Vesuvius in 1847, the focus has been on developing a greater understanding of volcanic eruptions to predict, assess and mitigate their effects on nearby communities (McGuire 1995b). Today, over 70 observatories employing hundreds of staff are monitoring the earth's volcanoes (Siebert & Simkin 2002). Hundreds of books and thousands of journal articles have been written on the subject of volcanoes and volcanic eruptions and conferences and workshops dedicated to furthering the study of volcanoes and volcanic hazards have been convened throughout the world. However, even with all the new technologies employed, the dedicated institutions set up and countless hours put into the monitoring and study of volcanoes and volcanic eruptions, people are still dying during eruption events.

Some fatalities during volcanic eruptions are, perhaps, unavoidable; people get too close, take unnecessary risks and pay with their lives. However, some fatalities suggest the question, did this have to happen? When a volcano erupts suddenly, seemingly without warning, or an unexpected event occurs during the course of an eruptive episode taking the scientific community surprise, we look back in retrospect and ask "What did we miss?" This thesis focuses on eruptions and events that came "out of the blue" and whether we will ever be able to accurately predict the onset and course of all volcanic eruptions.

1.1 Blue-Sky Eruptions

The term "blue-sky eruption" (referred to hereafter as "BSE") is a unique term used in New Zealand to describe volcanic eruptions that were unexpected or not preceded by any recognised increase in activity. The term may also be used to describe volcanic eruptions that produce unexpected phenomena, that is, events the monitoring body or the public were not prepared for. The recognition of these eruptions is important as they pose a significant risk to persons living near, or on the volcano at the time as, by their nature, they come with little or no warning. Additionally, blue-sky eruptions require a different response to that of other eruptions which may have had a monitored "ramp up" of activity.

While the event itself may have been unexpected, retrospective analysis of BSEs on well-monitored volcanoes has furthered the understanding of precursory activity (Keller 1986; Narvaez et al. 1997; Jimenez et al. 1999). Often volcanoes are shown to have provided some indications of their imminent eruption. A good example is the 1993 eruption of the Galeras volcano in Columbia, an event which will be discussed in this thesis. These retrospectively-explained eruptions can provide valuable insights into the role of monitoring on volcanoes which can produce BSEs.

1.2 Issues Surrounding Blue-Sky Eruptions

A question which arises from the above introductory remarks is whether blue-sky eruptions actually exist or whether they are a result of technological ineffectiveness, human error (including both errors in judgement or interpretation of precursory signals) or a combination of the two. Some may argue they are an artefact of currently inadequate technologies or methodologies and like many secrets in science, will be resolved as technology and understanding of the science advances. For example, while certainly some historical eruptions such as the 1886 eruption of Tarawera (described later in this thesis) were preceded by some activity (Keam 1988; Barnard 2003), the subsequent eruption was a surprise as the implication of that activity was not fully understood. These retrospectively explained eruptions, which were unexpected at the time of their occurrence but not completely unannounced, are very important to the science of volcano eruption prediction (particularly in BSEs) and their role will be described fully in this thesis.

Important questions to ask regarding blue-sky eruptions include:

- What constitutes a BSE?
- Is the term useful outside New Zealand?
- Why are BSEs important?
- Should we take into account our lack of knowledge surrounding an evolving science at the time of an eruption when trying to identify BSEs?
- Should we take into account the available monitoring technologies when assessing historic BSEs?
- If an eruption occurs on an inadequately monitored volcano, can we define it as a BSE?

Most of these questions are addressed in this thesis, the importance of BSEs is now considered.

1.3 The Importance of Blue-Sky and Retrospectively-Explained Eruptions

For years, scientists from all over the world have converged on volcanoes that begin a phase of activity, sometimes following centuries of inactivity. While the geological history of a volcano may be long, the historical record of eruptions is comparatively very short (Zeilinga de Boer & Sanders 2002). This means that scientists mostly rely on the geological record in developing an eruptive history and, from that, a model for future eruptions. The problem with this approach is that only the largest eruptions will be represented in the record. Discrete or transient eruptions, often explosive in nature, such as the 1993 eruption of Galeras Volcano in Columbia or the 2007 eruption of Ruapehu in New Zealand, will probably not be preserved in the geological record; but both these eruptions resulted in deaths and/or injuries. In fact, the precursory activity that preceded these eruptions was not identified in a useful way for the purposes of eruption prediction. It is only now, in retrospect that the scientific community has recognized the subtle signals that heralded the onset of these eruptions and begun to incorporate them into their eruption models (Narvaez et al. 1997).

While Ruapehu and Galeras Volcano were both considered to be active volcanoes, El Chichón volcano in Mexico was not. In fact, over 500 years had passed since El Chichón was last active, so that local residents and government officials did not consider it to be active at all (Espindola et al. 2000b; De la Cruz-Reyna & Martin Del Pozzo 2009). When the volcano started showing signs that it was beginning to reawaken, it was too late and the eruptions occurred before monitoring authorities could arrive on site. This eruption, as well as the eruptions of Ruapehu and Galeras, will be discussed in Chapter 3.

Eruptions at reawakening volcanoes can be particularly hard to predict. As the repose period between large eruptions of a volcano can be many times longer than a human lifespan, no record may exist of the precursory activity expected before an eruption at a volcano. Activity caused by the intrusion of a new magma source and its ascent to the surface may be entirely different to the activity expected by the reactivation of an existing active system (Menand & Tait 2001). Additionally, Scarpa and Gasparini (1996) noted that precursory activity detected before eruptions from reawakening volcanoes at the end of last century (e.g. Mt. St. Helens, Pinatubo, Unzen, El Chichón) differed between sites and, furthermore, patterns observed between eruptions at the same site could also be very different.

The historical record for many volcanoes extends only 100 to 200 years at best. As volcanic activity can be cyclic (Takada 1997; Denlinger & Hoblitt 1999) the pattern of activity leading up to an eruption can be the most important piece of information needed for mitigating the hazard. However, we do not really know what to expect in the way of precursory activity from a volcano until we see it. The great geological mantra, “The past is the key to the future" (Francis & Oppenheimer 2004, p. 448) tells us that the best indication of future activity is past activity, so in this respect, retrospectively explained eruptions can give useful insights for prediction.

A blue-sky eruption or event is important because it emphasises gaps in knowledge. Whether or not any precursory activity is later identified in retrospect, blue-sky events are an important factor to be considered in any effective hazard analysis or mitigation programme. Planning for the unknown and recognising there are gaps in our knowledge are equally as important as planning for events based on what we know.

1.4 Thesis Outline

Chapter 1 provides a brief outline of the issues surrounding blue-sky eruptions and why they are important to the science of volcano monitoring and eruption forecasting.

Chapter 2 defines blue-sky eruptions and blue-sky events and provides background information on volcano alert level systems. Additional background information is provided on volcanic eruption styles and volcanic hazards in regards to their applicability as blue-sky events.

Chapter 3 describes blue-sky eruption and event case studies with examples drawn from New Zealand and overseas. Here a discussion on the cause of and eruptions blue-sky status is also provided as to whether they have physical or social triggers.

Chapter 4 outlines volcano monitoring techniques in a general sense and with regards to New Zealand's volcano monitoring network. Discussion on effective monitoring networks for forecasting blue-sky eruptions is also provided.

Chapter 5 describes the U.S. NVEWS (National Volcano Early Warning System) review of volcanoes under the jurisdiction of the USGS (United States Geological Survey) and CUSVO (Consortium of U.S. Volcano Observatories). The review model is applied to New Zealand volcanoes to test its application in a New Zealand Setting. There discussion on the NVEWS review and how it relates to a New Zealand setting in terms of volcano monitoring and eruption forecasting (particularly BSE forecasting). Recommendations are made for any NVEWS-style review that may be undertaken in New Zealand.

Chapter 6 discusses the mitigation and management of blue-sky eruptions in terms of reducing the risk of BSEs if effective eruption forecasting is not available. Recommendations on mitigating BSE risk from New Zealand volcanoes are also made in this chapter.

Chapter 7 provides a summary of the main conclusions and recommendations of this study.

2

Blue-Sky Eruptions and Events

2.1 Definition

2.1.1 Blue-Sky Eruption

To those outside New Zealand, the term “blue-sky eruption” is relatively unknown. In New Zealand it has been used to describe eruptions that occur without any precursory activity such as the 2007 eruption of Ruapehu.

To effectively distinguish BSEs from their more expected counterparts, they should be clearly defined. However, as the activity preceding eruptions clearly varies between individual volcanoes and the criteria for raising the concern of the monitoring authority also varies, the definition of what constitutes a BSE should be flexible. A simple definition would describe BSEs as eruptions that occur when the agency responsible for monitoring the volcano has not recorded any increase in activity that would normally precede an eruption. In other words:

- *A BSE is an eruption that occurs suddenly when a volcano is in a quiescent state.*

However, many of the world’s volcanoes are in a perpetual state of activity, however low-level it may be. In New Zealand these volcanoes are distinguished as “Frequently Active” and have a completely different alert level system from volcanoes currently not exhibiting any activity, known as “Reawakening” volcanoes. “Frequently Active” volcanoes have a different set of criteria for raising and lowering the level of alert (described in §2.2). A definition could use the Volcanic Alert Level system of the monitoring authority which could describe BSEs as occurring when the volcano in question is at the lowest level of alert in its system. Such as:

- *A BSE is an eruption that occurs suddenly, when a volcano is in its quiescent state, or the volcano alert system is at a level typically representative of the volcanoes level of activity.*

This would indicate that the monitoring authority is not sufficiently concerned with activity on the volcano to declare an increase in risk. It would also cover eruptions such as the 2007 eruption of Ruapehu, which was at alert level 1 (not 0) when it erupted. Ruapehu is considered a “Frequently Active” volcano and has maintained a minimum alert level of 1 since its last major eruptions in 1995–1996.

2.1.2 Blue-Sky Events

Defining what would constitute an unexpected volcanic *event* is slightly more problematic. Firstly, an eruption event can be described as a particular phase or facet of an eruption. Often described as volcanic hazards, what are described here as “volcanic events” are events that occur during the course of an eruption or events that would not have occurred without the influence of the eruption.

Because volcanic eruptions are complex and can change their nature during the course of a single eruptive episode, classification nomenclature often lends itself more to describing phases of activity (Francis & Oppenheimer 2004). While it is true that the most likely nature of an eruption from any given volcano can be predicted based on the type of magma available to that system, other factors such as extraneous water, flank stability and even the weather can affect the progress of the eruption.

As described in more detail in §2.4, different eruption styles can result depending on the composition of the magma supplied to the system and the temperature and pressure conditions it experiences on ascent. Once an eruption is underway, a blue-sky event is best described as a facet or phase of the eruption that occurs and takes the users of the mountain or the monitoring authority by surprise. Many of the hazards described in §2.5 can be expected during certain eruption styles, perhaps suggesting that they cannot be classified as blue-sky events at all. When a hazard or process of a volcanic eruption deviates from this "expected behaviour", it becomes a "blue-sky" event. Taking this into account, a suitable definition for a blue-sky event could be:

- *A blue-sky event is a destructive process that occurs during the course of an eruption that deviates away from the expected behaviour of that event.*

2.2 The New Zealand Volcanic Alert Level system

The New Zealand Volcanic Alert System was designed to define the status of New Zealand's volcanoes and to allow the reporting of changes in activity which may indicate the onset of an eruptive episode (Coetzee 2004). It was developed as part of the 1994 National Civil Defence Plan by the Institute of Geological and Nuclear Science (now GNS Science Ltd) and what is now the Ministry of Civil Defence and Emergency Management (MCDEM). While alert systems differ greatly between countries, New Zealand's six-level system, with separate subsystems in use for "Frequently Active Cone Volcanoes" and "Reawakening Volcanoes" (Figure 1).

Table 1 lists the active volcanoes currently recognised in New Zealand and classifies them into "Frequently Active" and "Reawakening" states.

Table 1 – "Frequently active" and "Reawakening" volcanoes in New Zealand (GNS 2009).

Frequently Active Volcanoes	*Reawakening Volcanoes*
Ruapehu	Auckland Volcanic Field
Tongariro/ Ngauruhoe	Mayor Island
White Island	Northland
Kermadec Islands	Okataina
	Rotorua
	Taranaki
	Tarawera
	Taupo

Frequently Active Volcanoes		Volcano Alert Level	Reawakening Volcanoes	
Volcano Status	*Indicative Phenomena*		*Volcano Status*	*Indicative Phenomena*
Usual dormant or quiescent state.	Typical background surface activity; seismicity, deformation and heat flow at low levels.	0	Usual dormant or quiescent state.	Typical background surface activity; seismicity, deformation and heat flow at low levels.
Signs of volcano unrest.	Departure from typical background surface activity.	1	Initial signs of possible volcano unrest. No eruption threat.	Apparent seismic, geodetic, thermal or other unrest indicators.
Minor eruptive activity.	Onset of eruptive activity, accompanied by changes to monitored indicators.	2	Confirmation of volcano unrest. Eruption threat.	Increase in number of unrest indicators (seismicity, deformation, heat flow etc).
Significant local eruption in progress.	Increased vigour of ongoing activity and monitored indicators. Significant effects of volcano, possible effects beyond.	3	Minor eruptions commenced. Real possibility of hazardous eruptions.	Minor steam eruptions. High increasing trends of unrest indicators, significant effects on volcano, possibly beyond.
Hazardous local eruption in progress.	Significant change to ongoing activity and monitoring indicators. Effects beyond volcano.	4	Hazardous local eruption in progress. Large-scale eruption now possible.	Eruption of new magma. Sustained high levels of unrest indicators, significant effects beyond volcano.
Large hazardous eruption in progress.	Destruction with major damage beyond volcano. Significant risk over wider areas.	5	Large hazardous eruption in progress.	Destruction with major damage beyond active volcano. Significant risk over wider areas.

Figure 1 – Volcanic Alert Level system for New Zealand (after Coetzee 2004)

2.3 Worldwide Alert Level Systems

In some cases, a single monitoring authority may monitor many different volcanoes, for example the United States Geological Survey (USGS). However, many volcanoes are monitored by individual observatories and have their own guidelines and alert level systems. Here, the alert level systems of two monitoring authorities are described briefly. It must be noted that the level of monitoring and reporting will differ greatly between individual authorities and volcanoes.

2.3.1 United States Geological Survey (USGS), U.S.A.

The USGS provides a single 4-level volcano alert system and a corresponding aviation colour code system (Figure 2; Gardner & Guffanti 2006). This system was designed to accommodate the diverse volcanic hazards associated with the 169 volcanoes which the agency monitors. It is designed to be used with a bulletin detailing the nature of the activity and potential or current associated hazards. The volcano alert level is provided with a colour code describing the eruptions hazard to aviation (i.e. Watch–Orange). The Aviation Colour Code system was developed by the International Civil Aviation Organization, (a UN specialist agency) as part of the International Airways Volcano Watch, a universal warning system for civil aviation.

Volcano Alert Levels	Aviation Colour Code
Normal Volcano is in a typical background, non-eruptive state. *Volcanic activity has ceased and volcano has returned to non-eruptive background state.*	**Green** Volcano is in a typical background, non-eruptive state. *Volcanic activity has ceased and volcano has returned to non-eruptive background state.*
Advisory Volcano is exhibiting signs of elevated unrest above known background level *Volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.*	**Yellow** Volcano is exhibiting signs of elevated unrest above known background level *Volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.*
Watch Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain. **OR:** Eruption is underway but poses limited hazards.	**Orange** Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain. **OR:** Eruption is underway with no or minor volcanic-ash emissions (plume height specified if possible).
Warning Hazardous eruption is imminent, underway, or suspected.	**Red** Hazardous eruption is imminent, with significant emission of volcanic ash into atmosphere likely. OR: Eruption is underway or suspected with significant emission of volcanic ash into atmosphere (plume height given if possible).

Figure 2 – USGS Volcano Alert and Aviation Colour Code system. Note the alternate meaning for the decrease in activity listed here in italics (from Gardner & Guffanti 2006).

This system has a certain level of flexibility to accommodate different eruptions styles because the two alert systems can operate independently. For example, an eruption at Kilauea Volcano in Hawaii may pose a significant risk to those on the ground, but may not produce any significant amounts of volcanic ash. Therefore, the alert for an eruption such as that shown in Figure 3 would trigger an alert of "Warning" but an aviation colour code of "Orange" whereas an eruption of a volcano in the Aleutian Islands may produce significant amounts of ash and produce both a "Warning" and "Red" alert.

Figure 3 – Lava flows at Kilauea volcano in 1986. Note while these eruptions represent a significant hazard, they do not produce large ash emissions constituting significant aviation hazard (photo: U.S. Department of the Interior, U.S. Geological Survey).

While this system seems effective, a "one-size-fits-all" system does produce some problems. For example, when the Halema'uma'u crater began vigorous gas emissions for the first time in decades in mid-2008, the aviation alert level was already at "orange" as it was tied to the "watch" volcano advisory even though the threat had increased considerably (J. Kauahikaua pers. comm., 2008). The system was not intended to have a rigorous connection but has over time developed an intrinsic link between the two alert systems and now, only certain combinations are permitted within the overall framework of the system (Figure 4).

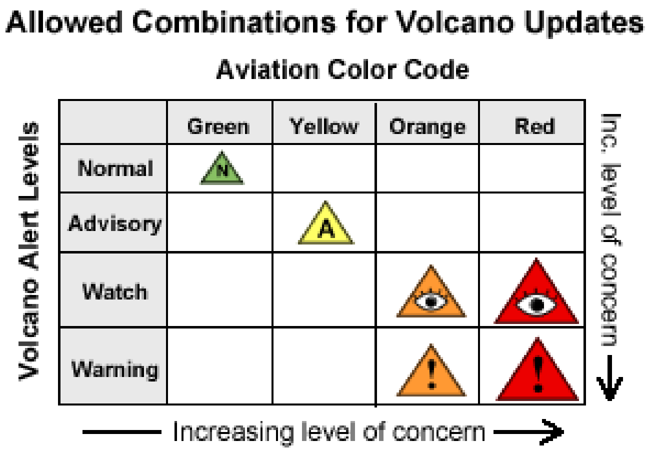
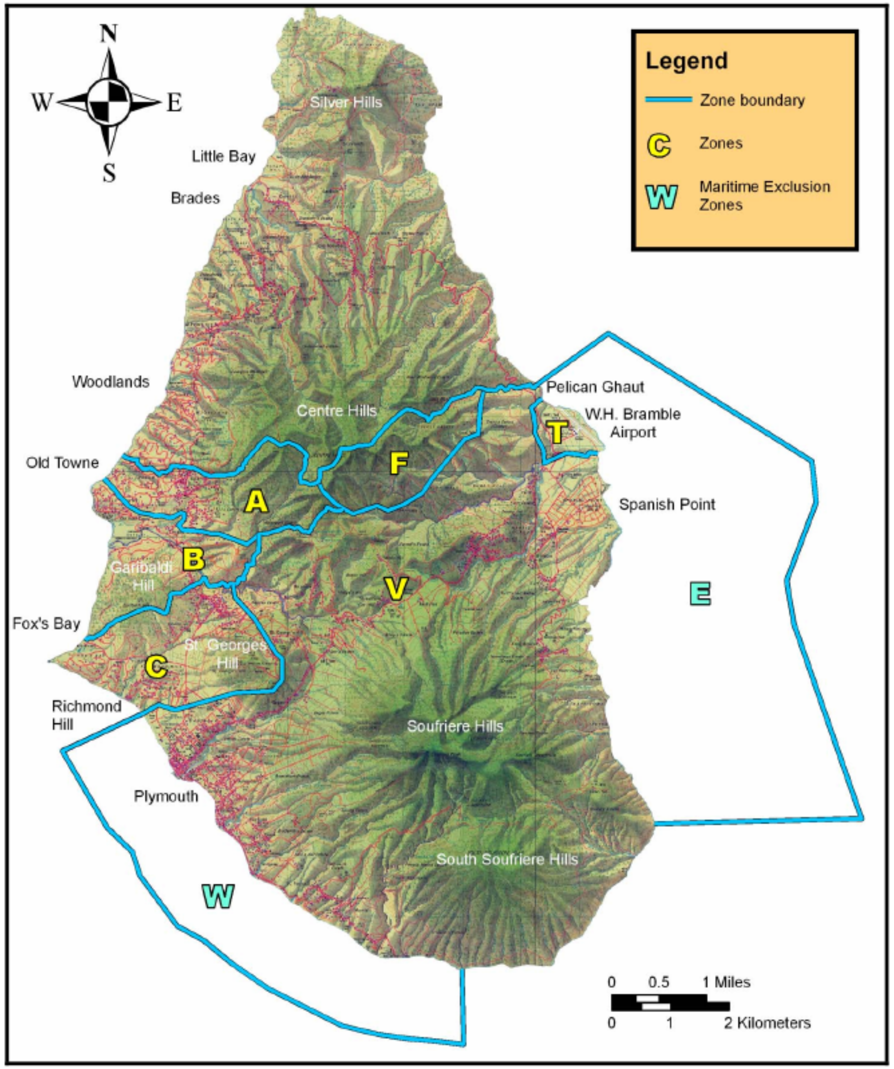


Figure 4 – Combinations permitted within the USGS Volcano Alert Notification System (from Gardner & Guffanti 2006).

Among the 5 volcanic observatories operated by the USGS there is variation in the way the alerts are presented: the different observatories provide different amounts of additional information. In the case of the Hawaiian Volcano Observatory, considerable additional information on the local hazards associated with the ongoing eruption at Kilauea is provided (J. Kauahikaua pers. comm., 2008). Currently the most effective means of accessing the volcano alerts for the USGS is through the internet: bulletins are issued by the different observatories to local media and government agencies as appropriate.

2.3.2 Montserrat Volcano Observatory (MVO), Montserrat, West Indies

In April 2008, the British Geological Survey handed management of the MVO over to a joint team of the Eastern Caribbean's two major geotechnical organisations, the Seismic Research Centre (SRC) of The University of the West Indies, Trinidad and Tobago and the Institut de Physique du Globe de Paris (IPGP), France. Together with the Disaster Management Coordination Agency (DMCA), a new Hazard Level System was developed to replace the old Alert Level System in August 2008. The Hazard Level System divides the southern end of the island of Montserrat into six zones with two maritime exclusion zones also defined (Figure 5). With changing hazard levels, access permitted in the eight zones also changes with a general decrease in access with an increase in hazard level.



Hazard Level[1]		1	2	3	4	5
Typical Activity[2]		More than one year with no measured activity.	No activity that threatens the north or west.[3] Low measured activity.[4]	Mild activity that threatens the west.[5] Significant change of measured activity.[6] High measured activity.[7]	Lava extrusion that threatens the north or west. Large unstable dome to the north or west.	Threat of large pyroclastic flows to the north or north-west. Threat of lateral blast or sector collapse.
Zones	A	Unrestricted	Unrestricted	Unrestricted	Unrestricted	Controlled access
	B	Unrestricted	Unrestricted	Unrestricted	Controlled access	Controlled access
	C	Unrestricted	Daytime access	Controlled access	Controlled access	Essential workers
	F	Unrestricted	Daytime access	Daytime access	Controlled access	Controlled access
	V	Daytime access to some areas	Controlled access	Essential workers	Essential workers	Essential workers
	T	Daytime access	Controlled access	Controlled access	Essential workers	Essential workers
Maritime Exclusion Zones	W	Unrestricted	Daytime access	Daytime transit	Essential workers	Essential workers
	E	Unrestricted	Essential workers	Essential workers	Essential workers	Essential workers

[1] The Hazard Level is not related to the Alert Level used prior to 1 August 2008.

[2] The descriptions of types of volcanic activity are indicative only. The level will be set by the MVO based on assessment of the actual activity.

[3] For example, growth contained by the crater or non-growing lava dome contained by the crater.

[4] Measured activity refers to all the monitoring techniques used by the Montserrat Volcano Observatory (MVO) including seismic, ground deformation, gas measurements and visual observations.

[5] For instance, mild ash venting from vents located on the northern or western side of the crater with no measured activity that might be a precursor to larger activity.

[6] Any change in measured activity which may be the precursor to an eruption caused by a sudden rise of magma beneath the dome. This may, or may not, be accompanied by surface activity such as explosions or dome growth.

[7] A high level of measured activity which may be the precursor to an eruption caused by the steady rise of magma within the volcano. This may, or may not, be accompanied by surface activity such as explosions or dome growth.

Figure 5 – The new Montserrat Volcano Observatory Hazard Alert System. Note with an increase in hazard level, different levels of access are permitted within the different zones defined on the map. Note the colour system is not related to the Aviation Colour Code system (MVO 2009).

This differs from many alert systems: it integrates the changes in volcanic activity with the changing hazard to the local community. It accomplishes two tasks in one, informing the public on the state of the current activity, and allowing the immediate restriction or releasing of access to different areas at risk on the island. While the former task is typically a responsibility of a monitoring authority, the latter is often considered a "response" action and is often coordinated by another agency on the basis of the current alert level. This integrated system is a result of the relative small size of the community and their needs.

As many residents on Montserrat do not have regular access to the internet, a comprehensive information and outreach programme is employed by the MVO.

2.4 Eruption Styles

2.4.1 Magmatic Eruptions

In very general terms, there are two types of magmatic volcanism, effusive and explosive. An explosive eruption can be used to denote any eruption in which lava is fragmented and ejected from a vent in a stream of gas (Parfitt & Wilson 2008). Fragmentation can range from clots of lava, sometimes larger than a meter in diameter being hurled hundreds of meters into the sky during Hawaiian-style fire fountaining events to tiny particles produced during Plinian eruptions and carried many tens or hundreds of kilometres from the source. An explosive eruption is more likely to termed "blue-sky" because of the volcanic hazards it produces (these hazards are outlined in §2.5). Whether an eruption is going to be effusive or explosive depends on the properties of the magma involved as well as the setting in which the eruption occurs.

In some cases, eruptions are explosive because the rising magma interacts with a water body of some sort, either shallow surface water (described as Surtseyan eruptions) or groundwater (often called phreatomagmatic eruptions). Often interactions between a crater-lake and rising magma produce particularly explosive events which may herald the onset of a volcanic episode. When an external water source is not present or affecting the current phase of an eruption, the rheology of the magma plays a stronger role in the style of eruption.

Typically, a magma contains three phases; melt, crystals and gas. The compositions, size and concentration of these phases dictate the final erupted product. The processes behind the composition of an erupted lava and the mechanisms of eruption are quite well understood and described in literature (Cas & Wright 1993; Francis & Oppenheimer 2004; Parfitt & Wilson 2008) and outlined in Figure 6.

	Volcanic Rock (endmember) Types		
	Basalt	Andesite	Rhyolite
Volume at Earth's surface	80%	10%	10%
SiO2 content	45–55%	55–65%	65–75%
	Increasing SIO_2 →		
Temperature of magma (°C)	1,000–1,300	800–1,000	600–900
	Decreasing Temperature →		
Viscosity	Low → High		
Water dissolved in magma	~0.1–1 wt. %	~2–3 wt. %	~4–6 wt. %
Gas exsolution	Easy → Difficult		
Eruptive Style	Effusive → Explosive		

Figure 6 – Volcanic endmembers and the origins and properties of their magmas.

In their comprehensive treatise on volcanic facies and successions, Cas and Wright (1993) noted that magmas may erupt coherently then flow as coherent flows, they might fragment during flow or erupt explosively to form various pyroclastic products. These authors also described the relationship between the originally erupted material the resulting deposit. They noted that the factors that affected the rheological behaviour of magmas included temperature, density, viscosity and mechanical (tensile) strength. While viscosity can be controlled by a number of factors including temperature and pressure, it is also strongly influenced by the magmas chemical composition, particularly the volatile and silica content. The most common volatiles dissolved in magmas are H_2O and CO_2 but H_2S, SO_2, HCl and HF are also often present (Parfitt & Wilson 2008).

The role of volatiles in magmas and bubble nucleation is pivotal to understanding why a magma produces an explosive eruption. The process is described fully in simple terms in Parfitt and Wilson (2008) and Cashman et al. (2000) and only briefly described here. Simply, different magma compositions allow different quantities of volatiles to be dissolved in the melt at different pressures. When this quantity is exceeded during magma ascent, that is, when the magma passes its saturation point, it becomes supersaturated and the excess volatile exsolves out of the magma, forming bubbles.

Bubble nucleation is complicated. As a bubble forms, surface tension acts against it, trying to force the volatile molecules back into the melt. If a melt contains crystals, the uneven surface of the mineral crystals provides a good location for volatiles to accumulate, facilitating bubble growth at greater depths. If no crystals are present in the melt, bubble growth can be significantly delayed by as much as ~100MPa (corresponding to approximately 4 km depth) and the melt can become supersaturated in volatile elements.

As it continues to rise and the pressure on the system decreases, more and more volatiles will be exsolved from the magma. Bubbles then begin to grow though one of three processes. *Diffusion* occurs where volatile compounds still dissolved in the magma migrate into the forming bubbles. *Decompression* occurs where the volume of the bubble is governed by Boyle's Law, meaning if the pressure on the bubble decreases, as happens during ascent, the volume of the bubble increases. *Coalescence* occurs where the buoyancy of the bubbles in the magma encourages them to rise as the magma itself rises, catching up with and incorporating smaller, more slowly moving bubbles.

In low viscosity magmas, bubble coalescence and magma ascent rate determines the style of eruption. If the ascent is slow, bubble coalescence encourages the gas to segregate from the magma entirely, forming a series of magma slugs as seen in strombolian and vulcanian eruptions (Figure 7). If magma ascent is rapid, bubble coalescence cannot occur and gas and magma remain linked, resulting in continuous explosive eruptions such as Hawaiian fire fountaining events. As the gas can escape easily through the lower viscosity lavas, the system releases pressure slowly and constantly. Highly-evolved, silica-poor magmas restrict gas movement as they are more viscous and result in explosive eruptions.

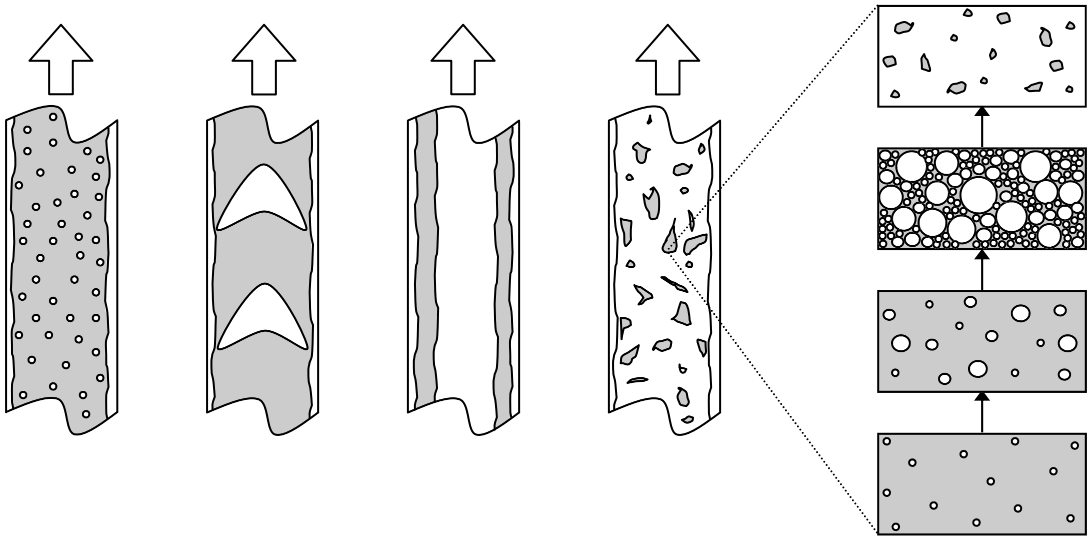


Figure 7 – A. Lava flow regimes. Suggested resulting eruption styles from left to right; effusive hawaiian, strombolian or vulcanian, hawaiian fire fountaining, phreatomagmatic or plinian and the four stages of bubble growth during magma ascent, leading to magma fragmentation in phreatomagmatic and plinian eruptions (modified after Jaupart 2000; Parfitt & Wilson 2008).

Different volatiles have different levels of solubility in magmas. Water, for example, has a higher solubility in rhyolite magmas than in basaltic magmas (Parfitt & Wilson 2008). In theory, this means that bubble nucleation will begin in basalts at a much greater depth than rhyolites. CO_2 is much-less soluble in both basaltic and rhyolitic magmas and as such will begin to nucleate at a much greater depth than water. This makes changes in CO_2 production at a volcano a good indicator of magma ascent in the system.

Bubble formation can directly influence the fragmentation of a magma (Figure 7) and is governed by a number of factors, chiefly, but not exclusively, by the magmas composition. As seen in Figure 6, the quantity of dissolved volatiles (here represented by water) is higher in the more evolved magmas like rhyolites as is the silica (SiO_2) content. The high silica content makes the magma more viscous, which restricts bubble movement and does not allow the gas to escape as the magma ascends. This effectively locks the gas in place in the magma allowing diffusion and decompression to occur. The higher volatile content can result in larger amounts of exsolved gases which create a more fragmented flow. This effect can be seen above in Figure 7 as bubble growth increases to a point where the walls break down, creating a dispersed flow where magma fragments are carried to the surface in a stream of gas. As the gas is unable to escape effectively, the system becomes highly pressurised and gas is eventually released suddenly and explosively.

2.4.2 Phreatic and Hydrothermal Eruptions

Phreatic and hydrothermal eruptions differ from magmatic eruptions in that no juvenile material is produced. There is, however, confusion regarding the use of the term “phreatic”. Some authors (e.g. Barberi et al. 1992) use the term synonymously with “hydrothermal”, that is, an eruption or explosion that occurs as a result of the flashing of water to steam without the input (either mass or energy) of a magma source. While others (e.g. Browne & Lawless 2001; Francis & Oppenheimer 2004) use the term to describe an eruption or explosion that occurs as a result of magma coming into contact with (or otherwise heating) water. Here, the nomenclature of Browne and Lawless (2001) will be used, which describes phreatic eruptions as having a magmatic heat source but producing no juvenile material. Browne and Lawless describe hydrothermal eruptions as an eruption that ejects at least some solid material and whose energy is solely derived from heat loss and phase changes in a convecting hot water or steam dominated hydrothermal system (Browne & Lawless 2001, p. 300).

Hydrothermal eruptions often originate close to the ground surface and result from the sudden depressurization of a system causing steam generation. The generation of the steam provides the energy required to fracture and eject country rock until steam production falls to a level that no longer supports the eruption. Hydrothermal eruptions can be a result of exploitation of the geothermal system or occur as part of the natural systems evolution (Browne & Lawless 2001). They differ from geysers in that they contain some solid material and that the ejection mechanism for geysers is a volume change due to boiling and is often cyclic.

2.5 Volcanic Hazards

Volcanoes can present a number of hazards to both human life and property and to the wider environment. The hazard posed by any single volcanic eruption depends on a number of factors including; the type of volcano, time elapsed since the last eruption, location of the volcano, local climate and even the time of year (Parfitt & Wilson 2008).

Effusive volcanism such as that at Kilauea volcano in Hawaii causes a different set of volcanic hazards than explosive volcanism like that of Stromboli in Italy. Additionally, as those eruptions are ongoing, they provide different threats than eruptions from volcanoes with longer periods of repose such as Pinatubo and Mount St. Helens. Often, the properties of magma and the volcanic setting are the most influential parameters in the type of volcanic hazards possible during an eruption (Figure 6).

With nearly three quarters of Earth's surface is composed of igneous rocks and approximately 10% of the planets population living near active or potentially reawakening volcanoes, mitigation is not a simple case of avoiding the hazard (Peterson & Tilling 2000). As noted in a report by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2008), since 1950 the population of the earth has increased from 2.5 billion to over 6.5 billion at an average growth rate of 1.79% per annum. The same report predicted that by the year 2050, the population will grow to an estimated 9.15 billion. With over 900 million people living close to volcanoes and many millions more at risk from distal volcanic hazards associated with ash and airborne particulates and gases, understanding the possible hazards is essential in constructing effective mitigation.

Numerous hazards are associated with volcanoes and volcanic activity ranging from poisonous gas emissions to tsunamis created by flank collapses. Descriptions of different types of volcanic hazards and their effects can be found in a number of books and papers both in general terms (e.g. Sigurdsson 2000a; Francis & Oppenheimer 2004; Parfitt & Wilson 2008) and in respect to individual volcanoes or volcanic complexes (e.g. Nairn et al. 1996; Stix et al. 1997a; Marti et al. 2008). Here, volcanic hazards will be briefly discussed in terms of their potential to be manifested as blue-sky events.

2.5.1 Lava Flows

Lava flows are a common eruption hazard, but pose more risk to property and infrastructure than to people (Peterson & Tilling 2000) because lava flows have velocities low enough to allow evacuation ahead of the lava flow front.

Lava flow velocities depend on silica content (and therefore its viscosity), the rate at which it is discharged from the vent and the angle of the slope upon which it is travelling. Pahoehoe flows have been measured travelling at 64 km/h on a 10° to 25° slope during the 1855 eruption of Mauna Loa in Hawaii and a narrow aa-lava flow was measured travelling at a rate of 3.6 km/h during the Eldfell eruption in Heimaey in Iceland (Tiedemann 1992). Lava velocities of up to 30 km/h have been measured in lava tubes during the most recent eruptions at Kilauea (K. Wooten pers. comm. 2008) During an exceptional eruption of the Nyiragongo volcano in the Democratic Republic of Congo in 1977, the extremely fluid, foiditic lava reached up to 100 km/h as it drained suddenly from the lava lake, covering an area of 20 km^2 in less than one hour (Tazieff 1977).

Some lava flows may exert very little force on the structures they encounter with cases of flows engulfing masonry structures up to the 2nd floor without destroying the building (Tiedemann 1992). Workers in Heimaey during the 1973 eruption of Edfell volcano in Iceland used the masonry buildings and streets to channel the lava and cool it (Jonsson & Matthiasson 1997). Wooden structures, both in the direct path and along the periphery of lava flows, are usually destroyed by fire (Figure 8).

Other less-obvious hazards associated with lava flows have both physical and social consequences. One such is landslides due to slope instability created by the additional weight of new lava flows on hillsides. Social and health hazards associated with the forced relocation of people whose homes are either destroyed or in danger and the destruction or damage of vital supply and transportation networks are another less immediate possible consequence of lava flow emplacement (Peterson & Tilling 2000).

Figure 8 – The masonry buildings of Heimaey (above) withstood the lavas onslaught and were able to be restored to use within a year of the 1973 eruption. Wooden homes in Kalapana, Hawaii were completely incinerated when the thin lava fronts entered their communities, during the extended eruption of Kilauea (photos: HVO 2007).

In general terms, it is unlikely that lava flows could produce blue-sky events unless they were of an exceptionally fluid composition, such as those at Mt. Nyiragongo in the Democratic Republic of Congo. In recent years, computational numerical modelling has been employed to model lava flow paths on some volcanoes (e.g. Felpeto et al. 2001; Crisci et al. 2004; Del Negro et al. 2005). This approach has had reasonable success particularly in modelling the 2002 eruptions at Mt Etna, Italy (Figure 9).

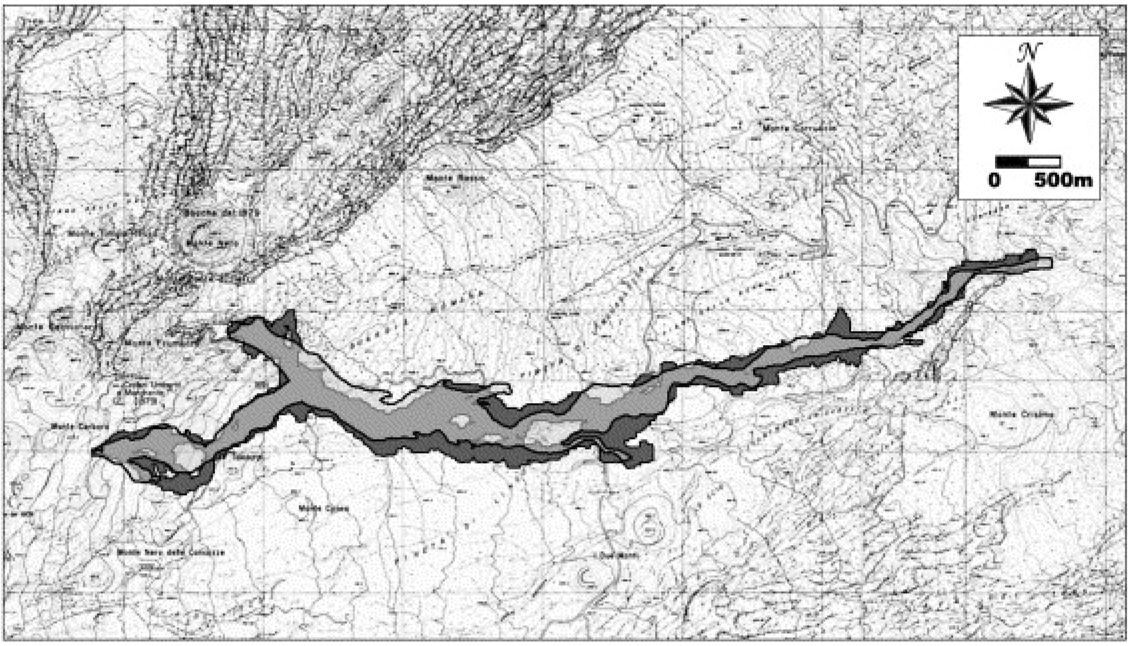


Figure 9 – Real (light grey) vs. simulated (dark grey) lava flow paths using SCARIA γ2 release for the 2002 eruption of Mt Etna (from Avolio et al. 2006b).

2.5.2 Air-fall Tephra

Tephra is a term which describes all fragmental material released from a vent during an eruption or explosion. It can also be used to describe material transported in the form of pyroclastic flows and surges. However, in this section we will only consider tephra in terms of material ejected from vents, travelling along ballistic trajectories or falling out of eruption columns and clouds. Tephra is classified by size. Fragments greater than 64mm in diameter are called *blocks* or *bombs* depending on whether they were solid or still partially melted when ejected from the vent (respectively). The term *lapilli* denotes pyroclasts that range in size between 2mm and 64mm and *ash* fragments are less than 2mm in diameter (Cas & Wright 1993). Air-fall tephra can travel in ballistic trajectories or be carried buoyantly inside eruption columns, until the upwards motion of the plume can no longer support them and they fall back to earth. Eruption columns that reach higher into the sky can disperse clasts of a given size much farther than lower eruption columns (Francis & Oppenheimer 2004).

Tephra fallout is the most common and widespread of volcanic hazards. The hazard from air-fall tephra is not usually from the direct impact of the material but rather the accumulation of the material (e.g. on roof tops of structures downwind of the volcano).

The hazards caused by air-fall tephra can be greatly affected by the weather at the time of the eruption. During the 1991 eruption of Mt Pinatubo in the Philippines, Typhoon Yunya passed within 75 km of the volcano on the same day as the paroxysmal event. The added weight of the torrential rainfall which saturated the ash accumulated on the roofs of structures downwind of the volcano (Figure 10), dramatically increased the level of destruction they caused (Oswalt et al. 1996). The variable winds caused by the typhoon also caused ash to be distributed about a larger range of azimuths than it would have otherwise been.

Figure 10 – Rain-saturated ash from the 1991 eruption of Mt Pinatubo in the Philippines collapses a roof in a public market (photo: T. J. Casadevall U.S. Geological Survey).

Fine airborne tephra is also a significant hazard for the aviation industry. Aircraft encounters with volcanic ash between 1980 and 1998 caused more than US$250 million in damages to aircraft and deaths due to multiple engine failure were only narrowly averted during eruptions in Indonesia, Alaska and the Philippines (Miller & Casadevall 2000). As volcanic ash clouds do not normally appear on aircraft weather instruments, a pilot can be completely unaware of approaching the ash-cloud. The ash is highly corrosive and abrasive and will immediately abrade the exterior forward-facing surfaces of the aircraft including the windshield. Ash will accumulate in the engines and cause abrasion damage to the engine parts, particularly the fan blades. As the melting temperature of the silica within the ash is often within normal operating temperatures for a large jet engine (700°C or higher), it can result in melting and resolidification of ash particulate over vital avionics and engine equipment (Miller & Casadevall 2000).

Pilots now have operational guidelines to assist them in if they find themselves flying into eruption clouds (USGS 2006). Additionally, the formation of the International Airways Volcano Watch (IAVW) by the International Civil Aviation Organisation (ICAO) allows any of the nine Volcanic Ash Advisory Centres (VAAC) to respond to reports of volcanic ash in their region and provide forecasts to the aviation community (Wellington VAAC 2009).

2.5.3 Pyroclastic Flows, Surges and Block and Ash Flows

Pyroclastic flows, also known as pyroclastic density currents (or PDC's), are among the most devastating events associated with volcanic eruptions. Pyroclastic flows contain mixtures of hot lava fragments, ash, pumice and gas and can travel incredibly quickly. They take a number of forms and can originate either from the gravitational collapse of Plinian eruption columns, collapse of lava flows and domes or directly from the vent itself (Nakada 2000). They are among the best studied volcanic hazards and detailed descriptions of their flows and deposits can be found in many textbooks (e.g. Cas & Wright 1993; Sigurdsson 2000a; Parfitt & Wilson 2008). Here they are discussed as they satisfy the criteria for a blue-sky event in terms of the unexpected onset and behaviour.

A pyroclastic flow usually consists of 3 parts, the basal avalanche, the ash cloud surge and the overriding ash cloud. While PDC's generally travel along topographic lows such as valleys and river beds, in certain circumstances they can 'decouple', that is, the ash cloud surge and ash cloud can travel independently from the basal avalanche even over bodies of water (Tiedemann 1992). This means that while the basal avalanche may follow the topography, the ash cloud surge may ride up over topographic boundaries. This phenomenon can occur very quickly and without warning and there are documented cases of ash cloud surges overriding topographic highs and overwhelming those who thought they were safe. This was the case during the 1991–1995 eruption of Unzen volcano in Japan (Fisher 1995; Fujii & Nakada 1999) and the ongoing eruption of Soufrière Hills, Montserrat, West Indies (Edmonds & Herd 2005). It is also the mechanism by which many thousands died during the historical eruptions of Krakatoa, Indonesia, in 1883 and Mount Pelée, Martinique, West Indies, in 1902 (Fisher 1995).

As with lava flows, modelling of pyroclastic flow paths for the purposes of hazard assessment has been undertaken on many volcanoes (Figure 11; e.g. Wadge et al. 1998; Takahashi & Tsujimoto 2000; Avolio et al. 2006a). These and other simulations have resulted in a better understanding of pyroclastic flow dynamics and allowed more accurate hazard assessment maps to be created (Saucedo et al. 2005). As our understanding of the dynamics of pyroclastic flows increases, the extent to which they can be consider "blue-sky" decreases. For this reason, unless a pyroclastic flow propagates in a way that is totally unexpected, it is unlikely they can be considered a BSE.

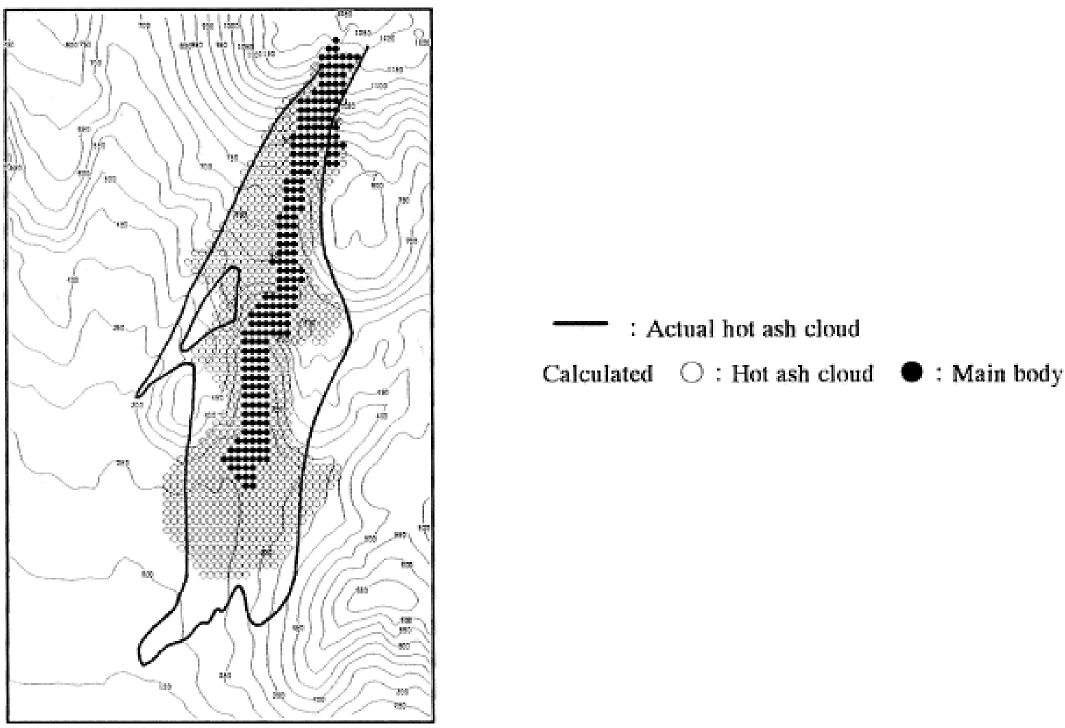


Figure 11 – Real vs. Simulated pyroclastic flow path modelling for a pyroclastic flow from the 1991 eruption of Unzen Volcano, Japan (from Takahashi & Tsujimoto 2000).

2.5.4 Lahars and Mudflows

Lahars and mudflows are also destructive and deadly volcanic hazards (Rodolfo 2000). They can be hot, if unconsolidated material is eroded from a recent pyroclastic flow or hot tephra bed (Parfitt & Wilson 2008). Lahars flow further down the slopes of volcanoes than pyroclastic flows, and can carry blocks and debris to more heavily populated plains. Lahars can change their character as they flow downstream, eroding and scouring out the river beds they tend to follow, adding sediment to their load (or "bulking up") to the point where they become hyperconcentrated debris flows. They can then transform back into water-rich hyperconcentrated flows or floods in distal regions (Vallance 2000).

Lahars can have a number of origins. Remobilization of pyroclastic material after an eruption due to rainfall is the most common origin but lahars can also be triggered by melting of ice or snow-caps by hot ejecta, crater lake evacuation or failures or by volcanic landslides (United States Geological Survey 2009). Lahars triggered by torrential rain falling on poorly consolidated pyroclastic deposits are not usually considered 'volcanic events' as the trigger for these events does not have a volcanic origin (Vallance 2000). For this reason, this style of lahar is not considered a blue-sky event herein. Additionally, crater-lake break-out, unless they occur as a direct result of a volcanic eruption, are also not best described as "blue-sky" events. For example, the 1953 Tangiwai train derailment, New Zealand's worst volcanological disaster, occurred after a lahar generated by the partial failure of the crater rim of Ruapehu, washed away the railway bridge at Tangiwai. This disaster resulted in the deaths of 151 people but occurred 8 years after the 1945 eruption had ended (Manville et al. 2007). Indeed, this style of lahar, which results from a failure in the crater wall, often requires a length of time to have passed after an eruption has ceased in order to refill the crater lake.

Both the amount of unconsolidated or loose debris on volcanic slopes and the integrity of the crater rim (and height of the crater lake) are able to be monitored. As lahars tend to follow river and stream channels, their paths are somewhat predicted. It follows that the hazard posed by these styles of lahars should be somewhat manageable in respect to the preservation of life. They can be, however, extremely destructive. While the size of a potential lahar caused by a crater lake break-out is constrained by the volume of the crater lake itself, rainfall triggered lahars are only limited by the size of the deposit they are eroding. This means that for eruptions that produce large amounts of tephra, especially pyroclastic flows and poorly consolidated flank deposits, lahars can continue to be generated by heavy rainfall for years after an eruption i.e. until the deposit has been completely eroded or vegetation prevents erosion. This was the case in the Philippines where Mt Pinatubo erupted in 1991 creating 5 to 6 km^3 of pumiceous pyroclastic flow deposits and 0.2 km^3 of air-fall tephra deposits on the flanks (Pierson et al. 1996; Scott et al. 1996). The lahars generated each rainy season from these deposits have been relatively small, but numerous and have completely altered the landscape. These deposits are still being eroded away as the post-eruption laharic activity continues today, almost 20 years after the eruption.

Landslide or flank-collapse triggered lahars are caused when part of a volcanic edifice detaches. This may occur during earthquakes (either volcanic or tectonic), following periods of torrential or extended rainfall, when a volcanic cone becomes unstable during magmatic intrusion or when an explosion (such as a lateral blast) propagates sideways through one of the flanks (USGS 2009). Apart from those landslide-generated lahars caused by torrential rainfall, these can occur as blue-sky events because of their inherent link to volcanic activity and the abruptness in which they occur. Flank collapse can also be the result of gradual edifice deformation over a spreading substrate (e.g. Socompa Volcano, Chile: van Wyk de Vries et al. 2001) but being non-eruptive these are not considered as BSEs herein.

Lahars originating from the melting of snow or ice by erupted material are probably the most likely form of lahar to be described as blue-sky events (Figure 12). These lahars are only as predictable as the eruptions that cause them. Some of the largest and most destructive historical lahars have been caused in this fashion either by pyroclastic flows melting large amounts of snow and ice deposited on a volcanoes flanks, or by the eruption of lava beneath a glacier which can lead to a substantial “glacial outburst” (United States Geological Survey 2009). These outbursts, called Jökulhlaups in Iceland, have resulted in the largest lahars in terms of discharge in historic times (Vallance 2000). During the 1918 Katla eruption, a Jökulhlaup was created with a discharge of between

300,000 and 400,000 m^3 per second, 20 times the discharge of the Mississippi River (Rodolfo 2000).

Figure 12 – Lahars caused by the melting of the summit snow cap stream down the flanks of Mount St Helens during its 1980 eruption (photo: Austin Post, U.S. Geological Survey).

2.5.5 Explosions and Directed (Lateral) Blasts

Strombolian and (particularly) vulcanian eruptions are characterised by a series of discrete violent explosions. These explosions are accompanied by ballistic ejection of blocks and bombs, atmospheric shockwaves and air-fall tephra (Morrissey & Mastin 2000). Occurring as either a single discrete event or in a pulsatory fashion, these explosions can herald the onset of plinian or sub-plinian eruptions, and can occur towards the end of such eruptions or without any accompanying larger magmatic event.

Vulcanian explosions are particularly violent producing higher ejection velocities (200–400 m/s), with shockwaves that rattle windows many kilometres from the vent and ejecting blocks and bombs to greater distances than other eruption-styles (Morrissey & Mastin 2000). The main hazard from these summit explosions is the direct effect they will have on anyone unfortunate enough to be at the summit at the time. This was the case during the 1993 eruption at Galeras volcano in which a vulcanian explosion killed six volcanologists who were carrying out research at the summit and three members of the public who had followed them to observe (Williams & Montaigne 2001).

Directed blasts (also called lateral blasts) can result from catastrophic depressurisation of a magma chamber usually caused by collapse or deep-seated failure of a volcano flank. Removal of the overlying rock allows the instantaneous expansion of pressurised steam in the cracks of the volcano and the exsolution of gasses dissolved in the underlying magma. During the 1980 eruption of Mount St Helens in the United States, a lateral blast travelling up to 1000 km/h destroyed everything within an area approximately 370 km^2. Directed or lateral blasts can also result from the explosive decompression of a lava dome (Belousov et al. 2007).

While the lateral blast at Mount St Helens is the most documented in historic times, the blast at Bezymianny Volcano, Kamchatka in 1956, was of a similar magnitude but observed from a greater distance (Belousov et al. 2007). Smaller blasts have occurred in recent times at Soufrière Hills, Montserrat in 1997 (Belousov et al. 2007), at Shiveluch Volcano, Kamchatka in 1964 (Bogoyavlenskaya et al. 1985) and at Lassen Peak, United States in 1915 (Eppler 1987).

2.5.6 Volcanic Gases and Limnic Eruptions

As mentioned in §2.4, volatile gases are produced during volcanic eruptions similar to those found in geothermal. Along with gas emissions such as carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrogen chloride (HCl), hydrogen fluoride (HF), hydrogen sulphide (H_2S), carbon monoxide (CO) and radon (Rn), heavy metals such as lead and mercury (Hansell & Oppenheiner 2004).

It is arguable whether gas emissions can constitute blue-sky events. It is more often the long-term exposure to, or the accumulation of volcanic gases that can cause serious injury or death. However, the National Park Service (NPS 2009) does monitor the SO_2 levels and wind direction at the Kilauea summit in Hawaii on a 15 minute basis and updates an advisory webpage in real-time. This site gives an estimation of the plume trajectories based on wind data and an advisory system with 5 levels based on SO_2 levels measured at 2 stations (Figure 13). Activities at the park are limited or cancelled based on current SO_2 levels at the summit as read from this site.

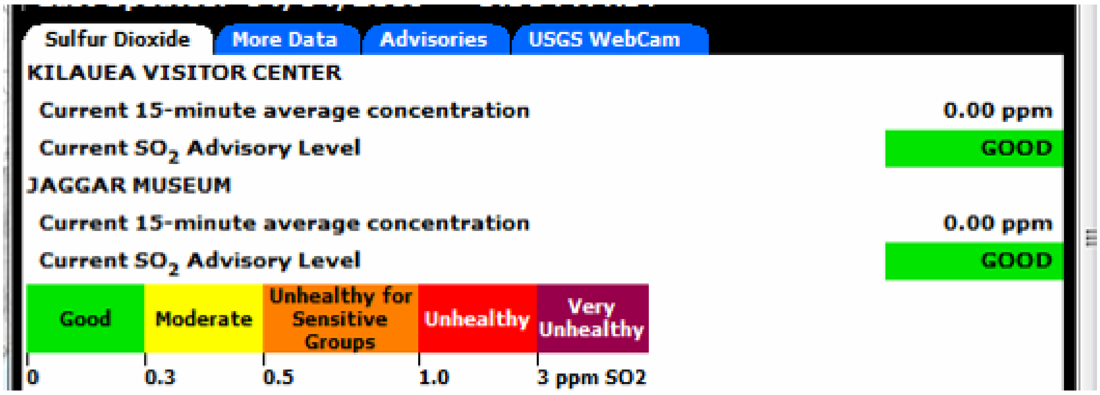


Figure 13 – NPS SO_2 advisory system (NPS 2009).

Limnic eruptions, also known as lake overturns, are less-known volcanic gas hazard. Limnic eruptions occur when a water body becomes heavily saturated with CO_2, either through magma degassing or the decomposition of plant material. The CO_2 accumulates at the base of the lake, kept in place by thermal stratification within the lake waters and the lack of disrupting forces such as direct interaction with a magma body or other turbulent processes. Because CO_2 is more soluble in water at high pressures, deep lakes can contain huge amounts of dissolved gases. When the water body is sufficiently saturated with CO_2, a trigger can cause the lifting of some saturated water into higher levels in the lake, where pressures are not sufficient to keep the CO_2 in solution. The CO_2 begins to exsolve and bubbles form and rise, dragging the saturated water towards the surface. A 'geyser' of gas forms, effectively sucking the CO_2 saturated water remaining at the bottom of the lake to the surface where it too undergoes decompression and exsolution of the dissolved gases in a runaway reaction. A small tsunami can occur as surface water is displaced by the erupting gas which then flows over the shores of the lake. As CO_2 is denser than air, it hugs the ground, displacing breathable air and causing asphyxiation and death to any livestock or people not sufficiently high enough to escape the cloud.

Limnic eruptions are very rare and have only been observed on two occasions, both in Cameroon. The eruption at Lake Monoun on 15 August 1984 killed 37 people while the second event, at Lake Nyos on 21 August 1986 killed between 1700 and 1800 people and thousands of livestock (Kling et al. 1987). In both instances, the CO_2 is suspected as having come from volcanic sources but the trigger mechanisms were most likely landslides into the lake, disturbing the stratified layers or an earthquake in the region.

Efforts to lower the amount of dissolved CO_2 in the lakes have included experiments in the creation of mini-limnic eruptions to continuously degas the bottom of Lake Nyos. A self-sustaining water pumps, draws CO_2 saturated water from the bottom of the lake through a vertical pipe, propelled by the waters own buoyancy as the CO_2 exsolves from the water (Figure 14). The same suction mechanism involved in the major limnic eruptions means that once the process is begun, it does not require any ongoing pumping (Halbwachs 2007).

Figure 14 – The self-sustaining geyser experiment at Lake Nyos, Cameroon (photo: Bernard Canet; Halbwachs 2007).

3

Blue-Sky Eruptions and Blue-Sky Events: Case Studies

In §1.2, a number of issues regarding the definition of an eruption as "blue-sky" were outlined. Many issues concerned the evolution of the science of volcanology and volcano monitoring and if this should have any bearing on whether an eruption should be classed as "blue-sky" or not. With a view to nullify these issues, emphasis has been placed on modern eruptions; those within the last 30 years. However, the 1886 eruption of Tarawera is also discussed due to its interesting eruption style. Case studies are described by their eruption style (magmatic or hydrothermal) and listed in chronological order.

3.1 Blue-Sky Eruptions – Magmatic

3.1.1 Okmok Volcano, Alaska U.S.A – 12 July 2008

Okmok Volcano is a large basaltic shield volcano in the Aleutian Islands, Alaska, U.S.A. A relatively young caldera (~2000 years old), Okmok erupts on average once every 10–20 years (Miller et al. 1998). On 12 July 2008, the Alaskan Volcano Observatory (AVO) was alerted to an eruption underway at Okmok by the U.S. Coastguard whose assistance had been requested for evacuation by a family living on the flanks (Larsen et al. 2009). The eruption was a complete surprise, having been only preceded by less than 5 hours of seismic activity. This was only identified in hindsight as being precursory activity, and only noticeably intensified an hour and a half before the eruption.

Okmok is one of the most active volcanoes in the Aleutian Arc with 14 confirmed eruptions since 1817 (Miller et al. 1998). Activity in the 20th century at Okmok Volcano has been characterised by effusive eruptions producing blocky basalt flows and minor explosive activity (Miller et al. 1998). The last major eruption in 1997 produced a 6 km long lava flow and intermittent low-level ash plumes (Patrick et al. 2005). The 2008 eruption lasted 5 weeks and was calculated at VEI 4, making it the most explosive eruption from Okmok Volcano in the last century (Larsen et al. 2009). It produced an initial eruption column estimated to have reached 16 km in height and was sufficiently explosive as to cause the family living on a cattle ranch on its flanks to self-evacuate (Figure 15).

Figure 15 – 20 July eruption plume of Okmok Volcano. Taken from an Alaskan Airlines commercial jet at 37,000 ft. Plume top estimated to be at 20,000 ft (photo: P. Walgren, courtesy of the AVO).

Discussion

The AVO monitors more than 20 volcanoes on the Aleutian Islands and Alaskan Peninsula, many of them solely through satellite remote sensing and telemetered networks (Moran et al. 2008). The 2008 eruption of Okmok Volcano fits this author's definition of a BSE very well. This eruption marked the first time in the history of the AVO that a volcano went directly from Volcanic Alert Level "Normal", Aviation Colour Code "Green" to "Warning" and "Red" (Figure 2), from one end of the alert spectrum to the other in a matter of hours (Larsen et al. 2009). For volcanoes at alert level green (as Okmok was prior to its eruption) the AVO protocol for monitoring activity involves a staff member physically checking the telemetered and remote sensing data twice a day (J. Larsen, pers. comm., 2009). The frequency was based on experience as the most rapid onset of an eruption prior to Okmok (moving from colour code green to red) which was 24 hours at Pavlof Volcano in 1996. According to Larsen (pers. comm., 2009) during regular working hours, a staff member is typically looking at the continuous seismic data constantly; however, as the eruption occurred on a Saturday morning, and there was no inclination of unusual levels of activity, the normal twice daily monitoring protocol was in place. The 1.5 hours of clear precursory activity increase occurred after the morning seismic check and therefore was missed. Staff only confirmed the eruption through seismic and satellite signals after the observation from the Coastguard.

Deformation has been monitored on Okmok Volcano since 1992 through InSAR and GPS studies (Fournier et al. 2009), and continuous, real-time seismic and deformation monitoring began in 2003. Although the 2008 eruption was the first to be monitored by real-time high temporal resolution ground instrumentation, no geodetic changes were noted prior to the 2008 eruption (Larsen et al. 2009). After the 1997 eruption, continuous inflation was detected at Okmok until 2005 when it ceased and remained quiescent until a short period of noticeable inflation in early 2008. Remote monitoring of this eruption was hampered by the water-rich nature of the 2008 ash plume, making satellite detection problematic as it obscured the ash signals (Larsen et al. 2009).

Due to the extremely fast onset of the eruption, the presence of a real-time seismic and deformation monitoring network, and the extensive eruption history of Okmok Volcano, the 2008 eruption is classed as a physical BSE. The eruption also highlighted issues with satellite detection and tracking of water-rich ash plumes.

3.1.2 Raoul Island, Kermadec Arc – 17 March 2006

On 17 March 2006, Raoul Island volcano erupted killing Department of Conservation employee Mark Kearney. Mr Kearney was taking measurements as part of the monitoring programme on the island near the crater lake when the eruption occurred (Cole et al. 2006). At the time, monitoring at Raoul Island consisted of a single seismic monitoring station and weekly direct measurements of temperature, geochemistry and phenomenology at the summit lakes. The last eruption of Raoul Island occurred in 1964 and since then a number of periods of increased activity have occurred without eruption. From 1989–1995, intermittent earthquake swarm activity had been detected, with large swarms occurring in 1989 and 1995 (Table 2). No eruption occurred at these times and the signals were largely interpreted as being volcano-tectonic in origin, with very few volcanic earthquakes detected (Cole et al. 2006). The only precursory activity measured before the 2006 eruption was an earthquake swarm, starting intensely on 12 March and declining steadily towards the eruption 5 days later.

Table 2 – Unrest at Raoul Island since 1964 (modified after Cole et al. 2006).

Year	Activity	Outcome
1964	11 days of strong seismic activity (max ~M5.9), Rises in summit lake levels. Increases in fumarolic activity and temperatures	Phreatic eruption
1989	300+ volcano-tectonic earthquakes. No other changes.	No eruption
1990	Earthquake swarm (up to ~180/day). 4 volcanic earthquakes, possible tremor. No other changes.	No eruption
1991	Six volcanic earthquakes and 4 periods of tremor (lasting 1–2 hours.	No eruption
1992	3 volcanic earthquakes (possible).	No eruption
1993	Earthquake swarm (up to 1 per minute, max ~M4.3) of volcano-tectonic earthquakes. Summit lake level rise. No change in temperatures or fumarolic activity.	No eruption
1995	Approximately 100 volcano-tectonic earthquakes. No other changes.	No eruption
2006	Earthquake swarm of high-frequency events. No volcanic tremor or other changes.	Phreatic eruption

Because in previous eruptions Green Lake had exhibited changes in level of the order of meters as well as increases in temperature, weekly measurements of these two parameters had been undertaken at the summit since 1964. Additionally, programmes monitoring ground temperature, lake tilt, geochemistry of the hydrothermal water and gas discharges were introduced in the 1980's and 1990's and continued regularly up until the 2006 eruption. These additional monitoring techniques yielded no discernable increase in activity prior to the 2006 eruption and were dominated mainly by seasonal variations and regional rainfall (Cole et al. 2006).

The occurrence of the 12 March earthquake swarm prompted a request from GNS Science for a closer data set to better monitor what could be the move away from baseline activity at the island. The frequency of measurements and observations at the summit increased from weekly to daily, a protocol similar to one employed after an earthquake swarm in 1993 prompted a 1.2 m increase in the level of Green Lake. The number of earthquakes then slowly declined until they were almost at background levels during the 12 hours preceding the eruption (Christenson et al. 2007).

Although the eruption was small in volume (approximately 200,000 m^3) and short in duration, it was particularly violent around the summit lakes (Rosenberg et al. 2007). Explosions from at least 35 sub-craters created a low plume which blanketed an area ~9 km^2 in tephra and devastated an area within 0.5 km of Green Lake with a series of lateral blasts (Figure 16). The eruption was later interpreted as a magmatic-hydrothermal event triggered by a swarm of local earthquakes (Christenson et al. 2007).

Figure 16 – Photo looking south over the eruption site at Green Lake (GNS 2009).

Discussion

In 2004, diffuse carbon dioxide (CO_2) flux measurements were conducted at Raoul Island in the area surrounding Green Lake. This indicated the total approximate flux of CO_2 was approximately 100 T/day, significantly lower than White Island (600–3000 T/day) or Ruapehu (400–1600 T/day) (Cole et al. 2006). As described in §2.4.1, the presence of CO_2 in the soils surrounding a vent can indicate the presence of a significant magmatic heat source at depth. Approximately 5.5 hours after the eruption, the OMI (Ozone Monitoring Instrument) satellite operated by NASA detected a plume above Raoul Island which contained approximately 200 tonnes of sulphur dioxide (SO_2). The presence of SO_2 would also indicate a magmatic origin to the eruption. However, later analysis showed none of the seismicity detected prior to the eruption was consistent with magma movement (Christenson et al. 2007). Additionally, analysis of the deposits of this eruption yielded no evidence of juvenile material indicating there was very little, if any, magmatic influence on the system.

Christenson et al. (2007), proposed a conceptual model for the 2006 eruption of Green Lake at Raoul Island. In their model, the lack of any precursory activity prior to the eruption was explained by the presence of a mineralogic seal between the hydrothermal system and the former eruption conduits. This allowed volatile magmatic gases to accumulate in the region below the seal. Hydrostatic pressure at the base of the seal increased as gas continued to accumulate until it ultimately failed. This would account for both the lack of seismicity attributable to magma movement prior to the eruption and the lack of lake level rise that would normally have been expected if the magmatic volatiles had been allowed to interact with the hydrothermal system.

3.1.3 Nyiragongo Volcano, Democratic Republic of Congo – 1997 & 2002

Nyiragongo Volcano, a stratovolcano in the Virunga volcanic group, is located in the central East African Rift system, on the northern shore of Lake Kivu (Hamaguchi et al. 1991). Since its discovery in 1894, Nyiragongo Volcano has fascinated the scientific community with its persistent lava lake and extremely silica-poor (>40 wt%), foiditic lavas (Tedesco et al. 2007). Only two documented eruptions have occurred at Nyiragongo Volcano on 10 January 1977 and 17 January 2002. Both eruptions resulted in the deaths of local residents, overtaken by the highly fluidic lavas which drained from the lava lake at speeds estimated to be up 100 km/h (Tazieff 1977; Komorowski et al. 2002; Chirico et al. 2009).

10 January 1977 Eruption

At approximately 0820 (LST), the 50+ year old lava lake at the summit of Nyiragongo Volcano drained suddenly, inundating an area of about 20 km² in less than a hour (Tazieff 1977). Draining through a series of perpendicular fissures collectively 20 km in length (orientated N–S and E–W from the summit) an estimated 20–22 million m³ of alkali-rich melilite nephelinite lava ran out into deserted jungle to the north and west and entered populated areas to the south and east of the summit crater. Here, the lavas ranging from 3m to a few millimetres in thickness, swept through multiple villages killing more than 70 residents, mostly children and the elderly (Komorowski et al. 2002).

The draining of the lava lake at Nyiragongo coincided with a flank eruption of its sister volcano Nyamuragira (also referred to in the literature as Nyamlagira (e.g. Tazieff 1977) and Nyamulagira (e.g. Komorowski et al. 2002; Tedesco et al. 2007)), 13 km north-north-west of Nyiragongo. Tazieff (1977) surmised the draining of the lava lake was probably preceded by an injection of new magma into the Nyamuragira-Nyiragongo system, evidenced by the both the eruption at Nyamuragira and overflow of the Nyiragongo lava lake in December 1976. However, Tazieff noted that large and comparatively quick fluctuations in the height of the lava lake at Nyiragongo were not unknown, occurring without eruption with successive eruptions at Nyamuragira Volcano throughout the 20th century.

After extensive retrospective analysis of the seismic record by Hamaguchi et al. (1991), precursory activity has been identified in the lead up to the 10 January 1977 eruption. This includes local reports of small felt earthquakes in the days leading up to the eruption and a M5.2 earthquake measured in the rift valley 130 km south of Nyiragongo on 6 January 1977. Volcanic tremor began after the 6 January earthquake, recorded on a regional seismic station closest to Nyiragongo Volcano. Hamaguchi et al. identified this seismic activity and the eruption of Nyamuragira on 23 December 1976 as a precursory signal of the Nyiragongo eruption but unlike Tazieff (1977), also categorised the fluctuation of the rising over the crater lake in the months before the eruption as precursory activity.

During this eruption, the lava flow front stopped approximately 3 km from the edge of the city of Goma, a town of over 500,000 inhabitants, but not before destroying many small villages higher on the flanks of the volcano. Goma lies approximately 15 km south of the volcano but Tazieff (1977) calculated that had 3 to 5 million m^3 of lava not drained through the North and West fissures, Goma and the nearby Rawandan town of Gisenyi would probably have been destroyed. Tazieff also postulated that fissure development and lava breakout was possible again, anywhere on the base of Nyiragongo Volcano, including areas close to, or even in, the cities of Goma or Gisenyi.

17 January 2002 Eruption

On 17 January 2002, lava again erupted from fissures on the southern flanks of Nyiragongo. This eruption was similar to the 1977 eruption with the lava originating from a series of N–S trending fissures which extended further southward than the previous eruption (Chirico et al. 2009). During an eruption lasting less than one day, 22 million m^3 of highly foiditic lava flowed down the flanks of the volcano (Francis & Oppenheimer 2004). Two highly-fluidic lava flows entered the city of Goma causing the spontaneous evacuation of over 300,000 people. Most evacuees escaped over the border into the neighbouring Rwandan town of Gisenyi (Favalli et al. 2009). Approximately 15% of the city was destroyed including part of the international airport and business district and 20,000 people were made homeless (Figure 17).

Precursory activity was similar in 2002 to the 1977 eruption. On 6 February 2001, Nyamuragira Volcano erupted and volcanic tremor and elevated levels of seismicity were recorded in the region, after 2 weeks the eruption had ceased. This activity was interpreted as heightened levels of fluid pressure within the volcano and reported by the Goma Volcanic Observatory (GVO) but was given very little attention by the local authorities (Komorowski et al. 2002). A tectonic earthquake on 7 October 2001 was followed by high-amplitude volcanic tremor and changes in the phenomenology at the summit including increases in the rate of degassing and temperatures recorded in fumaroles. However, it was not followed by an eruption as it was after the tectonic earthquake and high-amplitude tremor in 1977 and fumarolic activity eventually ceased at the summit.

Figure 17 – Fluidic lava flow destroys a house in Goma. Lava flows reached 200 feet in width (photo: Sayyid Azim; Associated Press).

On 4 & 7 January 2002, the sequence of events that occurred in October 2001 repeated in the Nyiragongo region. A tectonic earthquake of M4 was detected on 4 January but could not be located precisely and was accompanied by a dark plume emanating from the summit of Nyiragongo. Fumarolic activity was reactivated at the summit as a result of the 7 January event and seismicity remained at a high level in the region up to 16 January. The eruption of 17 January came after approximately 8 hours of very low levels of seismicity including the complete absence of volcanic earthquakes or tremor.

Again, the contents of the lava lake, present at the summit since 1995, drained through a series of fissures which opened at the base of the volcano. The eruption caused approximately 170 fatalities on 17 January and 60–100 more people were killed on 21 January when a gas station surrounded by still-hot lava exploded (Komorowski et al. 2002).

Discussion

The 1977 eruption at Nyiragongo is a good example of a blue-sky eruption. Although some literature has retrospectively identified precursory activity (Hamaguchi et al. 1991), the interpretation of these events was difficult due to the unique nature of the volcano itself (both in terms of geochemistry and phenomenology). Additionally, this being Nyiragongo's first eruption in historic times also made identification of precursors problematic.

Expansion of the border towns of Goma (D.R.C.) and Gisenyi (Rwanda) between the 1977 and 2002 was spurred by a series of humanitarian crises in the region (Tedesco et al. 2007). Nyiragongo lies in the east of the D.R.C. very close to the Rwandan border, in a region greatly affected by the refugee crises of the mid-1990's and ongoing armed conflicts. Vandalism and lack of funding meant the non-telemetered network maintained by the small GVO was often non-operational or operating only at partial capacity. This small seismic network comprising of 2 local seismograph stations (although it once consisted of 5 local stations) and another regional station located 100 km away, was the only monitoring effort on the volcano. The lack of instrumental coverage was partially overcome by the development of a network of well-informed local residents who liaised closely with the GVO, relaying valuable pre-eruption observations (Komorowski et al. 2002). While these observations did not clearly identify precursory activity, they indicated to the GVO scientists that a trend away from baseline activity had begun in the weeks leading up to the 2002 eruption.

In their comprehensive review of the 2002 eruption, Komorowski et al. (2002) explained that due to the lack of a multi-parameter integrated surveillance network in the region, other activity preceding the 2002 eruption, such as deformation and fracturing to the north of the volcano was missed. This coupled with the rarity of historical flank eruptions from Nyiragongo (the only other being the 1977 eruption), another fissure flank eruption as not considered a high probability. Additionally, clear interpretation of the data collected by the GVO was difficult due to the close proximity of Nyiragongo to Nyamuragira and the small number of operational seismic stations in the area (2, both analogue 1-component systems, up to 20 km from the volcano). It became impossible for GVO scientists to distinguish which volcano was producing the recorded seismic activity and a detailed study of the changes in phenomenology became more crucial in monitoring the volcano. Komorowski et al. (2002) noted that public concern would not have been high, as a survey conducted after the 2002 eruption showed that not one of the 995 respondents felt any seismic activity prior to the onset of the eruption.

The 1977 eruption of Nyiragongo is probably best interpreted as a blue-sky eruption that, when analysed in retrospect, was shown to have minimal, but detectable precursors. However, due to the rarity of these styles of eruptions and the ineffectiveness of the small monitoring network due to funding, access and security reasons, similar precursory activity was not clearly identified prior to the 2002 eruption. While some scientists point to the eruption of nearby Nyamuragira Volcano as a clear precursory signal (e.g. Komorowski et al. 2002; Tedesco et al. 2007), at least ten eruptions occurred at Nyamuragira between 1977 and 2002 that did not result in an eruption at Nyiragongo. The 2002 eruption further propagated fissures opened during the 1977 eruption and this, combined with the lack of lava emission on the northern side of the volcano, allowed lava flows to extend all the way to Lake Kivu, through the city of Goma. When coupled with the lack of precursory signals able to be discerned by the public, the people of Goma and the villages above it were taken by surprise when the eruption finally came on 17 January.

3.1.4 Galeras Volcano, Columbia – 14 January 1993

After resuming activity in 1988 following 50 years of dormancy, Galeras Volcano, Columbia, was declared a 'Decade Volcano' by the International Association of Volcanology and the Earth's Interior (IAVCEI). The only South American volcano on the list, Galeras was deemed to warrant special study and had been considered one of the most hazardous volcanoes in South America (Baxter & Gresham 1997). As a result, a special workshop run in conjunction with the International Decade for Natural Disaster Reduction was convened in the nearby city of Pasto in 1993 to discuss Galeras and future monitoring and research directions for the volcano. It was during a field excursion day, when the larger group split into small study interest groups to explore the volcano that the second in the series of 6 vulcanian eruptions occurred. The eruption killed 6 scientists and 3 tourists at the summit at the time.

This was a deeply felt tragedy, and because of it opinion as to the presence of precursory activity by the volcano is a hotly debated topic (Cortes & Raigosa 1997; Narvaez et al. 1997; Morrissey & Mastin 2000; Williams & Montaigne 2001). Debate revolves around the observations and activity of the volcano made by the survivors immediately before the eruption and the actions of those leading the expedition in the evacuation from the crater and cone (Williams & Montaigne 2001).

Galeras began its reactivation in 1988 with changes in gas emission rates, chemistry and seismicity (Stix et al. 1997a). In 1989 Galeras began producing explosive eruptions and in 1991 an andesitic lava dome was emplaced at the summit. The summit dome was destroyed by the first in a series of 6 vulcanian-style eruptions during 1992–1993. Harmonic tremor, which often precedes volcanic eruptions, was present for all 6 events but had subsided prior to the eruptions, as had other activity indicators such as gas emissions and other seismic indicators (Martinelli 1990; Narvaez et al. 1997; Stix et al. 1997a; Stix et al. 1997b). Only sporadic, screw-shaped seismic signals were recorded prior to the eruptions which, as the volcano had only recently reactivated, were not recognised as precursory activity (Figure 18).

The day prior to the eruption, scientists conducting microgravity measurements at the summit observed no unusual phenomenology at the summit and noted the presence of fumarolic degassing (Baxter & Gresham 1997). The eruption began at approximately 1340 (LST) with a vulcanian explosion and the ejection of red-hot blocks of juvenile material, up to 1 m in diameter. Ejected material gradually reduced in size until pea-sized lapilli and ash dominated. The seismic signal associated with the eruption lasted only 15 minutes (Cortes & Raigosa 1997) but eruptive activity continued for approximately 4 hours delaying rescue efforts (Baxter & Gresham 1997).

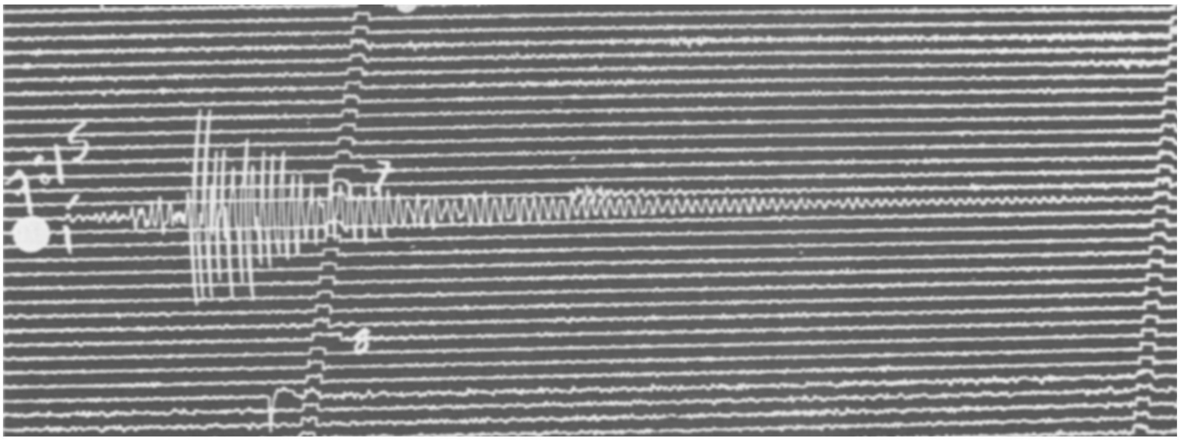


Figure 18 – Screw-shaped seismic signals, known as “tornillos” recorded prior to eruptions at Galeras (from (from Stix et al. 1997b).

Discussion

While retrospective analysis and subsequent eruptions have allowed the recognition of a cyclic pattern of magma pressurisation to emerge, those responsible for the crater excursion of the 14 January maintain it was unrecognizable at the time (Williams & Montaigne 2001). It serves, however, as a timely reminder of the dangers surrounding the prediction of behaviour of reawakening volcanoes.

If Galeras was a New Zealand volcano, it would be classed as “Frequently Active” and as such, some base level activity would be expected. Indeed it was the active fumaroles on the crater floor and rim that attracted the volcanologists to break from the rest of the party and hike down the amphitheatre and up the cone of Galeras (Williams & Montaigne 2001). There is, however, some strong evidence that Galeras had given precursory signals prior to the eruption in the form of what is now recognised as a characteristic earthquake swarm.

Known as ‘tornillos’, they represent a seismic signal with a characteristic shape, reminiscent of a screws thread (Narvaez et al. 1997). A tornillo swarm which lasted for 5 days, accompanied by a reduction in other measures of activity, preceded the first vulcaninan eruption of Galeras on 16 July 1992. What is now recognised as a second swarm began 16 days before the eruption on the 14 January 1993. However, the two swarms had very different characteristics including the length of the record that preceded the eruption and number of tornillo events recorded (Table 3). Indeed when analysed side by side, the tornillo swarms bear little resemblance to each other but do precede 5 of the 6 eruptions that took place between 1992–1993 (Narvaez et al. 1997). The swarms, and accompanying lulls in other activity, are now recognised as representing a partial solidification of magma and plugging of the conduit system of the volcano, which led to over-pressurisation and subsequent release in vulcanian style eruptions (Stix et al. 1997b).

Table 3 – Tornillo swarms preceding the 1992–1993 eruptions at Galeras Volcano, Columbia (modified after Narvaez et al. 1997).

Eruption Date	*Number of tornillo events*	*Days of activity recorded before event*
16 July 1992	9	5
14 January 1993	20	16
23 March 1993	74	37
4 April 1993	0	0
13 April 1993	6	3
7 June 1993	103	46

While recognition of this pattern came too late to prevent the deaths of the scientists and locals, the fourth eruption which occurred on 4 April 1993 was not preceded by this earthquake swarm or any other recognised seismic activity. This eruption occurred only 12 days after the previous eruption but it does not represent the shortest duration between events as it was followed only 9 days later by the 5th event in the series. Between the 4th event on 4 April and the 5th event on 13 April, a tornillo swarm was recorded consisting of 6 events in 3 days. Loss of life was most likely prevented due to this being the 4th eruption in less than one year and the short time since the 14 January event.

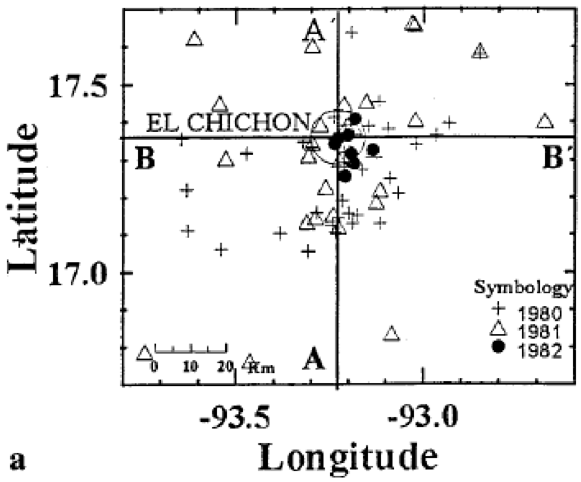
3.1.5 El Chichón Volcano, Mexico – March to April 1982

After approximately 500 years of quiescence, El Chichón volcano in south-east Mexico resumed eruptive activity in a series of eruptions over 7 days between 29 March and 4

April 1982 (Sigurdsson et al. 1984). While the first of the major eruptions (there were 10 in total) produced only tephra, the subsequent eruptions produced pyroclastic surges and flows which devastated a roughly circular region, 153 km² in area, around the mountain. The episode lasted only a week, but resulted in the deaths of an estimated 2000 local residents and the displacement of approximately 20,000 others (De la Cruz-Reyna & Martin Del Pozzo 2009). It was one of the largest volcanic eruptions in the 20th century (VEI 5), injecting about 7 million metric tonnes of sulphur dioxide (SO_2) and 20 million metric tonnes of particulate material into the stratosphere, a quantity only exceeded by Mount Pinatubo in 1991 (Robock 2002).

Although the chronology, geochemistry and stratigraphy of the previous eruptions have been described in depth in various papers (Sigurdsson et al. 1984; Macias et al. 1997; Espindola et al. 2000b; Tepley III et al. 2000; Krueger et al. 2008), the long period of repose led researchers to believe the volcano was extinct and consequently, it was not monitored. While the 1982 eruption came as a surprise to the larger scientific community, investigation in retrospect has again shown evidence of precursory activity, both empirical and anecdotal.

After activity had ceased, records were recovered from a seismic network set up to monitor the nearby Chicoasen dam system by the Comisión Federal de Electricidad (CFE) approximately 25 km south-east of the volcano (Jimenez et al. 1999). Operational from January 1980, in the 2 years before the 1982 eruption, around 240 individual seismic events (Figure 19) were identified, most with a depth of less than 25 km. While not ideally located or controlled to allow precise calculation of focal depth and location, the cautious approach taken by Jimenez et al. (1999) in their review of seismic activity attributed to the 1982 eruption leaves little doubt as to the association of these events with the subsequent volcanic activity.



Timeframe	No. of seismic events
1980	41
1981	28
Jan to Feb 1982	8
March 1982	171

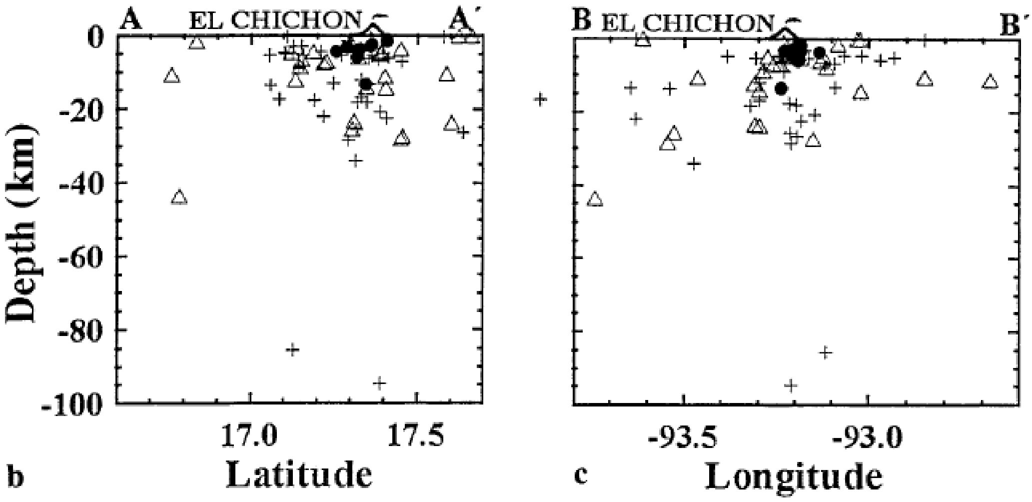


Figure 19 – Foci of events (2.8<MC<3.8) recorded between 1 January 1980 and 28 February 1982. Note the intense shallow activity starting in March 1982 is not represented (modified after Jimenez et al. 1999).

Intense shallow (<5 km depth) seismicity began approximately 1 month prior to the 29 March eruption and it was during this time that local residents began to feel some of the larger earthquakes. Reports of "underground noises" and shaking were made to the NSS (National Seismological Service) in Mexico City (Jimenez et al. 1999). Approximately one week before the onset of the eruption, local authorities requested the Instituto de Geofísica, Universidad Nacional Autónoma de México (IGEF) investigate the activity (De la Cruz-Reyna & Martin Del Pozzo 2009). At this time it was unclear to the IGEF whether the swarm was caused by volcanic or tectonic activity, the latter being not uncommon in the water-rich karstic rock of the Chiapas, or by dam impounding, the reason the Chicoasen seismic system was installed in the first place (De la Cruz-Reyna & Martin Del Pozzo 2009). There was, however, evidence of the presence of geothermal activity to accompany the seismic record made by geologists employed by the CFE during the course of their fieldwork on the mountain in December 1980 and January 1981 (Canul & Rocha 1981). This information was discussed internally by the Electricity Commission but was not, however, passed on to the IGEF until after the eruption.

Because of the remote location, deployment of a temporary seismic network was problematic and air support was required. The first flight, scheduled for 26 March was cancelled and rescheduled for 29 March, which, in an ironic twist, was the day after the first eruptions began.

Described in depth by De la Cruz-Reyna and Martin Del Pozzo (2009) in their first-hand account, the disaster that followed was a result of a number of factors, but due mainly to the decisions made by those in charge. As the early phases of the eruption were characterised by large amounts of ashfall, roads in the region quickly became impassable and local airports were shut down. This became problematic as the only large-scale disaster relief plan Mexico had on hand was one devised by the military in 1966 to deal with hydrometeorlogical disasters. This plan relied heavily on air support which made it impossible to implement immediately following the onset of the eruption due to the large amounts of ash. Additionally, this plan could only be enacted by presidential order, a further complication which saw the start of the plan delayed until 1 April.

As no civil defence or crisis-management institution existed at the time (the Civil Protection System was only created in May 1986 as a response to the 1985 Mexico City earthquake), initial actions were chaotic and un-coordinated. Roads became blocked in both directions with those trying to flee and those trying to enter the region looking for relatives or help with an unplanned evacuation. Although it was clear to scientists monitoring the new seismic network that the break in activity between 30 March and 4 April did not signal the cessation of the eruption, some of those evacuated were allowed to return to their homes while others were not evacuated at all. This led to the deaths of approximately 2000 people during the explosive eruptions and subsequent pyroclastic flows and surges on 4 April 1982.

Discussion

This catastrophe seems to have been attributable to a number of both man-made and natural factors. Firstly, the volcano was unmonitored. In New Zealand, El Chichón could be considered a “Reawakening Volcano” and therefore, the perception of local residents of the risks posed by the volcano was small. Although the volcano was considered to be ‘extinct’, indeed it had not erupted in at least 500 years, the geological record shows El Chichón volcano to be one of the most regularly active volcanic edifices in Central America, having produced more than 12 major volcanic eruptions in the past 8000 years (Espindola et al. 2000a). The seismic data showing direct evidence of an increase in activity, heralding, potentially, the start of a new eruptive event was only discovered after the catastrophe by those looking to retrospectively analyse the event. This meant the ascent of the magma was not discovered until the eruption was imminent, when earthquakes and other indicators were prominent enough to be noticed by the local residents.

The first eruptions predominantly produced ash and minor ballistics and occurred on the day representatives of the local scientific community were due to arrive in the region to investigate the local residents reports of increases in activity. This meant there was no organised evacuations before activity began other than those who chose to leave the area of their own volition. Additionally, there was no centralised emergency management group or plan made by the Mexican government and because of this, when the evacuations began, they were haphazard and poorly handled. It is estimated that the death toll from this stage of the eruption was a over 100 as people died when roofs and buildings collapsed due to a build up of ash (De la Cruz-Reyna & Martin Del Pozzo 2009).

After the temporary monitoring networks were set up, they were, by their own admission (De la Cruz-Reyna & Martin Del Pozzo 2009) autonomous and insular with little information sharing between the 2 major camps, the Instituto de Ingeniería UNAM (IINGEN) and the Instituto de Geofísica, Universidad Nacional Autónoma de México (IGEF). This was in part due to infrastructure systems in place that were able to cope with the conditions during the eruption, but also the lack of organised meetings between the groups. This meant the individual cells of scientists and the groups organising the evacuation (e.g. the Army and Government) only received a partial view of the eruption development.

The final Plinian stage of the eruption that occurred over 3 and 4 April 1982 came without warning. It was the pyroclastic flows and surges during this stage that killed upwards of 2000 within 6 km of the volcano. The temporary networks set up to record the ongoing eruption showed no evidence of the impending explosive phase and while it may have been anticipated, there was no indication of the timeframe in which it would occur (Jimenez et al. 1999; De la Cruz-Reyna & Martin Del Pozzo 2009). This was probably due to the initial ash-producing phases of the eruption, clearing the vent of obstructions and impediments to the final phase.

3.1.6 Historic Magmatic Blue-Sky Eruptions: Tarawera, New Zealand – 1886

A single eruption from Mt. Tarawera exists in the historical record. The eruption of Tarawera on 10 June 1886 marked the first major volcanic eruption in New Zealand since European settlement. It resulted in the deaths of approximately 120 people (this number is difficult to confirm as lists of the local Maori casualties differed and may be higher than previously recorded) and the destruction of a number of both European and Maori settlements (Keam 1988; Lowe et al. 2001). In particular, three Maori villages, Te Ariki, Moura and Waingongongo, were destroyed completely, buried under tonnes of volcanic debris and mud. The eruption at Tarawera is also the only eruption at a rhyolitic volcano in the Taupo Volcanic Zone in historical times, although this particular eruption was basaltic in nature (Walker et al. 1984).

The eruption began during the early morning hours of 10 June, when a series of earthquakes (which increased in intensity) heralded the start of a violent, short-lived eruption beginning at approximately 1:30 am and continuing for around 4 hours. The eruption began at, or near the Wahanga dome, one of 3 peaks which existed at the summit of Mt. Tarawera prior to the eruption, and opened a 7 km-long chasm across the upper parts of Tarawera (Figure 20; Walker et al. 1984). Additionally, craters (caused mainly by phreatic explosions) were created along an 8 km-long extension of the rift, south-west of the mountain which were in eruption during and after the main eruption at the summit rift zone (Cole 1970; Walker et al. 1984)

Figure 20 – The Tarawera rift system looking north-east. Tarawera above centre with Lake Rotomahana in the foreground. The Waimangu thermal valley continues south-west, from the front centre of the image (photo: GNS 2009).

Lying along the extensional rift to the south-west of the mountain was Lake Rotomakariri and Lake Rotomahana and within the latter lay the famous Pink and White Terraces. The 1886 eruption resulted in drastic changes to the Rotomahana Basin by the expulsion of a large amount of debris by the phreatic explosions during the eruption. The two original lakes were emptied and the streams through which they originally emptied into Lake Tarawera were destroyed. This resulted in a number of new lakes forming in and around their original location which continually filled and finally joined, creating the lake currently known as Lake Rotomahana. The Pink and White Terraces were probably completely destroyed (Cole 1970), although little sinter was discovered in the deposits of the surrounding area (Keam 1988).

Discussion

While hindsight allows the identification of a number of indications of an impending eruption in the days and weeks before the event, at the time there were not attributed to an increase in volcanic activity at the mountain, which was considered to be long extinct (Barnard 2003). In the years prior to the 1886, the Bay of Plenty region experienced a number of events that may have been linked to the eruption. In 1880, millions of dead fish washed ashore along the Bay of Plenty coast (Smith 1887). It was postulated by Smith to be caused by the submarine release of gases, changing the chemistry of the waters. The waters of Lake Rotokakahi experienced unaccountable rises and falls of up to 1.2m feet in April and October 1881 and in June of 1885, the crater lake of White Island disappeared (Smith 1887). While these events may not be directly linked to the 1886 eruption, they may have indicated a change in the stability of the Taupo Volcanic Zone system as a whole.

In the months and weeks preceding the eruption, the Rotorua Lakes District experienced changes in activity which may have been directly linked to the impending eruption. Increases in the geothermal activity in and around lakes Rotomakariri and Rotomahana and further afield in the Edgecumbe–Te Teko region to the north and the Wairakei area to the south were recorded in 1885 and early 1886. Additionally, reports of cessation and flooding of steams near the edge of Lake Tarawera were also recorded and, perhaps most significantly, reports of a wave, 9 inches to 1 foot in height on Lake Tarawera was recorded on 1 June 1886 (Smith 1887). Waves, or seiches, in lakes are often evidence of submarine debris flows or eruptions and, given the timing of these waves, could well have been associated with the subsequent activity at Mt. Tarawera.

A number of earthquakes were felt in the region prior to 10 June 1886, and were recorded by the new meteorological station at Rotorua. As there were no seismometers in the area, measurement of earthquake intensities was more empirical with earthquakes on 26 January, 30 March and 22, 28 and 30 April 1886, measured as “slight”, “slight”, “shock”, “shock” and “shock” respectively by Dr A. Grinders at the local meteorological station in Rotorua (Keam 1988). Although these records may suggest an increase in the intensity and frequency of activity in the region in the lead up to the 10 June eruption, the Bay of Plenty was considered an active region and these earthquakes were not considered in any way unusual, a notion reflected in the fact that these earthquakes were not recorded in any local media during this time (Keam 1988; Barnard 2003).

3.2 Blue-Sky Eruptions – Hydrothermal

3.2.1 Kuirau Park, Rotorua, New Zealand – 2001, 2006

Kuirau Park is a popular inner-city reserve in Rotorua. The Kuirau Fault underlies the park and is the permeable path along which hot geothermal fluids may be ascending in the area (Wood 1992). Rotorua lies within the Taupo Volcanic Zone in the central part of the North Island of New Zealand. The city overlies a large geothermal field that had been used to provide hot water and heating to the residents for much of the 20th century (Scott & Cody 2000). This practice continued until the 1980's when the effects of withdrawing the geothermal fluids on the regions geysers, significantly important in terms of tourism revenue for the city, were recognised and effective management strategies were put into place. One consequence of the exploitation of the geothermal system was an increase in hydrothermal eruptions in the city (Scott & Cody 2000).

On Friday 26 January, at approximately 3:30pm a muddy hot pool, identified as Spring 721, erupted. It was the first eruption in the park since 1964 (Scott 2001) and ejected blocks and mud up to 100m into the air. The pool, originally 2.5 to 3m in diameter became a steaming crater, 10m across (Scott 2001) and showered a region up to 120m from the vent with mud and blocks (Figure 21). Ejecta covered the adjacent highway and slopes of a nearby hospital, narrowly missing an English tourist who had withdrawn from the area after approaching to take a photograph and seeing the activity in the pool increase (Andrews 2001).

A second, smaller eruption occurred in the park on 10 December 2006. This eruption lasted over an hour and ejected mud and blocks 15 m into the air, landing up to 30 m from the pool (New Zealand Herald, 2006). This eruption, from Spring 615, occurred close to the 2001 eruption of Spring 721 but was much smaller in size.

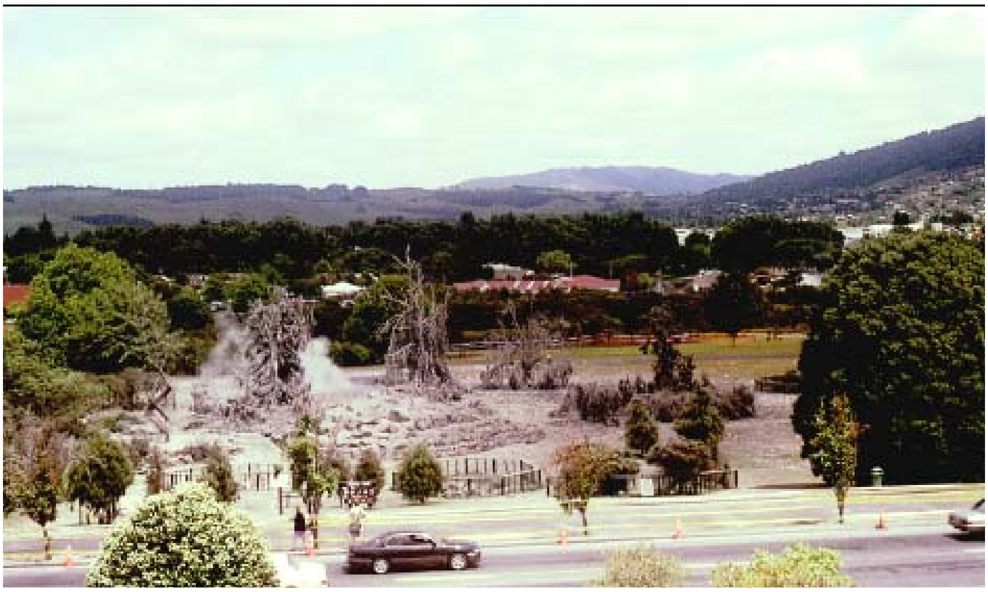


Figure 21 – Eruption of Spring 721 in Kuirau Park, 26 January 2001. Note the proximity to the walkway and road and the large amount of ejecta surrounding the crater (photo from Andrews 2001).

Discussion

In historic times, at least 91 hydrothermal eruptions have occurred within the city of Rotorua (Scott & Cody 2000). These eruptions appear to show a correlation between their frequency and large-scale disturbances (both natural and man-made) in the regional geothermal field. After the 1886 eruption of Tarawera (approximately 20 km east of Rotorua) many springs and geysers thought to be extinct or passively flowing began boiling and overflowing. Many hydrothermal eruptions occurred within the city in the weeks following the eruption indicating the eruption had caused wide-spread changes in the thermal activity of the region. The 20th century saw extensive drilling and exploitation programmes which correlate with peaks in the number of hydrothermal eruptions in the city (Figure 22).

A New Zealand Herald article written 3 days after the 2006 eruption of Kuirau Park quoted a geothermal inspector as saying that in hindsight, staff of the park had noticed a drop in water levels in a nearby geothermal pool. However, the only precursory activity noted before the 2001 eruption at the park was an overflow of muddy water near the pool (Andrews 2001).

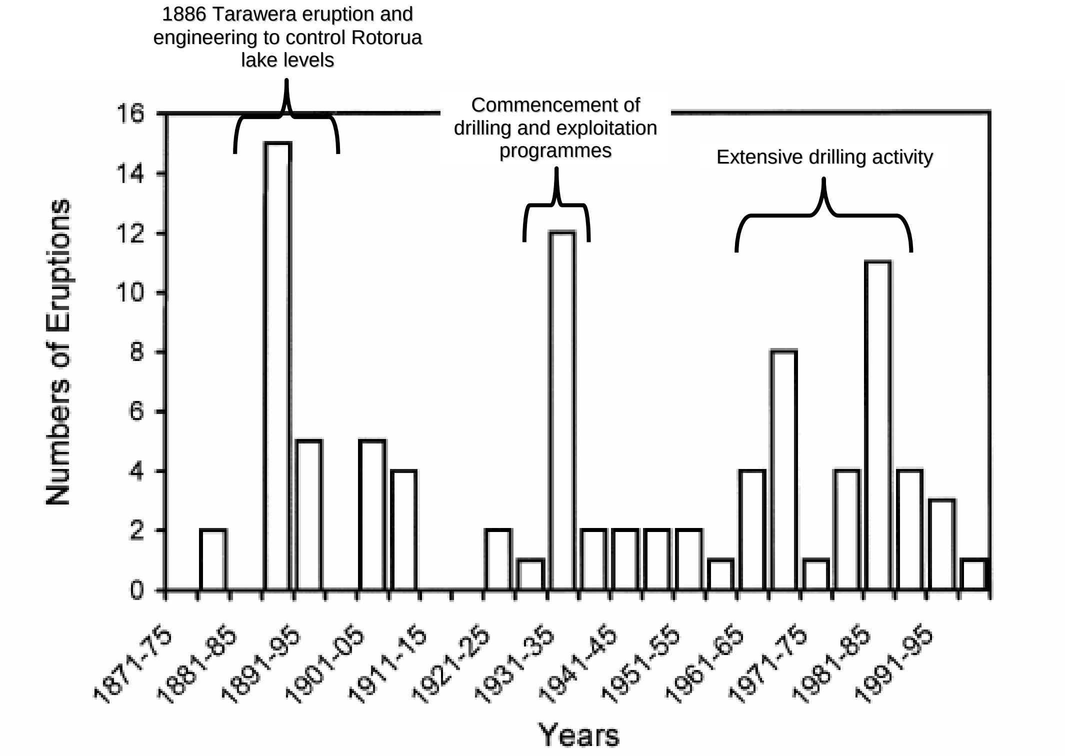


Figure 22 – Number of hydrothermal eruptions in Rotorua in historic times. Note the peaks in activity correlate to periods of disruption in the geothermal field (modified after Scott & Cody 2000).

3.2.2 *Agua Shuca, Ahuachapán Geothermal Field, El Salvador – 13 October 1990*

At approximately 0300 (LST) on 13 October 1990, the residents of the small village of El Barro were awakened by a hydrothermal eruption (Handal & Barrios 2004). The area of the eruption, known as Agua Shuca, or “dirty water”, was a ~25m in diameter zone of geothermal features including mud and hot water pools, surrounded by a number of small wooden dwellings. The initial blast was short in duration, lasting approximately 20–30 seconds, but was particularly violent, creating a “blast of wind, stones, and boiling water” (Bulletin of the Global Volcanism Program 1990b) affecting an area 200m in diameter. It then roared continuously for 10–20 minutes, decreasing in intensity until it ceased, leaving a steaming crater 30 to 40m in diameter, 5m deep (Handal & Barrios 2004).

No changes in activity were noted prior to the eruption by the local residents nor were any seismic signals detected by seismometers located 4 and 30 km away. A portable seismometer set up in the days following the eruption also detected no signals after the blast (Bulletin of the Global Volcanism Program 1990a). The ejected material had a volume of ~1600m³ and consisted purely of overburden, no juvenile material was detected in deposits (Handal & Barrios 2004). The initial death toll stood at 14 but grew to 26 as many victims died later in hospital from burns and other injuries (Bulletin of the Global Volcanism Program 1990a).

Discussion

The Ahuachapán geothermal field has been exploited as a source of geothermal energy since the 1970's (Bulletin of the Global Volcanism Program 1990b). However, Handal and Barrios (2004) calculated that CO_2 concentrations measured from fumarolic steam between 1975 and 1997 at Agua Shuca, suggest that extraction from the Ahuachapán geothermal field has had no effect on the Agua Shuca system and may not be the cause of the 2001 eruption. Thus, the eruption at El Barro is probably a result of the ongoing evolution of the geothermal field (Browne & Lawless 2001).

3.3 Blue-Sky Events

3.3.1 Mount St. Helens, Washington State, USA – 18 May 1980

The 18 May 1980 eruption of Mount St. Helens was not particularly large on the scale of worldwide volcanic disasters (Peterson 1986). However, it warrants discussion based on one aspect of the eruption, the directed lateral blast. The eruption itself and its precursory activity are well documented (Lipman & Mullineaux 1981; Foxworthy & Hill 1982; Keller 1986) and will not be discussed in any great depth here except to note that there were clear precursors and a "ramping-up" of that activity in the days and weeks leading to the paroxysmal eruption of 18 May.

The first precursory event was an earthquake of M4.0 on 20 March 1980 intensified into an earthquake swarm. Then, 59 days or tremor, phreatic explosions, and ground deformation preceded the paroxysmal eruption. The most noticeable of these precursors was the development of a substantial bulge of the northern flanks of the volcano.

The accessibility of the volcano and its location in the Cascade mountain range allowed extensive monitoring networks to be established as the possibility of an eruption became more tangible. By the end of April 1980 the barrage of instruments set up to monitor the ongoing crisis included seismometers, tiltmeters, gravity meters, magnetometers, hydrological sensors, time lapse cameras and survey equipment (Foxworthy & Hill 1982).

There is still debate as to whether the M5.1 earthquake triggered the flank collapse, resulting depressurization of the system and lateral blast or vice versa (Lipman & Mullineaux 1981; Foxworthy & Hill 1982; Peterson 1986) but, the resulting eruption was unlike any witnessed before it and largely unexpected.

The bulge visible on the northern flanks of the volcano had been created by the intrusion of a body of dacite magma, creating the cryptodome (Francis & Oppenheimer 2004). This destabilised the flanks of the volcano and when the earthquake occurred, a deep seated failure propagated through the slope, resulting in the explosive decompression of the superheated groundwater trapped in cracks and pore spaces of the flank. The cryptodome was exposed, triggering a full-blown magmatic eruption. The immense explosion was directed outward by the flank collapse and propagated northwards at incredible speeds (Foxworthy & Hill 1982). A seismic station, 3.5 north of the blast zone ceased transmission 77 seconds after the initial earthquake. If a delay of 20 to 30 seconds is employed between the earthquake and initiation of the lateral blast, this suggests a speed of between 350–400 km/h but some estimates have the blast increasing in velocity, reaching speeds of up to 1000 km/h (Tilling et al. 1990; Brantley 1997).

The lateral blast caused widespread devastation in an almost 180 degree arc from the summit as far as 30 km from the volcano. As described by Tilling et al. (1990), the area affected can be divided into 3 roughly concentric zones. The "*Direct Blast Zone*" spread out to approximately 13 km in radius and destroyed nearly everything, both man-made and natural, regardless of the topography. The "*Channelized Blast Zone*" extended out to 30 km in places and was channelled to some extent by the topography. This zone is characterised by the parallel alignment of trees toppled by the blast. Some survivors were found in this intermediate zone. The final zone, known as the "*Seared Zone*" or "Standing Dead" zone is the outermost area where trees remained standing but were singed by the blasts hot gases.

A pyroclastic density current (PDC) developed from the blast and avalanche. The PDC felled over 4 billion board feet of timber and killed almost everything within an area 370 km² (Cascades Volcano Observatory 2004). Water from the North Fork Toutle River and the slopes of the volcano (both groundwater and snow) was incorporated into the debris avalanche material, creating massive hot mudflows that swept down the river valleys leading away from the volcano.

Discussion

In 1975, Mount St Helens was labelled in a USGS report as the Cascade Range volcano, most likely to erupt (Foxworthy & Hill 1982). When seismicity began in March 1980, it was quickly identified as being indicative of resumption in activity at the volcano. A state of emergency was declared on 3 April 1980, 45 days before the eruption, and local officials began distributing leaflets to the local residents entitled “What to Do During a Volcano Ashfall.” (Peterson 1986). Professional scientists, the media and curious public flocked to the area all hoping to witness the imminent eruption. While most people respected the restricted-entry zones established by the U.S. Forestry Service, some bypassed the blockades, entering the exclusion zone by way of the numerous logging roads which crossed the region. Logging was allowed to continue on the eastern flanks but civilians were evacuated (sometimes unwillingly) from their homes and overnight stays were prohibited within a “Blue Zone” of exclusion reaching up to 32 km (20 miles) from the summit of the volcano (Foxworthy & Hill 1982).

The public, having only experienced active volcanism in the United States in the form of Hawaii’s effusive volcanoes, became sceptical of the cautious approach taken by scientists and officials. Reports from scientists in the media were mixed. Very few indicated any concern over the possibility of a cataclysmic eruption at Mount St Helens. Two weeks of relative quiet, in the last month before the eruption, led to many local residents to become frustrated with the disruption to their daily lives and pushed for greater access to their homes inside the exclusion zone (Foxworthy & Hill 1982). On 16 May 1980, residents inside the “Red Zone” (total exclusion zone) threaten to bypass the roadblocks *en masse*, without the permission of law enforcement if they were not afforded access to their homes. The next day, 17 May, 50 families are allowed to retrieve property from their homes within the “Red Zone”. A second convoy was to be allowed access to the “Red Zone” at 10am the following day. Two people, geologist David Johnston and Harry Truman, owner of the Mount St Helens Lodge, remain inside the “Red” zone after dark. Because of the number of logging roads, it is impossible to know how many civilians remained inside the “Blue” zone on the night of 17 May.

On the morning of 18 May, geologist David A. Johnston radioed results of a laser-beam ranging survey of the bulging north flank he had made that day. These results showed no apparent change in the activity of the mountain from the pattern of the preceding month (Tilling et al. 1990). Analysis of seismicity, SO_2 gas emission and ground temperature measurements revealed no change in pattern over the last month (Tilling et al. 1990). When the flank failure occurred, the speed with which the lateral blast propagated allowed very few warnings to be relayed to the coordination centre in Vancouver, Washington.

The 18 May 1980 eruption of Mount St Helens resulted in the deaths of 57 people. Among the dead were forestry workers, reporters, tourists and scientists. Only 4 deaths occurred within restricted areas, the majority of fatalities occurred in places considered to be “safe”. Most victims died as a result of the lateral blast but many were killed by lahars and mudflows generated after the initial event (Rodolfo 2000).

It appears the earthquake and resultant flank collapse provided the trigger for the eruption as opposed to any internal pressure release. Whether Mount St Helens would have erupted on 18 May without the influence of the earthquake is debateable as no changes in activity had been recorded in the previous month. The fact that most of the fatalities occurred outside the exclusion zone indicates the monitoring scientists were not prepared for the force with which the lateral blast propagated after the flank collapse. Immediately after the eruption, the Washington Department for Emergency Services increased the “Red Zone” limits to over 30 km, more than twice what it was the day before. The “Blue Zone” was extended more than 50 km to the north-east.

This eruption highlighted the hazard presented by lateral and directed blasts during volcanic eruptions and served as a reminder for the curious public as to why prudence is required by the local authorities when determining exclusion zones.

3.4 "Loss-of-Life" Events

It is important in the definition of blue-sky eruptions to distinguish them from many well-known volcanic events where fatalities have occurred that should not be classed as "blue-sky". They are typically volcanic hazard events that occur as a result of an eruption but these "loss-of-life events" (LOLEs) differ from blue-sky events in that they were not completely unexpected. In these cases, casualties occurred as a result of human error in either understanding of risk, or behaviour of the volcano.

3.4.1 Nevado del Ruiz, Columbia – 13 November 1985

On 13 November 1985, lahars caused by a relatively small plinian eruption of the Nevado del Ruiz volcano in Columbia, killed 23,080 people along the Chinchiná, Gualí and Lagunillas rivers (Pierson et al. 1990). An additional 4470 people were injured and approximately 50,000 were made homeless bringing the total number of people, affected physically by the eruption to over 77,000 (Witham 2005). Of the deaths, approximately 21,000 died in Armero, a town of only 28,700 residents, which was completely destroyed in the event (Figure 23). The lahars arrived in the middle of the night, hitting Armero in a series of pulses, the largest and most deadly of which arrived at 11:35 pm (Voight 1990).

Precursory and fumarolic activity began on the volcano approximately one year prior to 13 November 1985. In the anthology produced by the Journal of Volcanology and Geothermal Research (issues 41 and 42), Hall (1990) notes that in November 1984, anomalously high levels of seismicity were felt in the region surrounding the volcano and this was followed closely by an increase in fumarolic activity from within the crater itself (Barberi et al. 1990). Local state agencies, including the CHEC (a state run energy provider) investigated the early activity and suggested the volcano may be reawakening, recommending the implementation of a "geophysical and geochemical program for monitoring a probable eruption" (Hall 1990, p. 102).

Figure 23 – The town of Armero, Columbia, destroyed by lahars from the nearby erupting Nevado del Ruiz volcano (photo: R. Janda; U.S. geological Survey).

Colombian Civil Defense and INGEOMINAS (the National Institute of Geology and Mines) requested international advice in the form of a mission into the crater by UNDRO (United Nations Disaster Relief Office) and Swiss scientists. The resulting report concluded that such precursory events often precede large eruptions and recommended a specifically outlined monitoring programme to be implemented including seismic and fumarole monitoring. The report stressed the abnormality of the activity being experienced at Nevado del Ruiz, and outlined the responsibility of the authorities involved to protect the public through the immediate implementation of monitoring programmes by the INGEOMINAS. However, a report issued by INGEOMINAS, after that organisations visit in late February, released only weeks after the UNDRO report, described the activity as "normal for active volcanoes and does not represent imminent danger" (Hall 1990 p. 104).

Emergency response plans were prepared in April 1985 by Civil Defense in Caldas and scientists from WOVO (World Organisation of Volcanic Observatories) arrived in the area. By May INGEOMINAS officials were refusing to work further in the area noting other priorities were taking precedence and there was a lack of funds available (Hall 1990). In early May an interview was published in the Manizales newspaper published an interview with Minard Hall (1990) who noted the apathy of the Government in the installation of seismographs and recommended the implementation of a public awareness campaign. This prompted the Director of INGEOMINAS to approach the USGS (United States Geological Survey) for the seismograph equipment and technical support. From this point, collaboration between UNESCO, USGS and UNDRO resulted in the donation of equipment and services to INGEOMINAS.

A small phreatic eruption in the crater triggered a lahar which travelled 30 km down the Azufrado valley on 11 September 1985. Reports were published in local media declaring “The Ruiz activity is not dangerous” (LA PATRIA newspaper, 13 September 1985). However, plans were being formulated to manage the growing emergency by the officials in the Caldas, Tolima, Risaralda and Quindio provinces and by government agencies.

As the explosive activity of the volcano increased, the strength of the denial of the hazard posed to the communities surrounding Nevado del Ruiz also increased. The response in the media fluctuated between alarming predictions of possible cataclysms and reassuring reports calling for calm. When volcanic risk maps were finally prepared, showing Armero had a 100% chance of being affected if lahars were generated during an eruption, they were derided in local media as going to cause devaluation of local real estate (Hall 1990).

The message from the official channels was somewhat garbled, with reports from local officials such as INGEOMINAS often discounting the hazard and warning of the same dangers from one day to the next (Hall 1990). However, there were many steps taken by the local officials in response to the mounting risk. Handouts were distributed in the main city of Manizales describing what actions the public should take in the event of a volcanic eruption. However, these handouts were not distributed in the eastern province of Tolima, in the communities living along the rivers fed by the volcanoes snow cap.

On 12 November, the day before the eruption, at a regular meeting of the Committee of Volcanological Studies of the Caldas Community in Manizales, it was noted that the agency that donated the initial set of seismographs in April, wanted them returned for work on other projects. Concern was also noted at the lack of funding available for the monitoring of the seismic network and that both the seismic and deformation programmes had died out. The lack of public education programmes in the river valleys was highlighted as well as the Committees concern regarding the volcano and its monitoring programme (Voight 1990).

The following night, an eruption, relatively small in the history of the volcano, created lahars that swept away 28,000 inhabitants of Armero and other settlements in the valleys around Nevado del Ruiz. There was no evacuation, no warnings and no preparedness provided to the people in the river valleys. The eruption was at the same time both expected and a complete surprise to the officials of the Tolima Province and its people.

Discussion

The 1985 eruption of Nevado del Ruiz highlighted the need for improvement in the prediction and monitoring of volcano behaviour and communication between scientists, civil defence officials and government liaisons (Herd & Vulcanologicos 1986; Barberi et al. 1990; Voight 1990). This eruption confirmed the need for a comprehensive baseline of activity before the onset of activity from reawakening volcanoes and underlined the need for a comprehensive monitoring network in high-risk areas, something which was wholly lacking at Nevado del Ruiz (Hall 1990). It also advanced the understanding of lahar generation from snow and ice-capped volcanoes (Barberi et al. 1990; Pierson et al. 1990). Perhaps even more importantly, the 1985 eruption at Nevado del Ruiz showed the absolute necessity for civil defence preparedness measures and ongoing communication between the scientific community and emergency managers. The location of the settlements, the previous eruptive history of the volcano and the presence of an icecap on the summit all indicated that not only were the settlements destroyed by the eruption exposed to a severe lahar risk, but that evacuation may have been possible, were an alert immediately issued after the onset of the eruption (Barberi et al. 1990).

This eruption also highlighted the crucial role of the scientists in providing the public and local decision makers accurate, realistic and above all consistent information. On 23

September, a USGS scientist addresses a meeting in Manizales and stated an eruption would only affect populations with a 10 km radius of the summit (Hall 1990). Other reports from foreign scientists stated that “The lahars will not affect the populated centres of the region”. The information released from the number of international observers during the lead up to the eruption may have been conflicting and confusing for the inexperienced emergency managers to synthesise. As Barberi (1990) noted, his team were only one of many asked for assistance and advice in the weeks and months ahead of the eruption. This may have led to discrepancies in the evaluation of the risk posed to the population by differing experts. Confusion should be avoided at all costs during an emergency as it can not only obscure the message to those relying on the expertise provided by the experts, but also provide an alibi for the non-intervention of authorities.

While the disaster at Nevado del Ruiz may share many common traits with this authors definition of a blue-sky eruption, in this case, the eruption itself was not unexpected, nor was the outcome. The site of Armero has experienced lahars twice before in historic times. An eruption in 1595 and consequent debris avalanches triggered lahars into the surrounding valleys and was considered to be a larger eruption than that of 1985 (Mojica et al. 1985). Lahars also inundated the present site of the town in 1845 when around 1,000 deaths were recorded. However, these lahars were not immediately preceded by a volcanic eruption.

An article by Hall (1990) highlighted the response of the local authorities and scientific organisations to the growing crisis at Nevado del Ruiz. In it, Hall drew a number of conclusions as to the factors influencing the large number of casualties caused by the eruption. Hall noted that differences in culture and tradition in the two provinces most threatened by the eruption, Caldas and Tolima, led to contrasting levels of preparedness and response. Additionally, it influenced media coverage of the growing crisis and, in turn, public awareness. Hall also noted a high level of scepticism by the local government regarding an eruption at Nevado del Ruiz and an unwillingness to listen to advice from scientific advisors.

These points highlight the difference between BSEs and LOLEs. As summarised by Voight (1990, p. 349) the Ruiz "... catastrophe was not caused by technological ineffectiveness or defectiveness, nor by an overwhelming eruption, ... but rather by cumulative human error – by misjudgement, indecision and beauracratic short-sightedness. Armero could have produced no victims, and therein dwells its immense tragedy."

3.5 Conclusions

Table 4 provides a summary for the BSE case studies in this chapter. Commonalities in their case histories include a lack of historical eruptions and a poor understanding of a volcanoes eruption model and precursory activity. They occurred in a range of physical and social settings (including sites in rift zones and island arcs and sites in both developed and 3rd world countries) and represent both explosive and effusive volcanism.

In §1.2, a number of issues surrounding description of BSEs were listed. Two issues pertained to whether the evolving science of prediction or the increasing sensitivity of monitoring equipment should be considered in describing BSEs. To this end, a discussion on the nature of BSEs is warranted to determine whether they are a physical or social phenomenon: do BSEs exist that have no precursory activity which we can currently detect or are these eruptions are merely a result of ineffective technologies or methodologies. Analysis of the case studies indicates that they can be either or both.

Consideration of the 10 contemporary BSE case studies, both magmatic and hydrothermally driven eruptions (not including Tarawera), reveals that:

- 7 eruptions can be considered physical BSEs,
- 1 can be considered a social BSE and;
- 2 can be considered mixed-cause BSEs.

The 2008 eruption of Okmok Volcano, 2006 eruption of Raoul Island, both 1993 eruptions of Galeras and the eruptions of Kuirau Park and Agua Shuca can best be described as physical blue-sky eruptions. The 1982 eruption of El Chichón is a BSE with a social trigger and the eruptions of Nyiragongo are best described as mixed cause BSEs.

Table 4 – BSE case studies discussed in Chapter 3.

	Date	Eruption	Other historical eruptions?	VEI	Volume of deposit	Why Blue-Sky
Magmatic	2008	Okmok, Alaska	Yes–numerous	4	Not calculated	Eruption occurred while volcano was at lowest alert level, extremely short precursory activity identified in retrospect
	2006	Raoul Island, Kermadec Islands, New Zealand	Yes–1814, 1870, 1886, 1964	1?	2 x 10^5 m³	Lack of understanding of eruption mechanism and interpretation of precursory activity
	2002	Nyiragongo, D.R.C.	Yes–1977	1	2.2 x 10^7 m³	Inadequate monitoring, interpretation of precursory activity, bureaucratic red-tape
	1993 (4 April)	Galeras, Columbia	Yes–multiple VEI 2 & 3 4th of 6 explosions in eruptive episode	1[(i)]	Not calculated (low)	No precursory activity detected
	1993 (14 Jan)	Galeras, Columbia	Yes–multiple VEI 2&3 2nd of 6 explosions in eruptive episode	1[(i)]	Not calculated (low)	Incorrect interpretation of precursory activity
	1982	El Chichón, Mexico	Possibly	5	2.3 x 10^9 m³	Interpretation of precursory activity, inadequate monitoring, bureaucratic red-tape
	1977	Nyiragongo, D.R.C	No	1	2.0–2.2 x 10^7 m³	Inadequate monitoring, lack of understanding about eruption mechanism and precursory activity
	1886	Tarawera	No	5	1.3–2.0 x 10^9 m³	Interpretation of precursory activity, inadequate monitoring technology
Hydrothermal	1990	Agua Shuca, El Salvador	No	2?	~1600 m³	No recognised precursory activity
	2001, 2006	Kuirau Park, Rotorua, New Zealand	Yes–1966 possibly others	1?	Not calculated	No recognised precursory activity

(i) The VEI of the Galeras eruptions have been reported as 1 (Cortes & Raigosa 1997) and 2 (Global Volcanism Programme)

Although one may be tempted to consider almost all eruptions in Table 4 to be retrospectively explained eruptions (and therefore not BSEs at all), it is generally accepted that a single monitoring parameter should not be relied upon as evidence of precursory activity (Sparks 2003; Tilling 2003, 2008). Therefore, the tornillo signals preceding the 1993 eruption of Galeras, the earthquake swarm prior to the 2006 eruption of Raoul Island, and the abrupt increase in seismic activity prior to the 2008 eruption of Okmok should not be considered precursors in isolation. This will be discussed further in Chapter 4 of this thesis.

Okmok differs from the other physical BSE case studies in that it had a large VEI (4) and a long duration (5 weeks). It was relatively well monitored in real-time and yet only 5 hours of precursory seismic activity was noted when analysed in hindsight. For these reasons, it is a particularly interesting BSE and is the largest contemporary physical BSE in the cases studied.

El Chichón was found on retrospective analysis to have also produced an increase in seismic activity prior to its eruption in 1985. However, as discussed in the case study, unlike Raoul Island and Galeras, no monitoring of any kind was underway on the volcano (the seismic signals were discovered after the eruption from a seismic network installed near El Chichón to monitor a dam system) making correlations with other precursory phenomena impossible. The size of the eruption and volume of subsequent deposits were so large that it is unlikely that a simple monitoring network installed to monitor El Chichón with real-time, or near real-time temporal resolution would not have detected any pre-eruptive signals. For this reason, and the subsequent mismanagement of late-stage precursory phenomena (that is, phenomena that were strong enough or close enough to be detected by those living near the volcano), the 1982 eruption of El Chichón should be considered a BSE with a social trigger.

The eruptions of Nyiragongo in 1977 and 2002 differ from the other case studies in that their eruptions were not explosive in nature and did not originate at the summit but were flank fissure eruptions. The fact that the eruption mechanism was not well understood, and the monitoring network in place was insufficient to reflect this, gives BSEs both physical and social triggers.

It is apparent that there is no clear characteristic BSE. The physical and mixed cause BSE case studies present a range of different hazards. The main hazard from the 2008 eruption of Raoul Island, both 1993 eruptions at Galeras and the hydrothermally driven eruptions is provided by the explosive or violent nature of the eruptions themselves. The 1997 and 2002 eruptions of Nyiragongo provided a direct hazard to the people of Goma through lava flows. An indirect hazard was provided by the 2008 eruption of Okmok volcano in the form of a tall eruption column which was hard to track using satellite technology due to the water-rich nature of the plume.

The blue-sky event discussed here can be purely attributed to a poor understanding of the potential hazard at the volcano site. While there was evidence prior to the Mt St. Helens of a lateral blast, because of the growing instability of the flank of the volcano (Lipman & Mullineaux 1981; Foxworthy & Hill 1982; Peterson 1986; Tilling et al. 1990; USGS 2004), neither the mechanism nor the extent of the failure were fully realised, nor was the response of the cryptodome to the depressurisation.

The main difference between BSEs and blue-sky events is that BSEs are unexpected in their occurrence, while blue-sky events are unexpected in their action. Reducing the hazard from BSEs and blue-sky events may require scrutiny of current monitoring techniques or methodologies or specific management and mitigation measures.

4

Monitoring Volcanoes and Forecasting Volcanic Eruptions

The fundamental objective of volcanology is understanding and forecasting volcanic eruptions (Sparks 2003). As magma moves from depth towards the surface, it undergoes a series of transformations in physical properties due to changing temperature and pressure conditions. These changes, as well as interactions between the rising magma and its surroundings (i.e. hydrothermal systems, country rock, etc), can result in geophysical and geochemical phenomena (Moran et al. 2008). The objective of an effective monitoring programme is to firstly detect and secondly correctly interpret these phenomena to provide forecasts and information to the public and civil authorities (Burlini et al. 2007). Accurate and timely forecasts can allow authorities to create contingency plans, provide early warnings and facilitate evacuations potentially saving lives and property.

However, eruptions described as BSEs do not exhibit the typical levels of unrest detected before most historical volcanic eruptions. This chapter describes briefly the different methods of volcano monitoring currently employed around the world, focussing on the systems most effective for early warning and forecasting purposes. It also discusses the forecasting of BSEs in comparison to eruptions that exhibit some precursory activity.

4.1 Monitoring Volcanoes

Monitoring of “Frequently Active” or high-risk “Reawakening” volcanoes should be done for a number of reasons. With the ultimate goal of saving lives, volcano monitoring is done to forecast eruptions and provide timely information to the public and local authorities. To this end, one reason for volcano monitoring is the establishment of a baseline of activity when the volcano is at rest or not actively erupting. As the volcanic processes observed at a site can be individual to that particular system, the creation of a time series of activity may indicate changes in the system and the onset of a new eruption (McGuire 1995b). Acquiring a baseline of activity is also important to determine the typical range of seasonal variation or transient activity a volcano might experience (Tilling 2008).

Advances in monitoring technology since the 1990's have allowed more subtle, previously undetectable phenomena to be identified (Moran et al. 2008). As there are hundreds of currently or frequently active volcanoes in the world and numerous separate monitoring agencies, the level of monitoring and the types of monitoring techniques undertaken on any one volcano can vary. As monitoring technology evolves, some monitoring methods become obsolete and new technologies become standard. The rate at which a monitoring authority upgrades its technology is mostly dependent on policy and budgetary restrictions, so, some observatories may not upgrade as quickly as others leading to varying monitoring capabilities. In this sense, on an international level, volcano monitoring has no standard configurations or benchmarks.

4.1.1 Effective Monitoring and Forecasting

Effective monitoring systems should be conducted in real time or near-real time allowing the quickest possible indication of deviation from baseline activity at the volcano (Moran et al. 2008; Tilling 2008). Additionally, Woo (1999) states that it is unlikely that a single parameter would function as a clear indicator of imminent volcanic activity. This indicates that an integrated network of dynamically significant parameters should be selected and analysed in volcano monitoring, the number of which should reflect the complexity of the volcano.

While volcanic eruption forecasting is often referred to as more art than science, where a "gut-feeling" is often used to interpret geological evidence (Aspinall et al. 2003), more structured and unifying principles of analysis are being developed. Florian Schwander, previously co-leader of the World Organization of Volcano Observatories Database of Volcanic Unrest (WOVOdat), has identified 5 principles underpinning effective volcanic eruption prediction (Schwandner et al. 2007).

- the *principle of inflection points in trends* states that with unknown rates of change, a point in time is reached at which the volcanic system becomes unstable and will likely erupt (Marzocchi et al. 2004);
- the *principle of coinciding change* states that one monitored parameter alone may not yield significant symptoms to diagnose an imminent eruption, but unrelated trends of several monitored parameters may start co-evolving as the system approaches a state of instability (Sparks 2003; Tilling 2008);
- the *principle of known behavior* treats a volcano similar to a medical patient, assuming that responses to changes in the underground may be highly individual to a volcano's particular internal structure and can become better known by understanding past eruptive characteristics (Aspinall et al. 2003; Marzocchi & Woo 2007);
- the *principle of unexpected behavior* treats volcanoes, the public, and decision-makers alike as inherently inconsistent systems–leading to unexpected eruptions (e.g. fast magma ascent from unexpected depth), and mitigation failures (Tilling 2008; Woo 2008);
- the *principle of symptom-based short-term forecast* like all the other principles works like an epidemiological diagnosis and forecast based on symptoms and *patient history* (Aspinall et al. 2003; Sparks 2003; Tilling 2008).

Using these principles, a thorough volcanic hazard assessment can facilitate the development of effective monitoring systems at individual sites.

4.2 Volcano Monitoring Techniques

There are a number of techniques and technologies currently employed by different observatories and monitoring agencies around the world. Full descriptions of current monitoring techniques can be found in numerous books (e.g. Tazieff & Sabroux 1983; McGuire 1995a; Scarpa & Tilling 1996; Sigurdsson 2000b; Sigurdsson 2000a) and case studies of new technologies and existing monitoring networks (e.g. Battaglia et al. 2003; Marzocchi et al. 2004; Elias et al. 2006; Moran et al. 2008; Scott & Travers In press), and are only briefly outlined here.

4.2.1 Seismicity

Seismic signals are usually generated by the movement of magma, fluid or gas during ascent and/or fracturing country rock or old conduits (Moran et al. 2008). Over a century of seismological observation has indicated that nearly every eruption has been preceded by an increase in seismicity (McNutt 2000; Moran et al. 2008). However, while increases in seismic activity often precede eruptions, most volcano-tectonic crises do not result in an eruption (Sparks 2003). For this reason, high-quality, well-constrained seismic observations should not be considered in isolation but in conjunction with other observations such as deformation, gas geochemistry or phenomenology.

One important role of pre-eruption seismic monitoring is the ability to constrain the location of the hypocenter of the earthquake in 3 dimensions beneath the volcano. Migrations in earthquake hypocenters have been observed prior to eruptions at a number of volcanoes including the 1982 eruption of El Chichón volcano in Mexico (§3.1.5). Accurate location of earthquake hypocentres were used to identify new structures and possible failure paths beneath Mauna Loa volcano (Hawaii) prior to an eruption in 1984 (Baher et al. 2003).

The density of the seismometer network, their positions in relation to the hypocentres and the model for the heterogeneity of the subsurface lithologies and seismic velocities all affect the reliability of the computed location of earthquake hypocenters (Ferrucci 1995). While a single seismic station can detect and measure seismic energy release and earthquake rate, it is insufficient to determine the style or location of the seismicity. In their review of the monitoring networks of U.S. volcanoes, Moran et al. (2008) recommended a network of 4–6 stations around a volcano to provide redundancy and determine the type and location of earthquake hypocentres. The exact number of stations and the density of the network can vary based on the perceived activity risk or hazard at any site with more active or potentially destructive volcanoes having a greater number and density of stations.

As there are many different types of seismic signals generated during volcanic unrest, another important aspect of seismic monitoring is the ability to differentiate between these types of activity (Burlini et al. 2007). Ideally a seismic network would be a mixture of short-period and broadband seismometers, the latter being more effective in sensing VLP (very long period) signals and high frequency signals simultaneously.

4.2.2 Ground Deformation

Magma accumulation and migration under a volcanic centre often leads to ground deformation. As opposed to seismicity, where the amplitudes of movement are large and the timescales are short, ground deformation associated with volcanic activity has large amplitudes of movement and long timeframes (Francis & Oppenheimer 2004). The fact that magma must pool in a shallow reservoir or move through a dike or series of conduits before eruption means that deformation monitoring (along with seismicity) should be a useful monitoring technique in magmatically driven eruptions (Parfitt & Wilson 2008).

Until recently, deformation was monitored through methods such as precise levelling (a relative height measure), EDM (Electronic Distance Measurement) or theodolite angular measurement (both measures of horizontal displacement) and dry tilt (Murray et al. 2000). These were relative measurements using permanent markers, or benchmarks, as reference points with data expressed relative to one station, usually the one farthest from the centre of volcanic activity. Once a network of results has been established, deformation can be detected by repeated measurements at the same sites.

Precise levelling remains the most accurate methods of detecting changes in elevation (Moran et al. 2008). One disadvantage of precise levelling is that a levelling campaign is very labour intensive, taking many days to weeks to complete, making them possible only occasionally. It involves the use of two marker poles on either side of a sighted level moved along a series of known points on a specific path (Figure 24). Using this method, accuracies of 0.8mm over 1 km are possible (Murray et al. 2000). The Hawaii Volcano Observatory uses precise levelling to monitor changes in elevation in the caldera and along the east and west rift zones at Kilauea volcano. As this technique is costly in both time and personnel, levelling campaigns are only carried out yearly in the summer.

Figure 24 – Precise levelling campaign at the summit of Kilauea Volcano, Hawaii. Note the level in the centre of the image and second marker staff in the background (photo: Angela Doherty).

GPS can now be used to simultaneously measure horizontal and vertical changes to within a few millimetres (Moran et al. 2008). It replaces older methods. The relatively low cost and portability of the units allow GPS systems to be set up continuously or as part of a campaign.

Continuous mode GPS receivers provide excellent temporal resolution of ground deformation but spatial resolution is generally poorer than survey mode GPS campaigns. In survey mode, GPS measurements can be carried out in any weather including snow, fog and high winds (which preclude the execution of precise levelling campaigns) but continuous-mode GPS antennas can be adversely affected by icing or other extreme weather conditions. GPS surveys allow a smaller number of GPS receivers to cover a number of sites providing excellent spatial resolution. However temporal resolution is generally poor as a receiver spends only 1–3 days at a single site (Figure 25).

Figure 25 – GPS site in survey (left) and continuous (right) configuration (photos: Angela Doherty (left) and GNS 2009 (right)).

Sensitive, short-term, subsurface volcanic processes are detectable using tiltmeters. They are, however, sensitive to fluctuations caused by external influences such as rainfall and temperature and are best when isolated in boreholes, even if only a few meters below the ground surface (Murray et al. 2000). Borehole tiltmeters have been installed on many U.S. volcanoes including Kilauea and Mauna Loa and a combination tiltmeter-seismic borehole is planned for Ruapehu in 2009 (G. Jolly pers. comm. 2009). One disadvantage of tiltmeters is that they can experience problems with drift over long time-scales (months to years) and can be difficult to maintain and recalibrate if located in deep boreholes (Moran et al. 2008).

InSAR is an emerging technique whereby two satellite images of the same area are captured at different times and, using specialised software, are interfered to determine phase shift caused by deformation (Moran et al. 2008). The primary advantage of InSAR is the ability to construct high-spatial resolution data for large areas of interest. In this sense, InSAR is a good tool for studying regional deformation. It also needs no ground-based instrumentation meaning it can be used to monitor deformation at volcanoes where conventional monitoring networks are impossible due to their inaccessibility or difficult terrain (Murray et al. 2000). However, InSAR does have limitations including the availability of satellites which have other tasking priorities providing a low temporal resolution. For this reason, InSAR, like other survey monitoring systems such as precise levelling, should be used as a supporting technique to other deformation modelling with a higher temporal resolution.

Methods such as microgravity can be used in conjunction with ground deformation monitoring to provide a context to the recorded deformation. Microgravity can be used to identify changes in mass flux at depth (Moran et al. 2008); it allows the detection of changes in the mass beneath a site caused by the emplacement or ascension of a magma body, or change in distance from the surface to the core (which can have a number of causes). Measurements are corrected for tidal variations and expressed as a value relative to a base station outside the area of interest. When coupled with deformation monitoring, microgravity can estimate the density of the subsurface mass, distinguishing deformation caused by volcanic processes or that are due to other causes. While useful for establishing and monitoring baseline trends, microgravity surveys are often impractical in remote areas or certain (steep) terrain types.

4.2.3 Emissions Monitoring

As magma ascends, it experiences changes in temperature and pressure. These changes induce both physical and geochemical changes, the most prevalent of which is the exsolution of gases dissolved in the magma. The temperatures, ratios and absolute quantities of these gases can indicate the size and depth of a magma body (Diaz et al. 2002; Scott & Travers In press). For this reason, the detection of magmatic gases being released from a volcanic centre can be an invaluable monitoring tool. The detection of CO_2 and SO_2 can be one of the first indications of the onset of activity at a volcanic centre (Diaz et al. 2002; Moran et al. 2008). Other magmatic gasses such as H_2S, HCl and water vapour can provide information on both the geochemical and physical properties of the magma, and also on the properties of the substrate such as the presence of hydrothermal systems. SO_2 has a strong absorption spectrum and the sun provides an excellent source of UV light; this combination makes UV spectroscopy one of the key geochemical indicators in volcanic hazard assessment (Elias et al. 2006).

Direct sampling of fumaroles (or geochemistry of crater lakes or associated geothermal systems), measuring emission flux of major gas species (such as CO_2 and SO_2) and the measurement of CO_2 diffusion through soil are currently the tools most in use around the world for gas missions monitoring (Francis et al. 2000; McNutt et al. 2000; Diaz et al. 2002).

Monitoring geochemical and temperature changes in fumaroles and geothermal systems associated with volcanoes has been shown to provide useful indications of the resumption of activity at a site (Francis et al. 2000; Stix & Gaonac'h 2000). Samples are collected *in-situ* for laboratory analysis (Figure 26). This provides a complete description of the gases emitted at the volcano at that time (Diaz et al. 2002).

Flux measurement of the major gas species is carried out either through mobile surveys (either airborne or vehicle-mounted) or permanent stationary sites. Correlation Spectroscopy (COSPEC) has contributed successfully to monitoring SO_2 flux at volcanoes since 1971 (Francis et al. 2000). COSPEC is limited, however, due to large errors (mostly due to the absence of reliable wind data), the time needed to complete a survey (and therefore temporal resolution) and in terms of where it can be used. If aerial transects are not possible due to budget or equipment limitations, transects must be completed on roads. Transects should represent a straight cross-section of the plume, perpendicular to wind direction, taken at a constant speed. This is not always achievable on public (or private) roads or in unfavourable wind conditions where the plume is not ideally located. Additionally, COSPEC has been replaced by smaller, more portable spectroscopy technology such as FLYSPEC and is no longer manufactured making parts for maintenance and repair difficult to find (Francis et al. 2000).

Figure 26 – Gas sampling using evacuated sample bottle at Kilauea. The vacuum inside the flask draws a sample into the bottle once the stopper is released, the sample is then analysed using a mass spectrometer in the laboratory (photo: Angela Doherty).

The development of mini-spectrometers (such as DOAS and FLYSPEC) has allowed the introduction of systems capable of measuring sustained, high-temporal resolution data, from permanent mounting, such as the miniDOAS system (Edmonds et al. 2003; Galle et al. 2003). While FLYSPEC and COSPEC use calibration cells to derive plume transect concentrations, DOAS uses a laboratory reference spectrum making the sometimes difficult task of calibration in the field unnecessary (Elias et al. 2006). Automated, high temporal resolution spectrometry, to measure plume flux rates, has been successfully installed in a number of networks including Soufriere Hills, Montserrat (Edmonds et al.

2003) and White Island, New Zealand (Doherty 2008) where they are integral parts of the monitoring network. There are limitations to this system which include the time needed to process raw data into meaningful plume fluxes (up to 2 hours) and the fixed nature of the system requiring a favourable plume position and weather conditions in order to produce any results. COSPEC and FLYSPEC surveys can be complimented with Licor and Interscan systems which measure CO_2 and SO_2 (respectively) and can be used to calculate the ratio of the two gasses at the same time as flux rate is calculated (Scott & Travers In press).

The main source of error in calculating plume fluxes based on scanning spectroscopy is the calculation of wind speed which can contribute up to 40% of the total error (Stoiber et al. 1983). This must be calculated by hand-held devices or local weather stations and may not represent the conditions present at the location of the measurements. Additionally, the small field-of-view for scanning spectrometers provides only a localised cross-section averaged over the duration of the scan. This does not allow for variations in plume composition or flux rate during the scan (Bluth et al. 2007). An emerging technology, a hand-held ultra-violet camera, may help to reduce these limitations and sources of error by allowing imaging of the entire plume (or a large section of it) even if it is not visible. This promising technology (which is fully described in Bluth et al. 2007) can analyse a field of view of many square kilometres and allow for the evaluation of physical and chemical dispersion processes in the plume. Additionally, plume velocities can be calculated by tracking portions of the plume and SO_2 fluxes can be measured using this and the deriving of SO_2 slant column concentrations from measured plume absorbencies.

It is possible for CO_2 and other magmatic gasses to be diffused through the soils surrounding volcanic centres. Changes in CO_2 diffusion levels have been observed before many periods of volcanic unrest and, in some cases, are comparable with rates of gas emission from eruption plumes (Granieri et al. 2003). As with many gas emission monitoring methods, soil effusion rate monitoring can be run as a continual process or in survey mode.

Continuous monitoring of gas emissions is possible using permanent stations and telemetered networks allowing almost real-time data analysis. While allowing gas monitoring and interpretation at a higher temporal resolution than direct sampling techniques, they are usually targeted at a specific gas species and concentration range, making their use somewhat limited. Experiments in the use of *in-situ* mass spectrometry as a continuous gas monitoring tool have been conducted; this would allow the measurement of a wide variety of gas species at a dynamic range of concentrations (Diaz et al. 2002). This method was shown to be limited by contamination from air and water vapour (which do not condense at the time of collection as they do in bottle-sampling methods) and the restrictive power needs and cost.

4.2.4 Phenomenology

Visual observations of changes in phenomenology at a volcano have been identified retrospectively as being useful precursory signal (Tazieff 1977; Komorowski et al. 2002). Phenomena like rock falls, development or change in fumarolic activity or hot/steaming ground can indicate changes in activity at the volcano. Monitoring changes in phenomenology at the summit can be achieved through the use of telemetered web cameras at remote sites and visual observations from visits to the site.

Phenomenology, like other monitoring parameters, should be undertaken as part of a network as it is also not a definitive precursor. For example, only a few hours before the 2007 eruption of Ruapehu, William Pike and his climbing companion, James Christie, had spent the evening hiking around the summit and Crater Lake of the mountain. In a phone interview with Mr Pike, he noted that during his explorations, he noticed nothing unusual at the summit. There was no visible degassing, unusual noises or areas of unusual heat (it was winter and there was a thick covering of snow on the ground). He and his companion spent half an hour sitting above the Crater Lake enjoying the view and saw, heard or felt nothing that would cause him unease until the eruption at 8:15 pm.

4.2.5 Hydrology

Moran et al. (2008) noted that hydrologic monitoring can detect changes in temperature, water levels and chemistry in the streams, lakes and springs (or other water sources such as wells) in and around volcanic centres. These changes can be caused by volumetric strains or increases in gas flux associated with magmatic migration (e.g. Tarawera; Keam 1988). Additionally, hydrological monitoring can detect the presence of lahars caused by active volcanic processes. While the detection of lahars is an important part of volcanic risk reduction, it is not covered in this thesis as lahars relate mostly to syn- or post-eruption activity. A style of lahar, out-burst lahars, can occur as a blue-sky event and are discussed here.

If a persistent crater lake exists at a volcano whose volume has been increased by the presence of tephra or ice damming, continuous lahar monitoring should be employed. This is because out-burst lahars, created by the failure of the retaining section of a volcanogenic lake, can occur outside periods of heightened unrest, such as the 2007 out-burst lahar at Ruapehu and the lahar that caused the 1953 Tangiwai Train Disaster (Manville et al. 2007). The lahar warning system developed in New Zealand for Ruapehu will be described later in the chapter.

It is interesting to note here that prior to the two hydrothermal eruptions listed in Chapter 3, no changes in the water levels, or flow rates were recorded at the sites of the eruptions themselves. However, there may be some evidence to suggest changes in water level occurred at springs near the eruption sites, although this follows no pattern (Scott 2001). Additionally, Moran et al. (2008) note that upon comparison between many volcanic centres, hydrological variations appear to be specific to the individual centre and determining whether the changes detected are a result of volcanic unrest at all may be problematic.

In monitoring gas emissions, remote sensing has been typically used to detect and track the movement of eruption plumes (e.g. Pergola et al. 2001; Hillger et al. 2003; Dean et al. 2004). While this application can help lessen the hazard to airline traffic from eruption clouds through rapid detection and alert notification, it is not a precursory monitoring technique. Lahar and lava-flow mapping through high-resolution and radar imagery and the construction of high-resolution DEM (digital elevation models) have improved the quality of volcanic hazard assessments and process modelling. But the introduction of thermal anomaly monitoring using AVHRR, MODIS and ASTER and the development of a thermal anomaly alert system (Flynn et al. 2002) has brought remote sensing into the realms of precursory activity monitoring.

4.2.6 Remote Sensing

Here, the term “remote sensing” is used to describe monitoring techniques using primarily space-borne technologies. It differs from autonomous, telemetered systems and aircraft-mounted plume measurements such as those used in gas emissions monitoring and ground deformation, which are described elsewhere in this chapter. A range of volcanic processes can now be monitored from space commercial and research satellites which vary in both their spatial and temporal resolution and spectral coverage (UV, visible, mid-IR, and microwave) (Moran et al. 2008). Remote sensing in earth science (in particular volcano monitoring) is covered in depth (e.g. Francis 1989; Harris et al. 2000; McNutt et al. 2000; Mouginis-Mark et al. 2000; Wooster 2007). Here, a synthesis of current remote sensing projects and applications is presented.

Table 5 is a list of the main remote sensing satellites and their uses in volcanic monitoring. Satellite imagery is available through both commercial and research organisations and depending on location and funding and is used in varying degrees by many monitoring agencies around the world. It is particularly useful for monitoring remote areas where telemetered networks are impractical due to geographical and climactic issues, such as the Aleutian Arc volcanoes in Alaska. The greatest drawback of satellite remote sensing data is either the relatively low spatial, or low temporal resolution (or both) possible from the satellites. Tasking priorities on some satellites like ASTER make surveys only possible every 3–4 weeks unless specifically tasked.

Table 5 – Remote sensing satellites used in volcanic monitoring

Satellite	*Instrument*	*Spatial resolution*	*Temporal resolution*	*Swath width (km)*	*Use in Volcanology*	*Examples*
NOAA series	AVHRR˜	1.1 km²	≥12 hour	~2500	Tracking eruption plume growth and movement, detecting thermal anomalies and steam plumes prior to an eruption	(Harris et al. 2000; Pergola et al. 2001; Dehn et al. 2002; Pergola et al. 2009)
GOES (5 satellite series)		1–4 km²	~26 mins	Full disc	Detecting thermal anomalies. Detecting and tracking eruption plume growth and movement	(Harris et al. 2000; Hillger et al. 2003)
Terra^	ASTER	15–90 m ²	~16 day (can be tasked)		Detecting thermal anomalies in crater lakes and on flanks, creating detailed DEM	(Stevens et al. 2004; Pieri & Abrams 2005; Trunk & Bernard 2008)
	MODIS	250–1000 m²	1–2 days	~2300	Automated hotspot detection including thermal anomalies, lava-flows and lakes	(Flynn et al. 2002; Hirn et al. In press; Vicari et al. In press)
IKONOS *	-	1–4 m²	3–5 days (off nadir) 144 days (true nadir)		Creating high-resolution (2m) DEM	(Vassilopoulou et al. 2002)
Quickbird*	-	0.6–2.8 m²	1–3.5 days	16.5 x16.5	Creating 3D terrain models and DEM	
RADARSAT-1(&2)*	-	3–100			InSAR modelling and monitoring of deformation, mapping of lava flows	(Mahmood & Giugni 2001; Dean et al. 2004)
EO–1	ALI	10–30 m²	Tasking Spacecraft	37	High-detail mapping and monitoring of active lava flows	(Donegan & Flynn 2004)
EOS-Aura^	OMI	13 x 25 km	1 days	~2600	Detecting and tracking eruption plumes and other emissions	(Levelt et al. 2006; Carn et al. 2008)
SPOT series*	-	2.5–10m²	26 days		High-resolution mapping and creating of DEM	(Joyce et al. 2009)

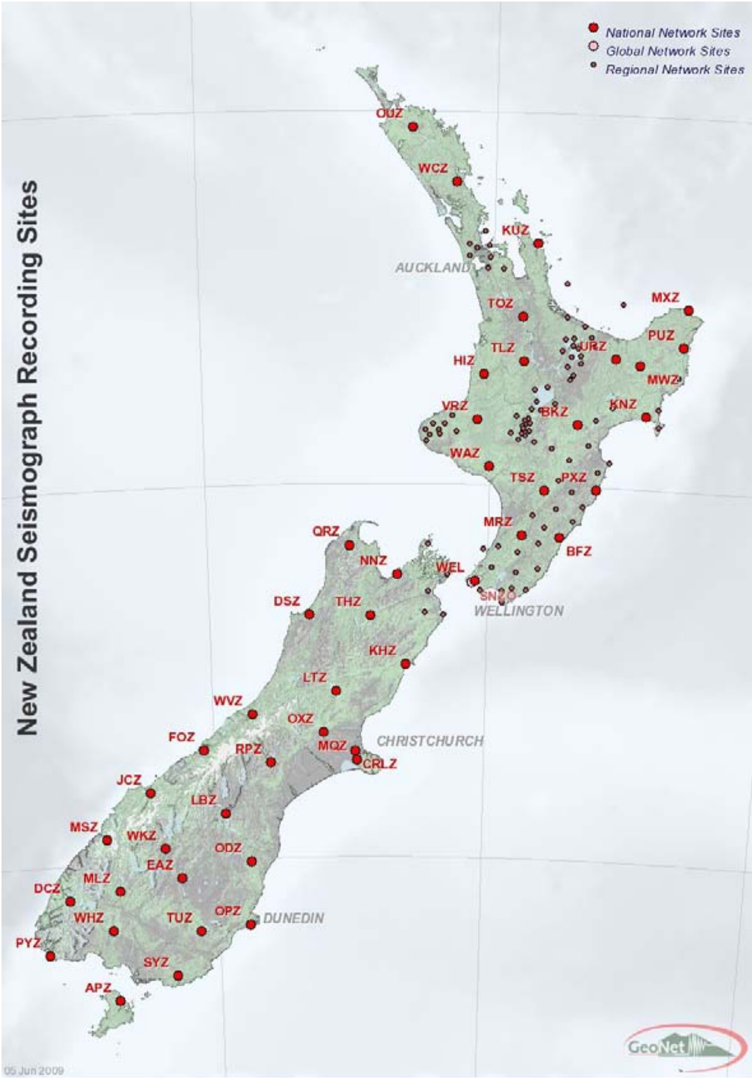
Owned by: ˜–NOAA *–Commercially owned ^–NASA

4.3 Volcano Monitoring in New Zealand

GNS Science, the agency responsible for monitoring New Zealand's geological hazards, identifies 12 volcanic complexes that it monitors through the GeoNet project. The GeoNet project, which began in 2001, was funded by the New Zealand Earthquake commission (EQC) with the aim of providing a real-time monitoring network for all of New Zealand geological hazards (Bland & Tresch 2007). As New Zealand lies above a convergent plate boundary, it is subject to a number of geological processes including seismicity, volcanic activity and landslides. As well as an evenly disseminated network of seismometers, GPS and strong motion accelerographs, GeoNet also maintains a tsunami gauge network around the coast of New Zealand and offshore islands. A full description of GeoNet's monitoring network is available on their website (www.geonet.org.nz).

The establishment of a baseline of activity is an important part of the GNS Science rationale for monitoring New Zealand's volcanic hazards (Scott & Travers In press). To facilitate effective event response, monitoring is undertaken in real-time with selected data continuously transmitted to a monitoring centre for analysis by duty officers. A number of destructive volcanic processes have been identified as posing a serious hazard to New Zealand including ash and pumice falls, pyroclastic density currents, airborne ash clouds, lava flows, lahars and volcanogenic gases (Scott & Travers In press). GNS Science has targeted their volcano hazards programme to reduce New Zealand's vulnerability to these hazards through combination of monitoring, modelling and in-depth hazard assessment.

The network of seismometer and GPS stations currently monitoring the country are presented in Figure 27. At the time of writing this thesis (June 2009), there are 144 seismometer sites in New Zealand's network, approximately 50 of which are broadband systems (C. Miller pers. comm. 2008). Approximately 134 CGPS (continuous GPS) sites are maintained by LINZ, GeoNet and others. Many sites are a combination of both seismic and GPS units and are either powered by mains electricity or solar power, depending on location.



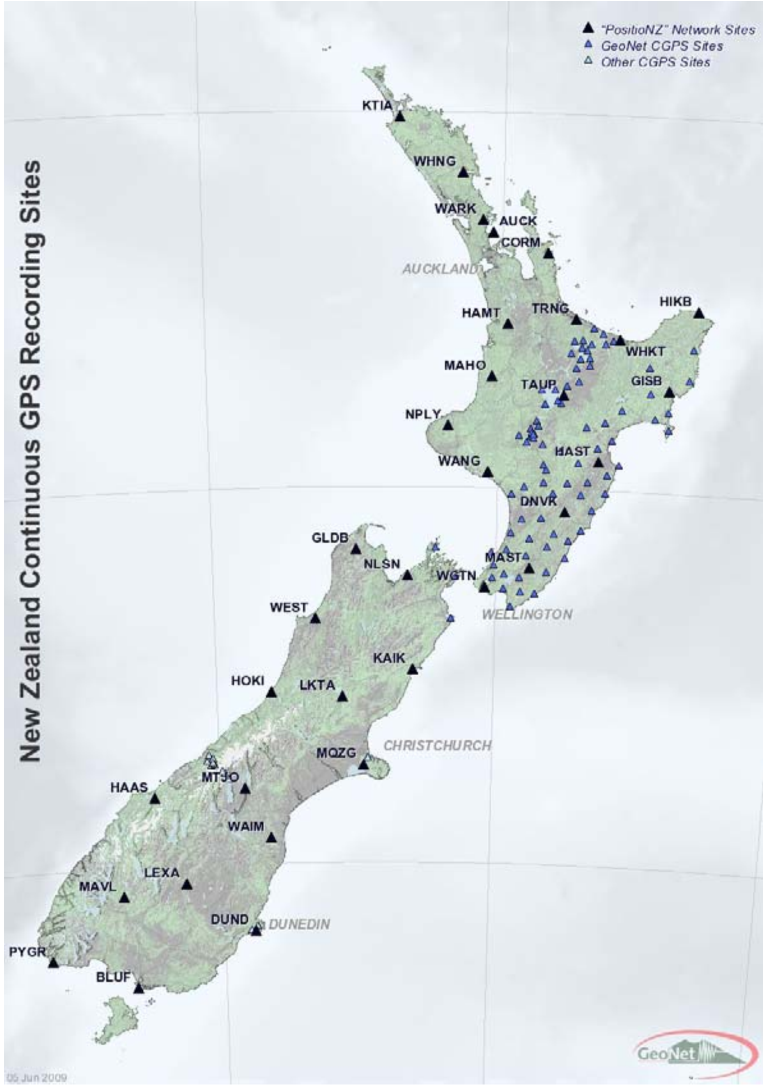


Figure 27 – (left) New Zealand seismometer stations. National sites plus approximately 7 regional systems are all broadband. (right) New Zealand continuous GPS recording network sites. 33 PositioNZ sites maintained by Land Information New Zealand, 85 GeoNet sites and 16 sites maintained by others are visible on this map (GeoNet 2009).

In addition to the national network, a number of additional sites function as regional networks in areas of special interest such as regions of active volcanism or areas at high risk of experiencing earthquakes or mass failure movements. In terms of monitoring volcanic hazards, the addition of these sites provides a higher spatial resolution in areas such as the Taupo Volcanic Zone and Tongariro National Park (Figure 28).

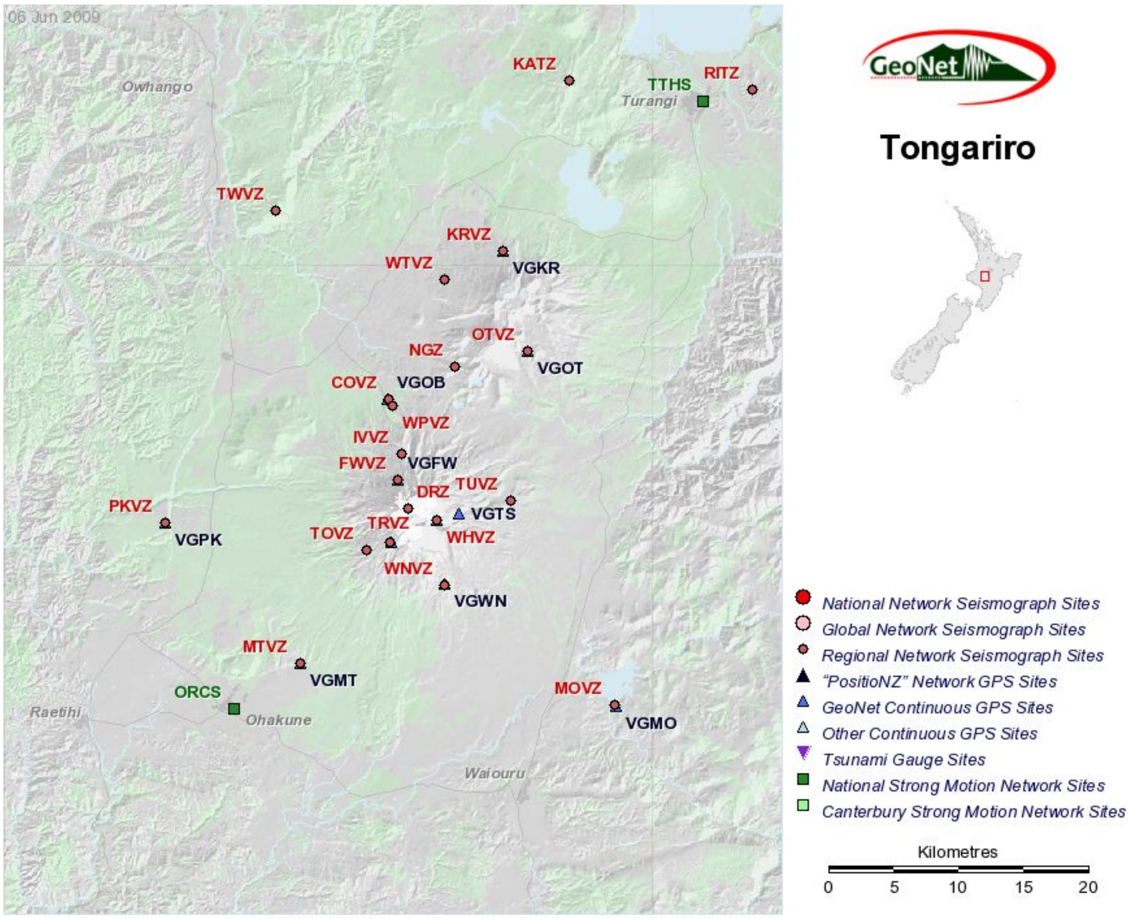


Figure 28 – Regional GeoNet seismic and GPS monitoring sites around the Tongariro National Park (GeoNet 2009).

Gas flights where COSPEC, InterScan and Licor plume sensing are conducted monthly (approximately) at Ruapehu. These are timed to coincide with monthly visits to the summit to sample the Crater Lake for geochemical analysis and to look for changes in phenomenology. The number of these flights is increased if any baseline anomalies are detected using other monitoring methods. Gas flights are also undertaken monthly to White Island but geochemical sampling occurs less often, approximately quarterly (C. Miller pers. comm., 2008). The commercial presence on White Island, which includes at least one daily trip to the island (two trips per day during summer), provides a good basis of phenomenological monitoring through a network of knowledgeable guides and operators thereby providing additional monitoring support. A number of telemetered web-cameras also monitor the island.

Gas flights and geochemistry surveys are performed less frequently on other "Frequently Active" volcanoes such as Ngauruhoe/Tongariro and are not performed regularly on currently inactive (although defined as "Reawakening") volcanoes such as Taranaki. However, these volcanoes are monitored through regional seismic and GPS networks which allow GNS to maintain a baseline of activity. Additionally, as at White Island, telemetered web-cameras and observations by the Department of Conservation (DoC) staff and other local operators allow GNS to monitor changes in phenomenology.

All New Zealand's active or potentially reawakening volcanoes, with the exception of those located in the Kermadec Islands, are located in the North Island. This allows monitoring through telemetered networks and direct sampling to be less prohibitive. However, GNS has begun to use remote sensing technologies in monitoring New Zealand's volcanoes. This includes the use of the ASTER instrument to monitor the temperature of the Crater Lake (Trunk & Bernard 2008) and map topography and lahar deposits on Ruapehu (Stevens et al. 2004). ASTER provides imaging of the Crater Lake every 3–4 weeks at a relatively low cost (ca. US$80 per image).

4.3.1 Monitoring of Blue-Sky Events in New Zealand– Break-out lahars

One blue-sky event that affects New Zealand regularly is break-out lahars (Manville et al. 2007). Standing bodies of water, often at altitude, with unstable margins in volcanic settings can give rise to range of syn- and post-eruptive hazards. In New Zealand, the highest risk volcanic event is arguably the out-burst lahar created by failure of a tephra dam on the south-west side of the crater lake of Ruapehu (Sherburn & Bryan 1999; Carrivick et al. 2009). The ERLAWS (Eastern Ruapehu Lahar Alarm and Warning System) scheme was initiated in 2000 after a tephra dam, which reformed after the 1995–1996 eruption of Ruapehu, allowed the Crater Lake to fill to a level much higher than its former elevation. This presented a potential to release ~1.4 million m^3 of water into the Whangaehu River Valley when it failed (Galley et al. 2004).

The ERLAWS system was installed in 2001/2002 and consisted of a collection of sensors at 3 sites in the upper Whangaehu River Valley (Keys & Green 2004):

1. Crater Lake outlet – three geophones to detect the vibration of the collapse and lahars, buried tripwire to detect collapse of dam and water sensors to detect a sudden drop in Lake level
2. NZ Alpine Club Hut – two geophones to detect vibrations from passing lahars
3. Tukino skifield – two geophones to detect the vibration from passing lahars.

Data is telemetered to a special ERLAWS website and sends warnings to staff pagers when activated. Additionally, ERLAWS has the ability to trigger warning lights and barrier arms on State Highway 1 which crosses the lower Whangaehu River.

In March 2007, the tephra dam failed and the New Zealand scientific and hazard management community was prepared. The ERLAWS system was successfully triggered and operated as expected, initiating alerts to staff members and road users along State Highway 1. Although the occurrence of the lahar has significantly lowered the risk in the region, the ERLAWS system still operates as part of the greater eruption warning system on the volcano. As the tephra dam is a recurring feature on the crater rim (it formed after the 1945 and 1995/1996 eruptions of Ruapehu) the ERLAWS system will most likely be needed as a dedicated lahar-warning system again in the future.

4.4 Forecasting Blue-Sky Eruptions and Events

4.4.1 Forecasting Blue-Sky Eruptions

Analysis of case studies indicates that BSEs do exist. Whether they are a result of a physical phenomenon or a social inadequacy is somewhat moot as in either case our current monitoring technologies and methodologies are not able to accurately forecast all volcanic eruptions. In the prediction of BSEs, whether they are identified as being social or physical phenomena, the approach should be based on the employment of an effective monitoring network, the establishment of a baseline of monitoring parameters and the detection and interpretation of precursory activity.

In 2006 the International School of Geophysics met in Erice, Italy, to discuss the topic: "Quantifying long- and short-term volcanic hazard: Building up a common strategy for Italian volcanoes" (Marzocchi et al. 2006). In this meeting delegates noted the controversy linked to the term "precursor" and discussed the definition of the term in regards to it being deterministic or statistical in nature. In other words, some at the conference described the term "precursor" as relating to a phenomenon that appears "necessarily" before an eruption while some described it as one that appears "mostly" before an eruption. Some delegates also pointed out that a precursor can ONLY be identified retrospectively (Marzocchi et al. 2007).

This debate presents a case for the existence of BSEs that only have identifiable precursory activity when analysed in retrospect. In this respect, the main purpose of monitoring on many volcanoes (particularly those that are "Reawakening" or have no record of historical eruptions) could be to establish a baseline and detect changes in activity prior to eruptions that can later be interpreted as precursory activity. This is done with an aim to build up an eruption model that can later serve as a basis for predictive monitoring. A "catch 22" situation arises when considering that a wide range of volcanic data (seismic, deformation, gas emissions etc.) are required to produce accurate eruption models, but it is difficult to predict when a historically inactive volcano will reawaken and installing extensive monitoring networks on all volcanic centres is not a financial, or practical possibility. The question then becomes, what should we be listening for?

Retrospective analysis of the case studies identifies that five of the seven eruptions (excluding Tarawera as it is a historical eruption) were proven to have some identifiable precursory activity (i.e. the January 1993 eruption of Galeras, the 1982 eruption of El Chichón, the 2006 eruption of Raoul Island and both 1977 and 2002 eruptions of Nyiragongo). However, the principle of coinciding change (§4.1.1: Sparks 2003; Schwandner et al. 2007; Tilling 2008) indicates that a single factor cannot accurately provide an indication of increasing activity. Therefore, even in retrospect, the 1993 eruptions of Galeras (excluding the April 1993 eruption) and 2006 eruption of Raoul Island cannot truly be excluded as BSEs due to their single identified baseline anomaly. More importantly for the prediction of BSEs, these eruptions should not be used as cases-in-point but merely as an indication that, when analysed in retrospect, some BSEs were shown to exhibit some unusual seismic signatures (tornillo signals at Galeras and a waning seismic swarm at Raoul Island). El Chichón was also found upon retrospective analysis to have produced an increase in seismic activity prior to its eruption in 1985. However, as previously discussed, unlike the other two case studies, no dedicated monitoring was actually underway on the volcano

The January 1993 eruption of Galeras is particularly difficult to clarify. While retrospective analysis has shown only a single precursory phenomenon was detected, analysis of subsequent eruptions throughout 1993 indicates this may be the only precursory signal produced by the volcano prior to eruptions of this nature. This may indicate that Galeras is one exception to the principle of coinciding change where only a single detectable pre-eruptive phenomena is indicative of an impending eruption. As described later in this section, the absence of an effective eruption model and the nonappearance of other precursory signals weighed strongly in the scientist's hazard assessment prior to their excursion to the crater. The January 1993 eruption of Galeras and its subsequent tragedy highlights the dangers of applying general models in the absence of historical records.

Volcanoes that have not experienced historical eruptions nor have an eruption model, have been assessed as they reawaken based on "general" models. However, the creation of an effective "general" model of pre-eruptive activity is difficult due to the different types of volcanic activity, the scarcity of detailed eruption histories for most volcanoes and the complexity of the processes involved (Marzocchi & Zaccarelli 2006). Forecasting is further hampered by differences in pre-eruptive activity between eruptions at the same site (e.g. Usu Volcano, Japan: Scarpa & Gasparini 1996).

In terms of activity prediction, volcanology lies between meteorology and seismology (Woo 2008). Our knowledge of pre-eruptive activity is significantly less than syn- and post-eruptive activity for a number of reasons. As most pre-eruptive activity occurs below ground, difficulties arise when assumptions need to be made regarding the nature, geometry and physical properties of the substrate and its reaction to the impinging magma. Computer modelling of subsurface processes has become an integral part of eruption modelling as laboratory experiments are not readily scalable to a volcanic environment (Woo 1999).

If any precursory activity is detected, the time between when it begins to manifest and the onset of an eruption can be days or weeks (e.g. Shishalden Volcano: Dehn et al. 2002), months or years (e.g. Pinatubo: Punongbayan et al. 1996) or may remain at a heightened level before decreasing again to background intensity without an eruption occurring (e.g. Rabaul Volcano: Mckee et al. 1985). Determining the most likely outcome of any heighten activity can be as difficult as detecting the activity itself (Tilling 2008).

In predicating BSEs, scientists are also hampered by the same uncertainties that exist in predicting any volcanic eruption. One problem is the relative scarcity of data and the poor knowledge of physical precursory processes (Marzocchi et al. 2008). Additionally, BSEs are typically short-lived, explosive phenomena, characterised by small volumes of erupted products that would not be preserved in the geological record (Table 4). Therefore a hazard assessment or eruption model based on the geological record of a volcano may not include BSEs, providing a false or misleading evaluation of risk at the volcano (e.g. January 1993 eruption of Galeras).

BSEs with a hydrothermal origin do not have the input of mass or energy from a magmatic source and as such, no signals typical of the emplacement of a magma body would be produced. Table 4 and the case studies of hydrothermal eruptions in Chapter 3 highlight the lack of pre- or post-eruption seismicity with only vague possible correlations between hydrological changes in the system as possible precursory signals.

4.4.2 Forecasting Blue-Sky Events

The prediction of blue-sky events is particularly difficult as, by their definition, their behaviour is totally unexpected for the volcanic process. Computer models, simulations and probabilistic determinations may be the only way to gain insight into the likely effect a volcanic process will have on the area including "worst case scenario" models. If a thorough hazard assessment is carried out at a site, an accurate determination of all possible scenarios should be available to scientists giving them the information necessary to predict the progress of an eruption.

As prediction of blue-sky events may not be possible, effective management and mitigation measures should be employed. This will be discussed later in this thesis.

4.4.3 Probabilistic vs. Deterministic Forecasting

While some recent research into short-term forecasting of volcanic eruptions has focussed on deterministic analysis (Voight & Cornelius 1991; Kilburn 2003) the complexities of the processes involved in volcanic eruptions and the stochastic nature of volcanic systems often make deterministic prediction of an impending eruption an unrealistic objective (Sparks 2003; Marzocchi et al. 2007; Marzocchi & Woo 2007). While a probabilistic approach to eruption prediction is more general, it is not incompatible with a deterministic approach and elements of the latter can be incorporated into the former (Marzocchi et al. 2008).

Marzocchi et al. (2007) described the 2-fold application of probabilistic analysis: setting up evidence-based models and creating a framework which merges many types of information (including volcanological, historical, theoretical and empirical) into a reliable hazard assessment. Probabilistic analysis has recently become increasingly important in the construction of volcanic hazard models (Newhall & Hoblitt 2002; Marzocchi & Woo 2007; Marzocchi et al. 2008). One advantage of probabilistic analysis is that it can also be integrated into dangerous volcanic event models such as the likelihood of pyroclastic flows during an eruption (Figure 29: Neri et al. 2008) and cost-benefit analyses for mitigation and management (Newhall & Hoblitt 2002). Probabilistic analysis can be useful for both long and short-term eruption forecasting using historical analysis when a volcano is in a quiet state, and for analysis of dynamic phenomena when activity is present (Marzocchi et al. 2008).

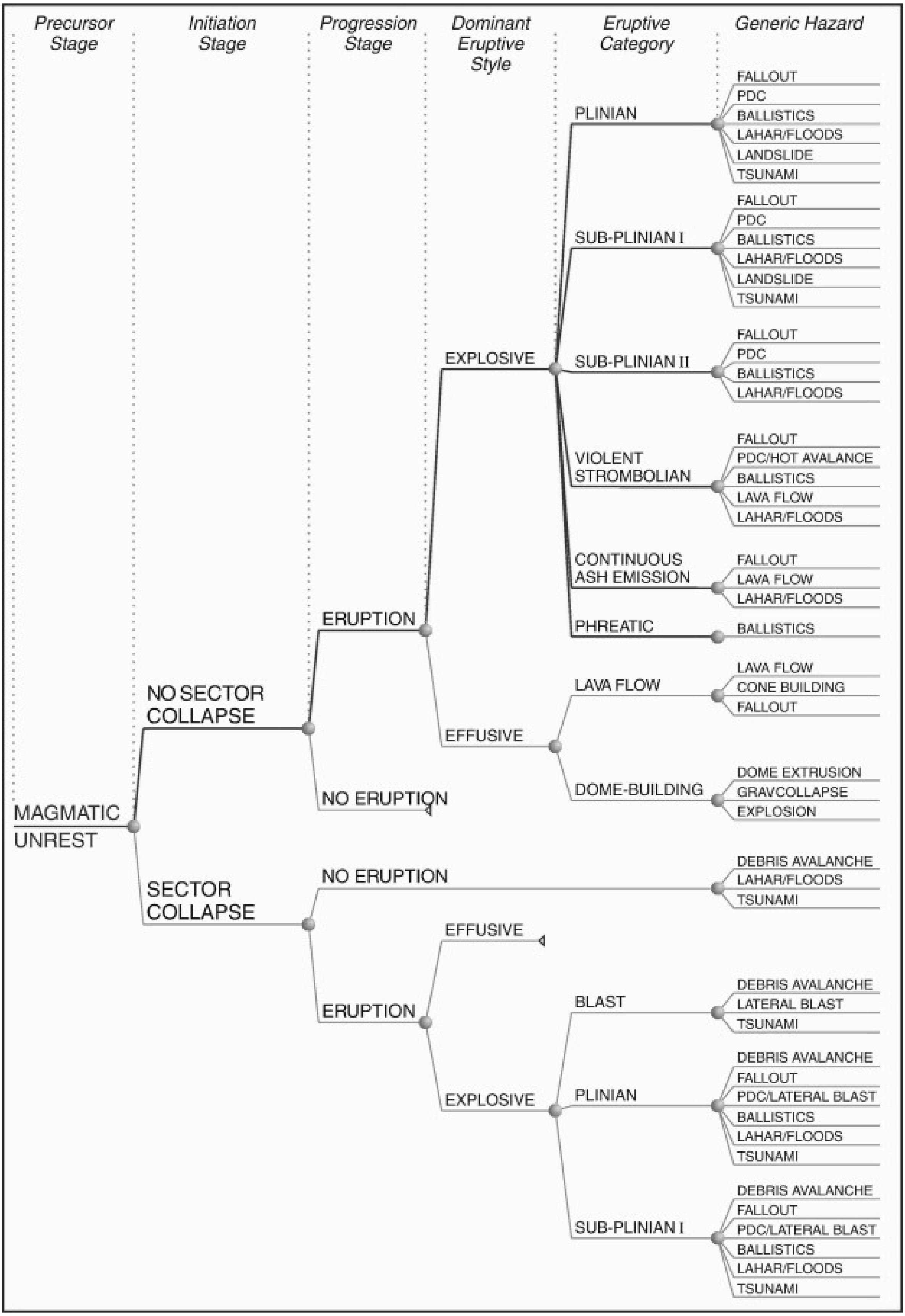


Figure 29 – Simple event tree summarising possible eruption scenarios at Mt Vesuvius. Based on historical records, probabilities can be placed on the likelihood of each scenario and a final probability of each eruption outcome can be derived (from Neri et al. 2008).

However, it must be remembered that probabilistic analysis tools are only as effective as the quality of the dataset used as an input, and incomplete or inaccurate data may cause inaccuracies in results (Marzocchi et al. 2008). As the number of historical eruptions is very low and the styles of volcanism represented in those eruptions is skewed (i.e. there has only been a single rhyolitic eruption in historical times; Chaitén, 2008), a general model based on historical precedents would be inaccurate. In the case of BSEs, their very nature implies an uncertainty in their production. Table 4 indicated that most BSEs discussed in this thesis had few, if any, historical eruptions. This indicates that the geological record will provide an incomplete eruption history as no data or precedent would exist for small eruptions that would not be preserved in the geological record. As described earlier, this can provide a skewed dataset for a probabilistic hazard analysis that may omit more frequent, smaller eruptions from their calculations.

An example of the application of a probabilistic assessment in the case of blue-sky eruptions is provided by a retrospective analysis of the 1993 eruption of Galeras Volcano (Aspinall et al. 2003). These authors found that, based on the activity that had occurred since the volcano's reactivation in 1988, the risk of imminent (meaning here within 1 week) explosive activity at the summit as of 13 January 1993 was between 1/10 and 1/47. 1/10 represents the likelihood of an imminent explosive volcanic eruption at the summit based on the presence of tornillo signals alone while 1/47 represents the likelihood of this event based on the tornillo evidence and the LACK of other precursory activity. As no reliable eruption model had been produced, the lack of other precursors would have weighted strongly in the scientist's calculation of the risk posed their site visit. This means a hazard assessment carried out on 14 January 1993 would have indicated a 2.1% chance of imminent explosive volcanic activity. As the base rate probability of an imminent explosive eruption was 1/51 (~1.9%), the presence of tornillo signals coupled with the absence of any other pre-eruptive activity raised the risk during that week only very slightly. Therefore, at the time, there was no perceivable increase in risk evident to the scientists on the ground. Retrospection indicates that the presence of tornillo activity should have been given greater weight than the negative evidence of the lack of any other precursory activity.

In this example, the eruption was preceded by an increase in volcanic activity at the site which allowed inclusion of historical data into the assessment. Other BSEs are characterised by a lack of historical activity so probabilistic analysis would be more generalised.

4.4.4 Monitoring for Effective Forecasting

Physical Magmatic BSEs

Retrospective analysis of the BSE case studies discussed in Chapter 3 indicates some BSEs have produced anomalous seismic signals prior to their eruption. While monitored in many cases (e.g. Raoul Island, Galeras), deformation was shown to not be an effective monitoring method for predicting BSEs. This could be due to the fact that both Raoul Island and Galeras (and to a certain extent Ruapehu could be described as (relatively) open, degassing systems. For this reason, there may be little, if any, ground deformation associated with gas movement or it may be so slight, it is immeasurable.

Additionally, as most of the physical BSEs have a VEI of 2 or less, they may not require the storage or migration of large amounts of magma and therefore, may not produce large deformation signals. In the recent eruptions of Raoul Island and Ruapehu, magma movement may not have even been involved (G. Jolly pers. comm., 2009). However, the 2008 phreatomagmatic eruption of Okmok volcano, did have a significant magmatic component and was monitored in real-time though both seismic and deformation techniques. As discussed in Chapter 3, no deformation and less than 5 hours of seismic activity was noted prior to the eruption. This may indicate that deformation monitoring may not be a useful monitoring parameter for BSE prediction. However, as physical BSEs are (in theory) driven by the same processes as other magmatic eruptions, their magmas should be subject to the same interactions and modifications as they ascend, therefore a combination of seismic and gas emissions monitoring may be a more effective method than seismic and deformation monitoring.

As the volumes of magma for small VEI events are typically low (Newhall & Self 1982), monitoring should be able to detect small changes in monitoring parameters, as well as dramatic changes, as is possible with large-scale eruptions (Punongbayan et al. 1996). Monitoring should also be conducted in real-time or near real-time to provide the temporal resolution needed to detect rapid changes in system activity. Additionally, alert systems must be able to capture extremely short duration precursory activity (e.g. Okmok Volcano). This provides the largest possible window (if any window is possible) for eruption forecasting or mitigation strategies to be enacted (Marzocchi & Woo 2007; Tilling 2008).

Physical Hydrothermal BSEs

The two hydrothermal eruptions described in Chapter 3 are potentially the harder of the two forms of physical BSE to accurately forecast. Some research indicates that instability in the hydrothermal system may be a result of exploitation or poor management of the regional hydrothermal resource (Scott & Cody 2000) or natural alteration (e.g. earthquake, large eruption or natural evolution) to the regional hydrothermal field (Browne & Lawless 2001). However, the lack of any signal detection at Kuirau Park prior to the 2001 and 2006 eruptions, despite the presence of a reasonable monitoring network around Rotorua and the lack of any post-eruption seismicity detected on seismometers installed the day after the eruption at Agua Shuca, indicates that these eruptions may be fundamentally un-predictable: true “blue-sky” eruptions. In this case, mitigation as opposed to prediction may be the only possibility and this is discussed later in this study.

Social BSEs

BSEs that are a result of inadequate monitoring networks or ineffective crisis management are much harder to resolve. The introduction of remote sensing has greatly improved the monitoring standards present in areas with resident populations but little funding or difficult site access (e.g. Ecuador: Carn et al. 2008). The ability to monitor many volcanoes at once from a single observatory with a few staff may provide support to a monitoring network where regular site visits or extensive instrumentation are not a possibility.

The eruptions at El Chichón in 1982 and at Nyiragongo in 1977 and 2002 highlighted the need for an effective, even if only small scale, monitoring network to be in place at reawakening volcanoes. This requires the identification of a volcano as having the potential to reawaken and pose a hazard to the population (this was not done for El Chichón). This can be achieved through a hazard assessment at all volcanoes within a country or protectorate by scientists familiar with the local historical and geological record of the area. Once potentially hazardous sites are identified, the installation of even a small network, monitoring one or two parameters of volcanic activity provide some indication of impending volcanic unrest. This can provide an adequate timeframe for local scientists and officials to issue timely warnings to those potentially affected.

4.5 Conclusions

There is international debate as to the nature of a volcanic eruption precursor, for example on whether a precursor is an event that always occurs before an eruption or whether it is statistically more likely to occur before an eruption; and also whether precursors can only be identified in retrospect. This indicates the importance of accurate eruption models in effective eruption forecasting.

The nature of most physical BSEs (low eruption volumes, high explosivity) indicates that they may not be fully represented in the geological record and hence, evidence-based (probabilistic) models may not have the information needed to anticipate them. However, in the absence of specific eruption models (as is the case with most reawakening volcanoes) general models should not be applied (e.g. the lack of importance placed on the tornillo events prior to the January 1993 eruption of Galeras). The notable exception is the 2008 eruption of Okmok Volcano which is estimated to have had a VEI of 4 and was a long-duration (5 weeks) eruption with a persistent ash plume. There was also an extensive eruption history with this volcano and an alert system based on an eruption model (which was not triggered by the time the AVO was notified the eruption was underway).

Monitoring should be undertaken at times of both activity and non-activity at volcanoes. In times of quiescence, monitoring should establish a baseline of activity to provide indications of when greater activity at a volcano might be returning. During times of heightened activity, monitoring should be used to construct and refine eruption models and help provide effective eruption forecasts to the public and local authorities. Monitoring should be undertaken in real time to allow adequate sensitivity to changes in the state of the volcano. However determining the outcome of a volcanic crisis may be more difficult as detecting the activity itself.

As there is no 'typical' BSE and the term can represent a diverse range of eruption styles and hazards, there is no clear system to eliminate the risk of BSEs. In the case of physical BSEs, some case studies indicated the possibility of precursory activity that is not well detected or understood (magmatically driven BSEs) while some suggested that no activity may precede their eruptions (hydrothermally driven BSEs). Advances in technology have allowed previously undetectable phenomena to be identified. This means that over time, technological advances have allowed the limits of detection to decrease and potentially, the window of detectable eruptions has increased (Figure 30). Therefore, if BSEs are purely a result of technological limitations, we may be able to eventually forecast all eruptions.

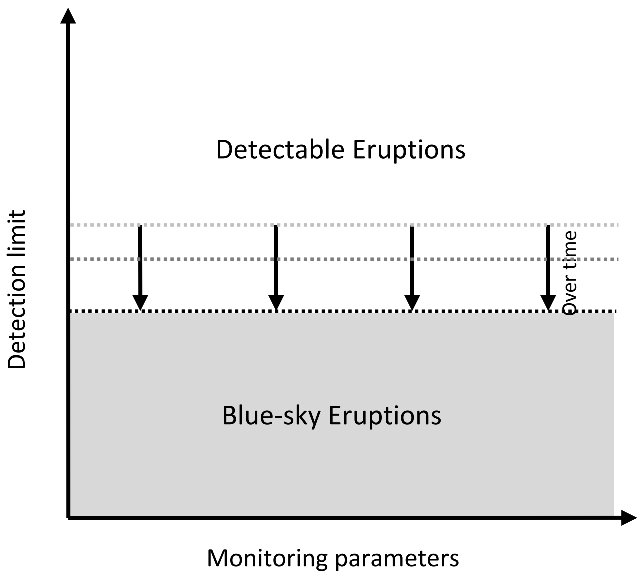


Figure 30 – Reducing the blue-sky eruption window. Technological advances allow the detection of smaller changes increasing the window of detectable eruptions.

Seismic signals have been identified in retrospect prior to many BSEs. However a single monitoring parameter should not be used in isolation to forecast volcanic eruptions. With regards to other monitoring parameters, gas emissions monitoring should provide a better indication than deformation monitoring of a change in activity prior to a BSE due to the low (or zero) movement of magma needed to produce a BSE. In the case of hydrothermally driven BSEs, no monitoring appears effective so mitigation and management of the hazard must take in the place of forecasting.

The installation of even a small monitoring network of two parameters monitored in real-time can reduce the risk of social BSEs. Seismology appears most effective as the movement of magma requires the displacement or fracture of country rock (or existing conduits). Remote sensing can provide an additional parameter when funding or site access is limited.

4.6 Recommendations

- Real-time seismic monitoring can provide the basis for an effective monitoring network
    - Seismic monitoring can be supplemented with gas emissions or other monitoring methods (e.g. phenomenology or remote sensing)
- Ensure monitoring is undertaken in real-time
- Ensure alert protocols are capable of capturing extremely short duration precursory patterns

5

The United States NVEWS review

If the detection of BSEs is reliant on monitoring sensitivity, it may be difficult to assess whether the monitoring network in place is sufficiently effective to reflect the hazard on the volcano. A review of monitoring standards based on the volcanic hazard at a site may be beneficial in reducing the risk of BSEs and volcanic eruptions in general.

In the wake of highly visible natural disasters such as the 2004 Boxing Day Tsunami in Indonesia and 2005 Hurricane Katrina, the Consortium of U.S. Volcano Observatories (CUSVO) began the development of the National Volcano Early Warning System (NVEWS). It is an effort to develop a proactive, integrated, national-scale monitoring system to assess and reduce the vulnerability to volcanic hazards in the United States (Guffanti et al. 2006).

The review had two purposes: 1) to provide a national framework of monitoring standards and techniques, and 2) to quantify risk of volcanic hazards at each U.S. volcano.

New Zealand and the U.S.A. employ similar methods of monitoring and volcanic hazard management. Both countries employ monitoring rationales with a focus on real-time (or near real-time) monitoring for the purposes of effective response and the implementation of mitigation measures (Scott & Travers In press). Both countries experience a wide range of volcanic hazards and volcanic styles and while smaller, the New Zealand monitoring network may benefit from a similar-style review and quantification process. This chapter provides a test of the NVEWS review in a different setting to explore its applications to New Zealand's volcanoes.

5.1 The Process of the Review

The review involved the assessment of the 169 geologically active volcanic centres in the U.S.A. and their classification into one of five threat groups based on hazard factors such as destructive natural phenomena produced by the volcano and exposure factors such as the volcano's proximity to people and property (Ewert et al. 2005). Full details of the scoring system can be found in Appendix 1 and a full explanation of the scoring system can be found in Ewert et al. (2005: p39–45).

The 5 threat groups (ranging from "Very Low"–Level 1 to "Very High"–Level 5) were then assessed for their monitoring needs and were divided into one of 4 monitoring requirement levels (Table 6). Gaps were identified between recommended monitoring level and actual monitoring level at high-risk volcanoes. A follow-up report produced by Moran et al. (2008) made detailed recommendations on the specific configuration of effective monitoring networks for the levels identified in the 2005 report. The second report's recommendations were based on the 5 categories of volcanic monitoring: Seismic, Deformation, Hydrology, Remote Sensing and Gas.

Table 6 – Threat group and monitoring definitions for the NVEWS review (modified after Ewert et al. 2005).

Threat Group	Monitoring Level	Definition
Very High	Level 4	WELL MONITORED IN REAL TIME Monitoring should provide the ability to track detailed changes in real-time and to develop, test, and apply models of ongoing and expected activity
High		
Moderate	Level 3	BASIC REAL-TIME MONITORING Monitoring should provide the ability detect and track pre-eruptive and eruptive changes in real-time, with a basic understanding of what is occurring
Low	Level 2	LIMITED MONITORING FOR CHANGE DETECTION Monitoring should provide the ability to detect and track activity frequently enough in near-real time to recognize that anomalous activity is occurring.
Very Low	Level 1	MINIMAL MONITORING Monitoring should provide the ability to detect that an eruption is occurring or that gross changes are occurring/have occurred near a volcano

While roughly half of the 169 volcanoes were assessed to be dangerous due to their eruptive style and number of communities and infrastructure within their reach, 57 volcanoes were identified as a priority as they are under monitored (Ewert et al. 2005). While some volcanoes were considered as posing a higher risk than others, some level of monitoring was recommended for every volcano in almost all categories of monitoring. These recommendations are listed in Table 7 and the complete list of U.S. volcano scores and categories can be found in Appendix 2.

The report noted that as the NVEWS is a long-term project, and that for the foreseeable future, most U.S. volcanoes will remain unmonitored or inadequately monitored (to the standards recommended in the report). As any of these volcanoes could awaken in this period, the report also recommended the formation of a cache of instrumentation to act as a mobile-response unit. Allowing for multiple areas of unrest simultaneously, this cache should be sufficient to bring two Level 2 networks up to Level 4 status and include a suitable cache of surface-based monitoring equipment; both ground-based and remote sensing (Moran et al. 2008 p. 35–36). In addition to this extensive list, sufficient power supply and telemetry equipment would also be required as well as cabling, housing and mounting equipment.

Moran et al. (2008) suggested that a cache could either be maintained collectively at each observatory along with their own spare equipment supplies or operated as a separate entity, available for all observatories to use but in addition to their own supply reserves.

Table 7 – Instrumentation recommendations for monitoring levels from the NVEWS report. (Moran et al. 2008).

Monitoring Level	***1***	***2***	***3***	***4***	
Volcano Threat Group	***Very Low***	***Low***	***Moderate***	***High***	***Very High***
Seismic	Five seismic stations located within 200 km, including two located within 50 km.	Five seismic stations located within 50 km, including two located within 10 km.	Six to eight seismic stations located within 20 km, including two or three located within 5 km; at least one broadband station located within 5 km.	12–20 seismic stations located within 20 km, including at least two or three located within 5 km, and at least six broadband stations (at least two located within 5 km). Collocated with these stations should be at least one strong-motion station within 5 km, and at least two infrasonic stations with two 2 sensors per station.	
Deformation	Occasional InSAR, GPS, and (or) levelling surveys.	Periodic (1–10 years) InSAR, GPS, and (or) levelling surveys; one continuous-mode GPS station located within 10 km.	7–10 continuous-mode GPS stations, four located within 5–10 km, one of which is outside expected area of deformation; four to six borehole tiltmeters located within 5–10 km. Supplemented by InSAR, GPS, levelling, and (or) microgravity surveys every 1–5 years.	16–20 continuous-mode GPS stations, eight located within 5–10 km, two located outside expected area of deformation; 5–10 borehole tiltmeters located within 5–10 km; one continuous gravimeter located near volcanic centre; Monthly InSAR surveys.	
Hydrology	Baseline water chemistry/temperature measurements at significant lakes/spring/streams every 10–20 years; for volcanoes with nearby population centres and (or) infrastructure, assess hazards for each drainage with LAHARZ program; response and survey equipment resides in equipment cache.	Same as for level 1, plus baseline water chemistry/temperature measurements at significant lakes/spring/streams every 5–10 years.	Same as for level 2, plus baseline water chemistry/temperature measurements at significant lakes/spring/streams every 3–5 years.	Same as for level 3, plus water–chemistry/temperature measurement at significant lakes/spring/streams every 1–5 years; install several continuous probes at two or three volcanoes.	
Remote Sensing	Daily scans of routinely collected satellite imagery to detect ash clouds, gas plumes, and thermal anomalies; acquire baseline imagery for hazard assessments and mapping.	Same as for level 1	Same as for level 1, plus install one telemetered camera	Same as for level 1, plus install two or three telemetered cameras, one low-light camera.	
Gas	-	Compile list of candidate sites for ground-based, airborne, or continuous gas monitor-ing; baseline fumarole-chemistry measurements every 5–10 years; airborne plume measurements if a plume exists; and continuous measurements where appropriate.	Same as for level 2, plus baseline fumarole-chemistry measurements every 3–5 years, airborne measurements every 3–5 years where appropriate, and long-term deployments and (or) measurement surveys where appropriate.	Same as for level 3, plus baseline fumarole-chemistry measurements every 1–2 years, annual airborne measurements, long-term deployments and (or) measurement surveys at volcanoes with adequate degassing levels.	

5.2 Application of the NVEWS Review in New Zealand

There is the possibility a NVEWS-style review of New Zealand's volcanoes and monitoring systems might be a beneficial practice. However, as GNS Science identifies only 12 geologically active (or potentially active) volcanoes and volcanic complexes within its jurisdiction (see Table 1), the scale of the review would be on a much smaller scale.

As this is a preliminary review of the NVEWS system as it relates to New Zealand volcanoes without the benefit of the same data resources as available in the U.S.A., a number of assumptions were made in the calculation of the *Exposure Factor* scores.

Aviation Exposure Score

As most currently monitored volcanoes and volcanic centres are located in the North Island, the regional air traffic hazard was calculated using data the annual statistics of the 4 (current) international airports in the North Island. This data was used to estimate possible daily passenger numbers in the region but different combinations of these statistics can be used depending on the location of the volcano under review (Table 8). It includes foreign passengers arriving in and departing from New Zealand from overseas and New Zealand nationals visiting and returning from international destinations.

Table 8 – Yearly passenger numbers for international airports in the North Island

International Airport	***Yearly Passenger Figures (i)***
Auckland	13,202,772
Hamilton	423,014
Palmerston North	508,780
Wellington	5,021,000
Total regional travel	19,155,565

(i) Figures include both enplaning and deplaning passengers and were obtained from the airports annual report for the year 1 July 2007–30 June 2008.

One major potential error in this method is the possibility of counting individual travellers twice in statistics if, for example, they are flying from Auckland to Wellington. However, the nature of New Zealand's location, being a series of islands, means that a significant portion of air traffic risk will be a result of national air travel and therefore regional enplaning and deplaning figures cannot be omitted. Numbers may also include travellers that may not be affected by an eruption in the North Island such as passengers travelling from Wellington to the South Island or vice versa. However, some of this error is probably absorbed by the omission of passenger numbers at regional airports such as Tauranga, Rotorua and Taupo. It would also not reflect the number of overflight passengers travelling from the South Island to destinations in the Pacific Ocean such as flights from Christchurch to Samoa. Even after recognising these errors, they were deemed acceptable as the addition or deletion of the data from both the least busy international airports (Palmerston North and Hamilton) would only result in a difference of less than one point.

Additionally, seasonal variations in air traffic will produce different daily passenger estimates at different times of the year. This is not reflected in the calculation of daily averages but is similarly not performed in the calculation of the Ewert et al. (2005) scores for U.S. volcanoes.

5.2.1 Application to New Zealand Volcanoes

The NVEWS review process is applied to 7 volcanic centres, the four volcanoes designated “Frequently Active” by GNS Science (Ruapehu, Tongariro/Ngauruhoe, White Island and the Kermadec Islands, the Okataina/Tarawera complex, Taupo Volcano and the Auckland Volcanic Field: Table 1). These sites were chosen as they represent a range of hazards and physical settings. Results are outlined in Table 9 and the full rank list of the U.S. and New Zealand volcanoes included in this review are listed in Appendix 2.

The following sections outline the application of the hazard rank score review at the individual New Zealand sites.

Table 9 – Results of the NVEWS rank score reviews for New Zealand's volcanoes. Scores based on scoring rationale listed in Appendix 1.

	Ruapehu	Tongariro/ Ngauruhoe	White Island	Kermadec Islands	Taupo	Okataina Volcanic Centre	Auckland Volcanic Field
Hazard Factors							
Volcano type	1	1	1	1	1	1	0
Maximum Volcano Explosivity Index (VEI) [(i)]	1	1	1	2	3	3	0
Explosive activity	1	1	1	1	1	1	0
Major explosive activity	0	0	0	1	1	1	0
Eruption recurrence	4	4	4	4	2	3	1
Holocene pyroclastic flows?	1	1	0	1	1	1	0
Holocene lava flows?	0	0	0	0	0	0	1
Holocene lahars?	1	0	0	0	0	0	0
Holocene tsunami(s)?	0	0	0	0	0	0	0
Hydrothermal explosion potential?	1	1	1	1	1	1	1
Sector collapse potential?	1	1	1	0	0	0	0
Primary lahar source?	1	0	0	0	0	0	0
Observed seismic unrest	1	1	1	1	1	1	0
Observed ground deformation	0	0	1	0	1	0	0
Observed fumarolic or magmatic degassing	1	1	1	1	1	1	0
Total of Hazard Factors	**14**	**12**	**12**	**13**	**13**	**13**	**3**
Exposure Factors							
Log_{10} of Volcano Population Index (VPI) at 30 km	3.9	3.9	0	0	4.5	4.9	6.1
Log_{10} of approximate population downstream or downslope	0	0	0	0	0	0	0
Historical fatalities?	1	0	1	1	0	1	0
Historical evacuations?	0	0	0	1	0	1	0
Local aviation exposure	2	2	2	0	1	2	1
Regional aviation exposure	4.7	4.7	3.6	3.4	4.7	4.6	4.6
Power infrastructure	1	1	0	0	1	1	1
Transportation infrastructure	1	1	0	0	1	1	1
Major development or sensitive areas	1	1	1	0	1	1	1
Volcano is a significant part of a populated island	0	0	0	1	0	0	0
Total of Exposure Factors	**14.6**	**13.6**	**7.6**	**6.4**	**13.2**	**16.5**	**14.7**
Relative Threat Ranking Score	**204.4**	**163.2**	**91.2**	**83.2**	**171.6**	**214.5**	**44.1**
Rank (out of 176)	**7th**	**13th**	**36th**	**44th**	**10th**	**4th**	**89th**

[(i)] Maximum VEI factor for Ruapehu is not "1" but received a score of 1 which represents VEI 3 or 4

5.2.2 NVEWS Relative Threat Ranking

Ruapehu

At the southern terminus of the Taupo Volcanic Zone in the North Island, Ruapehu is an andesite composite that reaches 2797 m above sea level (Neal et al. 1996). It is the most recent volcano in New Zealand to erupt with major eruptions in 1995–1996 and in 1945 but minor eruptions have occurred on average once every 1–14 years (Keys 2007; Leonard et al. 2008). The 1995/96 eruptions resulted in the distribution of at least 36 x 10 m^6 of sulphur-rich tephra over the central and eastern North Island (Cronin et al. 1998). The volcano is located in a National Park and has 3 skifields on its flanks. It is one of the 4 volcanoes designated as “Frequently Active” by GNS Science.

Because specific data were unavailable for an accurate population count within a 30 km radius of Ruapehu, a figure (5,722) based on the 2006 census population counts of the major town centres in the 30 km radius was used: Ohakune (1,101), Turangi (3,240) and Waiouru (1,381) (Statistics New Zealand 2008a). This was done as this region was split over two regional councils (Waikato and Horizons regional councils) and the rural population in this region is very low and their inclusion would result in a difference of less than a single point. A nominal daily population of tourists was calculated from annual visitor numbers (estimated at approximately 1,000,000 in 2007 (Keys 2007)) using the method described by Ewert et al. (2005). A final population figure of 8,462 was used in the factor score. However, the transient population is usually concentrated in the winter months when up to 20,000 skiers can visit a single skifield in a single day (Christianson 2006). This can result in an error in the final VPI_{30} score of up to half a point.

As Ruapehu lies in the centre of the North Island, its eruption could affect a large amount of the regional air traffic. In the calculation of the *Regional Aviation Exposure* score, daily passenger estimates were calculated by using data from all the North Island international airports (Table 8). These figures give a regional aviation hazard score of 4.7. This number is lower than the aviation hazard scores attributed to most Aleutian arc volcanoes due to the quantity of over-flight traffic they receive but higher than the figures calculated for the Marianas island volcanoes such as Anatahan which received a 4.0. This number may still be slightly high but will be used for the purposes of this experiment.

Using the same methodology used by Ewert et al. (2005), Ruapehu would receive a hazard score of 14 and an exposure score of 14.6 giving a total rank score of 204.4 (Table 9). This score places Ruapehu in the "Very High" threat group.

By the standards described in Moran et al. (2008), Ruapehu would currently be monitored by a Level 3 network, described as "Basic real-time monitoring" (Table 7). Even after taking into account the possibility of significant movement up or down the ranking table, the required monitoring for both "Very High" and "High" threat volcanoes is a "Level 4" system. This is the highest possible level of monitoring described by Ewert et al. (2005).

Tongariro/Ngauruhoe

Tongariro/Ngauruhoe is a complex system of cones, of predominantly andesitic volcanism, immediately north of Ruapehu in the central North Island of New Zealand. Activity over the last 2500 years has been principally confined to Ngauruhoe with an eruption occurring on average every one or two years since records began (*ca.* AD1830) (Rowlands et al. 2005).

As Tongariro/Ngauruhoe lies immediately to the north of Ruapehu, an eruption from this centre would produce the same hazard to regional air traffic as its southern neighbour in terms of the *Regional Aviation Exposure* score. Similarly, an eruption from Tongariro would endanger the same populations as Ruapehu therefore this score can also be used.

Using the same method as outlined in Ewert et al. (2005), the results of the NVEWS review for Tongariro/Ngauruhoe is outlined in Table 9. Based on a hazard score of 12 and an exposure score of 13.6, Tongariro would receive a total rank score of 163.2 placing it amongst the "Very High" threat volcanoes. This designation indicates Tongariro/Ngauruhoe should be monitored by a "Level 4" system as defined by Moran et al. (2008), as with Ruapehu.

White Island

White Island, located 48 km offshore in the Bay of Plenty, is currently New Zealand's most active volcano. An andesite stratovolcano, White Island is the subaerial expression of a large submarine volcano, at the north-eastern end of the Taupo Volcanic Zone. 11 sulphur miners died in a hot avalanche caused by the collapse of the southeast corner of the crater wall (Nairn et al. 1996). While not located on the mainland, White Island is a popular destination for thousands of tourists every year. Landing on the island is illegal without a permit and tourists can only visit on organised tours through specific providers.

The calculation of the *Regional Aviation Exposure* score was particularly difficult for White Island. Ewert et al. (2005) found similar difficulties in calculating daily scores for the Alaskan volcanoes and those in the Marianas Islands. In these cases, when the amount of over flight traffic is not known, conservative estimates were made.

The island's location offshore in the Bay of Plenty, the northernmost of the subaerial volcanoes in the Taupo Volcanic Zone, places it out of reach of most of the regional air traffic. We can estimate that air travellers flying from any international airport in the country (including the South Island) to destinations north and east of New Zealand (Oceania, the Americas and some travellers to Europe) may be affected by an eruption from White Island. Statistics New Zealand tourism and migration records (2008b) indicate that in the 2007 year, approximately 8,896,000 passengers intent on short-term visits to and from international destinations, were processed at New Zealand international airports. Of those, approximately 1,346,452 travellers were flying to, or departing from, ports in countries to the north and east of the country (i.e. Los Angeles, Tonga, Santiago etc.). This provides a daily passenger approximation of 3688. As it does not take into account numbers of overflight passengers (such as those travelling from Sydney to Santiago), a conservative estimate was made of 4000 estimated daily passengers at risk from an eruption, giving a Regional Aviation Exposure Score of 3.6.

A final *Relative Threat Ranking Score* of 91.2 would place White Island in the "High" threat group. Like these other "Frequently Active" volcanoes, it would also require a monitoring level of 4.

The Kermadec Islands/ Raoul Island

The Kermadec Islands are a group of volcanic island lying 750 to 1000 km north-north-east of New Zealand. While almost all the islands are reserves for flora and fauna and are presently uninhabited, Raoul Island (previously known as Sunday Island), the largest of the Kermadecs, is manned by a small group of Department of Conservation rangers and workers (Latter 1992). The Kermadec Islands are one of the 4 volcanic centres considered by GNS Science to be "Frequently Active" following the 2006 eruption of Raoul Island. This eruption was discussed as a case study for BSE status (see §3.1.2). For the purposes of this assessment, the relative threat ranking review will be undertaken only for Raoul Island, not the Kermadec Islands as a whole.

As with White Island, calculating the *Regional Aviation Exposure* score for Raoul Island proved quite difficult. As no airstrip exists on any of the isolated Kermadec Islands, the only hazard to aviation is the hazard to overflight air traffic. Estimates of daily passenger numbers were taken from Statistics New Zealand (2008b) data on flights to and from the Pacific Islands and Hawaii. Using this information, yearly passenger figures of 1,019,631 were derived giving an average daily 2800. Again, this figure does not fully take into account the overflight air traffic from other countries, not originating or travelling to New Zealand and represents a conservative estimate.

Raoul Island would receive a *Relative Threat Ranking Score* of 83.2, making it the lowest ranking of the "Frequently Active" New Zealand volcanoes. Like White Island, Raoul Island is placed amongst the "High" threat volcanoes requiring a monitoring level of 4.

Taupo Volcanic Centre

Taupo Volcano is located in the southern most region of the rhyolite-dominated portion of the Taupo Volcanic Zone (TVZ). The present-day caldera is largely a result of the 1170 km³ (tephra volume) Oruanui eruption (ca. 22.6 ka) and has been partially filled by Lake Taupo (Smith 1998). Regarded as the most active rhyolite volcano in the world (Wilson 1993), the most recent eruption of the volcano, the 1.85 ka Taupo eruption was the second largest eruption known from the volcano and the largest eruption in the world in the last 5000 years (Wilson et al. 2004).

Although Lake Taupo has an estimated volume of 60 km³, it does not a primary lahar hazard. Following the 1.8 ka Taupo eruption, lahars were generated in response to the emplacement of the Taupo ignimbrite, but not as a direct response to the eruption (Manville et al. In press). For this reason, in this review, Taupo is not considered a primary lahar hazard or as having produced lahars in the Holocene and no score was attributed to these two factors.

As the centre of Lake Taupo lies approximately 60 km from Ruapehu, they represent similar threats to aviation in regards to the Ewert et al. (2005) *Regional Aviation Exposure* threat score. For this reason, the same threat score of 4.7 is used in the NVEWS review of Taupo Volcano. VPI_{30} populations were calculated by combining the populations of the Taupo district, which surrounds the caldera (2006 census data). A summary of NVEWS review for Taupo Volcano is presented in Table 9 with the other New Zealand case studies. The relative threat ranking of 171.6 indicates that according to the Ewert et al. (2005) ranking system, Taupo is a “Very High” threat volcano. Although it is considered a “Reawakening” volcano by GNS Science, this rank score places Taupo with New Zealand’s “Frequently Active” volcanoes.

Okataina Volcanic Centre/ Tarawera

The Okataina Volcanic Centre (OVC) is a collection of rhyolitic domes and Haroharo Caldera in the Taupo Volcanic Zone, New Zealand. While defined as structures mainly bounded within the Haroharo Caldera (including the Tarawera, Haroharo, Okareka and Rotoma volcanic complexes), it also stretches south to Waiotapu and east to include Mt Edgecumbe. The OVC has produced mainly rhyolitic material (over 400 km³ in total : Nairn 1989) but basaltic magma has also been produced, the most recent eruption being the 1886 basaltic plinian eruption of Tarawera (Keam 1988).

Although GNS Science lists Tarawera and the OVC separately in their list of monitored “Reawakening” volcanoes (Table 1), here they are covered in the same review. This was done as the questions in the rank score review are either general to the area (i.e. population statistics and hydrothermal activity) or relate to the most recent period of volcanism, which is the 1886 eruption of Tarawera.

In the calculation of the *Regional Aviation Exposure* score, an estimate using just the upper North Island International Airports was used giving a daily passenger estimate of 37,331 and a score of 4.6. The score is subject to the same errors as the calculation of the other *Regional Aviation Exposure* scores.

The population was taken from the population of the Rotorua District from 2006 census data (www.stats.govt.nz). This was deemed to have only a slight error as the district surrounds the OVC and the largest population centre in the district, Rotorua, lies within 30 km of Tarawera. As with Ruapehu, the transient tourist population was added to the resident population by using estimates of yearly visitor numbers. With 1.6 million overnight and 1.7 million day visitors estimated to visit Rotorua in 2007 (RDC 2009), an additional 9041 people, representing a nominal daily transient population, was added to the resident population of the district (65,901) giving a final score of 4.9.

The review of the OVC produced the highest *Relative Threat Ranking Score* of all the New Zealand case studies (Table 9). A rank score of 214.5 places the OVC 4thth on the list of U.S. and New Zealand case study volcanoes. It is interesting to note that even though the OVC is designated “Reawakening” by GNS Science, it results in the highest hazard rank score of any of the New Zealand volcanoes.

Auckland Volcanic Field

The city of Auckland lies directly in the Auckland Volcanic Field (AVF), a basaltic field of 49 individual eruptive centres, covering an area of approximately 360 km^2 (Houghton et al. 2006). Being home to New Zealand’s largest city, the AVF has been the subject of a number of geological, geochemical and petrographic studies (Allen & Smith 1994 and papers therein) and recent hazard and risk assessments (Magill & Blong 2005; Magill et al. 2005; Magill et al. 2006).

In applying the Ewert et al. (2005) methodologies, the AVF would be a *Type 0* volcano (see Appendix 1 for scoring rationale), as it is a basaltic field. However, Ewert et al. (2005) provide for the possibility of explosive activity within basaltic fields in the *Exposure Factor* scoring rationale (Appendix 1). The presence of significant tuff and lapilli deposits (Allen

& Smith 1994) indicates a history of phreatomagmatic activity within the field and as such, aviation exposure scores were calculated.

The regional air traffic hazard score was calculated using the yearly figures supplied in Table 8 but only the data for Auckland Airport was used. As Auckland is the most northern and largest population centre in the country and contains the largest airport, it is unlikely there will be much “over-flight” air traffic other than overflight traffic from other countries (e.g. travellers from Australia to South America). However, due to the nature of the volcanism expected from the AVF (mainly basaltic, strombolian or phreatomagmatic), it is unlikely high-flying overflight traffic will be affected. This means the yearly passenger enplaning/deplaning numbers will provide a reasonably accurate representation of regional air traffic at risk from an eruption in the AVF. Average daily passenger numbers for the *Regional Aviation Exposure* are calculated as 36,172 giving a regional aviation exposure score of 4.6.

As the AVF represents an area of land as opposed to a point source such as a volcano, the Log_{10} population score was determined by taking the 2006 census population of the Auckland region (1,303,068). While this may be a slight overestimate, Auckland, having thee largest international airport and business centre would have considerable transient populations not able to be accurately calculated and this would likely absorb some of this error.

Regarding the *Hydrothermal explosion potential*; in a probabilistic assessment of the vent locations for the next eruption at the AVF, Magill et al. (2005) determined that it is most likely that the next eruption will occur in the ocean as opposed to on land. Of a simulation of 10,000 events (27,937 eruptions), 69% occurred in the harbour between Rangitoto Island and the mainland. This was deemed to represent a significant hydrothermal eruption potential and therefore was given a score of 1.

Another major difficulty was the lack of historical records describing the last eruption in the field, the formation and eruption Rangitoto Island. Rangitoto represents both the most recent, and most voluminous eruption to have occurred in the AVF, beginning eruptions around AD 1400 and comprising of 59% of the total erupted volume of the field (Magill & Blong 2005). At the time of the eruption, the neighbouring island of Motutapu was inhabited (Nichol 1982). Due to the explosive nature of phreatomagmatic eruptions, the estimated length of activity at the site (ARC 2007) and the production of copious ash deposits (Brothers & Golsons 1959), it is most likely that those populations would have had to evacuate the island. If a score was attributed to this factors the total *Relative Threat Rank Score* would be 47.1 and its rank would have only moved 4 places to 85th. As this would have no major implications for the rank of the volcano, this potential source of error was deemed acceptable and not included in the overall review of the AVF.

The summary of the relative threat ranking review of the AVF is provided in Table 9. It received a ranking score of 44.1, the lowest score of any of the New Zealand case studies. This provided a rank of 89th out of 176 and placed the Auckland Volcanic Field in the "Moderate" threat group.

5.2.3 NVEWS Monitoring Recommendations

The *Relative Threat Rank Score* of Okataina/Tarawera (215), Ruapehu (204), Tongariro/Ngauruhoe (163), Taupo (172), White Island (91) and Raoul Island (83) are sufficient to require Level 4 monitoring as described by Moran et al. (2008). The Auckland Volcanic Field has a significantly lower *Relative Threat Rank Score* (44) and would require only a Level 3.

A gap analysis showing the recommendations for these monitoring levels and comparisons with current monitoring on the volcanoes are found in Table 10 for the Level 4 "Very High" threat systems and Table 11 for the Level 4 "High" threat and Level 3 systems. Full description of all monitoring levels can be found in Table 7.

Table 10 – Suggested monitoring requirements for "Very High" threat volcanoes and monitoring currently underway on those New Zealand volcanoes.

	Suggested Level 4	Current Monitoring			
		Ruapehu (4)[i]	**Tongariro/Ngauruhoe (2)[i]**	**Taupo (3)[i]**	**Okataina (3)[i]**
Seismic	• 12–20 seismic stations located within 20 km, (at least two or three located within 5 km) • At least 6 broadband stations (at least two located within 5 km) • At least one strong-motion station within 5 km • At least two infrasonic stations with two 2 sensors per station	• 14 seismic stations within 20 km (6 within 5 km) • Approximately 4 broadband stations • 1 strong motion site at 20 km • 6 acoustic pressure sensors	• 14 seismic stations within 20 km (6 within 5 km) • Approximately 4 broadband stations (with a view to move to all broadband stations in the region) • 1 strong motion site at 20 km	• 8 seismic stations within 20 km (4 within 5 km) • One broadband station • 3 strong motion sites within 5 km	• ~10 seismic stations within 20 km (~6 within 5 km) • No broadband stations within 50km • 3 strong motion site at 20 km (none within 5 km)
Deformation	• 16–20 continuous-mode GPS stations, eight located within 5–10 km, two located outside expected area of deformation • 5–10 borehole tiltmeters located within 5–10 km • 1continuous gravimeter located near volcanic centre • Monthly InSAR surveys	• 7 continuous GPS sites within 10 km • Plan for a borehole tiltmeter near the chateaux • No continuous gravimeter or plans for one • No tilt (was tested, proven unsuitable) • No InSAR (was tested, proven unsuitable)	• 7 continuous GPS sites within 10 km • No continuous gravimeter or plans for one • No tilt (was tested, proven unsuitable) • No InSAR (was tested, proven unsuitable)	• 8 continuous GPS sites within 10 km, periodic high spatial resolution GPS campaigns • No continuous gravimeter or plans for one • 22 precise lake levelling sites with quarterly campaigns • Periodic InSAR investigations	• ~10 continuous GPS sites within 10 km • No continuous gravimeter or plans for one • Periodic InSAR
Hydrology	• For volcanoes with nearby population centres and (or) infrastructure, assess hazards for each drainage with LAHARZ program • Baseline water chemistry/temperature measurements at significant lakes/spring/streams every 1–5 years • Install several continuous probes at two or three sites	• LAHARZ surveys have been modelled for Ruapehu (2002) • Periodic water chemistry at crater lake • ERLAWS system: 3 acoustic flow monitors, level sensors	• Annual surveys of lake levels and chemistry	• Lake-levelling surveys 2–4 times per year (22 sites)	• Crater lake monitoring (at Waimangu • Periodic lake-levelling surveys at Lake Tarawera (3 sites) • Water chemistry at selected sites yearly

Continued over page.

Remote Sensing	• Daily scans of routinely collected satellite imagery to detect ash clouds, gas plumes, and thermal anomalies • Acquire baseline imagery for hazard assessments and mapping • Installation of two or three telemetered cameras, one low-light camera	• AVHRR and MODIS monitoring of eruption cloud and hotspot anomalies • Analysis of ASTER images when available looking at crater lake temp (3–4 weekly) • 2 web cameras	• 2 web cameras (one monitoring each side of the volcano)	• No webcameras, GNS Science offices within 15 km	• No web cameras but regular phenomenological observations by local operators
Gas Emissions	• Airborne plume measurements if a plume exists • Continuous measurements where appropriate • Baseline fumarole-chemistry measurements every 1–2 years • Long-term deployments and (or) measurement surveys at volcanoes with adequate degassing levels	• Periodic (monthly) airborne surveys • Periodic (monthly) crater lake chemistry and temperature measurements • Fumarole chemistry campaigns, not regular	• Monthly airborne surveys • Soil CO2 and temperature campaigns • Fumarole chemistry campaigns, not regular	• None appropriate	• None

[i] *Indicates current NVEWS monitoring level on the volcano; see Appendix 3 for clarification*

Table 11 – Suggested monitoring requirements for “High” and “Moderate” threat volcanoes and monitoring currently underway on those New Zealand volcanoes.

	Suggested Level 4	***Current Monitoring***		***Suggested Level 3***	***Current Monitoring***
		White Island (2) [i]	***Kermadec Islands/ Raoul Island (2)*** [i]		***Auckland Volcanic Field (2)*** [i]
Seismic	• 12–20 seismic stations located within 20 km, (at least two or three located within 5 km) • At least 6 broadband stations (at least two located within 5 km) • At least one strong-motion station within 5 km • At least two infrasonic stations with two 2 sensors per station	• 1 seismic stations on the island • No broadband sites • No accelerograph sites within 20 km • 1 microphone to detect explosions	• 3 seismograph including 1 global network unit	• 6–8 seismographs located within 20 km,(incl. 2 or 3 located within 5 km) • At least 1 broadband station located within 5 km	• 8 seismograph stations (5 within the field)
Deformation	• 16–20 continuous-mode GPS stations, eight located within 5–10 km, two located outside expected area of deformation • 5–10 borehole tiltmeters located within 5–10 km • 1continuous gravimeter located near volcanic centre • Monthly InSAR surveys	• No GPS within 50 km • Plans to experiment with a continuous gravimeter • No tilt • No InSAR	• 1 continuous GPS station • Periodic levelling surveys	• 7–10 continuous GPS stations, 4 located within 5–10 km, 1 of which is outside expected area of deformation • 4–6 tiltmeters located within 5–10 km • Supplemented by InSAR, GPS, levelling, and (or) microgravity surveys every 1–5 years	• 1 GPS unit at Whangaparoa, ~28km from city centre • Occasional InSAR imagery analysis
Hydrology	• For volcanoes with nearby population centres and (or) infrastructure, assess hazards for each drainage with LAHARZ program • Baseline water chemistry/temperature measurements at significant lakes/spring/streams every 1–5 years • Install several continuous probes at two or three sites	• Quarterly trips to sample crater lake temperature and geochemistry	• Telemetered continuous lake level and temperature measurements • Weekly temperature readings at Green and Marker Lakes	• For volcanoes with nearby population centres and (or) infrastructure, assess hazards for each drainage with LAHARZ program • Baseline water chemistry/temperature measurements at significant lakes/spring/streams every 3–5 years	• None appropriate

Continued over page.

Remote Sensing	• Daily scans of routinely collected satellite imagery to detect ash clouds, gas plumes, and thermal anomalies • Acquire baseline imagery for hazard assessments and mapping • Installation of two or three telemetered cameras, one low-light camera	• 3 web cameras (two on island, one on shore)	• 1 telemetered webcamera • AVHRR and MODIS monitoring of eruption cloud and hotspot anomalies • Phenomenology observations by DoC staff	• Daily scans of routinely collected satellite imagery to detect ash clouds, gas plumes, and thermal anomalies • Acquire baseline imagery for hazard assessments and mapping • Installation of one telemetered camera	• None
Gas Emissions	• Airborne plume measurements if a plume exists • Continuous measurements where appropriate • Baseline fumarole-chemistry measurements every 1–2 years • Long-term deployments and (or) measurement surveys at volcanoes with adequate degassing levels	• Sporadic airborne surveys • Soil CO2 and temperature campaigns • Quarterly fumarole chemistry campaigns	• Occasional soil gas and fumarole sampling campaigns (roughly annual)	• Compile list of candidate sites for ground-based, airborne, or continuous gas monitoring • Same as for level 2, plus baseline fumarole-chemistry measurements every 3–5 years • airborne measurements every 3–5 years where appropriate • Long-term deployments and (or) measurement surveys where appropriate.	• None appropriate

[(i)]*Indicates current NVEWS monitoring level on the volcano; see Appendix 3 for clarification.*

5.3 Discussion

When tabulated with results from the Ewert et al. (2005) review, 6 New Zealand volcanoes rank in the top 50 hazardous volcanoes between the two countries (Table 9). Ewert et al. (2005) noted the heavy reliance the final rank score had on the "Exposure Factors" and how hard these were to quantify. The "Hazard Factors" are easily attributable based on historical and geological records.

The hardest factor to quantify was the *Regional Aviation Exposure* score. If Ruapehu is taken as an example, the fact that it is a "Frequently Active" volcano located in the middle of a populated island, might lead one to expect it to rank higher than the volcanoes in the Aleutian Arc, Alaska (the highest of which ranks 12th in the list). However, the authors of the Ewert et al. (2005) report acknowledge this scoring system did not provide a high enough aviation score for the Alaskan volcanoes based on the extremely high threat these volcanoes pose to overflight aviation. Most of the aviation threat scores at these volcanoes were less than a point higher that Ruapehu. Significant errors would be found in this score as the level of overflight air traffic would not be able to be quantified properly.

This review also failed (admitted by the authors of the report) to take into the account the additional aviation hazard posed to air-cargo and, perhaps more importantly for New Zealand, sea-cargo. The city of Auckland (and Port of Auckland) lies within the Auckland Volcanic Field (AVF) on an isthmus between two harbours, the Waitemata and the Manukau. The Waitemata is the largest harbour containing the commercial shipping hub, the Ports of Auckland and the Royal New Zealand Naval base at Devonport as well as numerous marinas and ferries. Magill et al. (2005) suggest there is a very high probability that the next eruption of the AVF will take place within the Hauraki Gulf, most likely in the water between Rangitoto Island and the North Shore (Figure 31; Magill et al. 2005). This is also the main shipping channel for the Waitemata Harbour and Ports of Auckland. As the harbour is generally shallow (9–11 m in the shipping channel; Monro 1975) and must be dredged regularly to keep the shipping channel open, an eruption in this area would very likely destroy the channel. This means not only would an eruption in the harbour be potentially devastating to the city, and also the country (since much of New Zealand's imports are channelled through Auckland) but long-term recovery will be hampered by the loss of the city's major port entry.

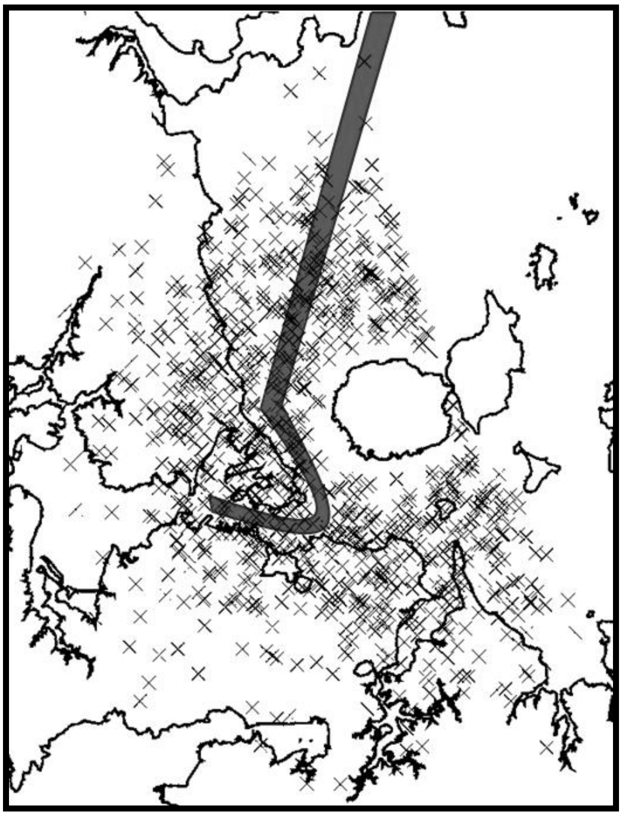


Figure 31 – Waitemata Harbour with shipping channel (grey stripe) and probabilistic analysis of vent locations (crosses) for the next AFV eruption (modified after Magill et al. 2005).

The *Relative Risk Rank Score* of Auckland compared to other New Zealand volcanoes is particularly low. As the final *Relative Threat Rank Score* was the product of the *Hazard Factors* and the *Exposure Factors* scores, the low score the AVF received in the *Hazard Factors* section of the review, kept the overall score low despite the highest *Exposure Factors* score of any New Zealand volcano. The NVEWS review incorporates both elements of a hazard assessment (hazard factors) and vulnerability assessment (exposure factors) with the purpose of deriving the best monitoring solution for forecasting purposes. While in New Zealand, we may consider the hazard posed by an eruption of Ruapehu to be more of a "nuisance" than the hazard caused by an eruption in the Auckland Volcanic Field, for the purposes of forecast monitoring, the "Frequently Active" Ruapehu requires more attention than the currently inactive Auckland Volcanic Field as the threat is potentially more imminent.

As a whole, the questions posed in the review lent themselves more to individual volcanoes than to volcanic fields. However, it was implied that it could be used for basaltic fields (i.e. *Volcano Type – If volcano type is cinder cone, basaltic field, small shield, or fissure vents: Score = 0; If volcano type is stratocone, lava domes, complex volcano, maar or caldera: Score = 1*) and the review was applied to volcanic centres in the U.S. like the Lassen Volcanic Centre, the Ugashik-Peulik complex and Mono Lake Volcanic Field. While the scoring rationale included in the Ewert et al. (2005) report stated that a point should be derived close to the geographic centre of the field, to base population calculations from, this assumes that the centre of the field is the likely source of future eruptions.

The Ewert et al. (2005) report was devised and constructed around the hazards posed by U.S. volcanoes and so, focuses on styles of volcanism, most prevalent in the U.S.A. For this reason, emphasis was placed on lahar and lava flow hazards, with some exposure factors only being calculated if there was significant hazard from these two events (i.e. Log_{10} of population downstream or downslope). Probably the biggest issue with applying the NVEWS-style review to New Zealand volcanoes as it stands is the lack of focus on pyroclastic density currents caused by silicic caldera eruptions. Scott and Travers (In press), describe these hazards as posing an “Extremely high” treat to both people and property in New Zealand, affecting a local to regional area depending on the size of the eruption. Eruptions of this type from Lake Taupo extended over 60 km in the 26.5ka Oruanui eruption (Wilson 2001) and 80 km ± 10 km during the 1.8ka Taupo eruption (Wilson 1985) (Figure 32). This may indicate that the calculations of part of the exposure factors are less applicable in a New Zealand setting than in a U.S. setting.

The monitoring benchmark recommendations listed in Moran et al. (2008) lend themselves more to volcanoes on the mainland than volcanic islands. This means that two of New Zealand’s “Frequently Active” volcanoes (i.e. White Island and Raoul Island) show large discrepancies between the benchmark recommendations and the present level of monitoring on the volcanoes.

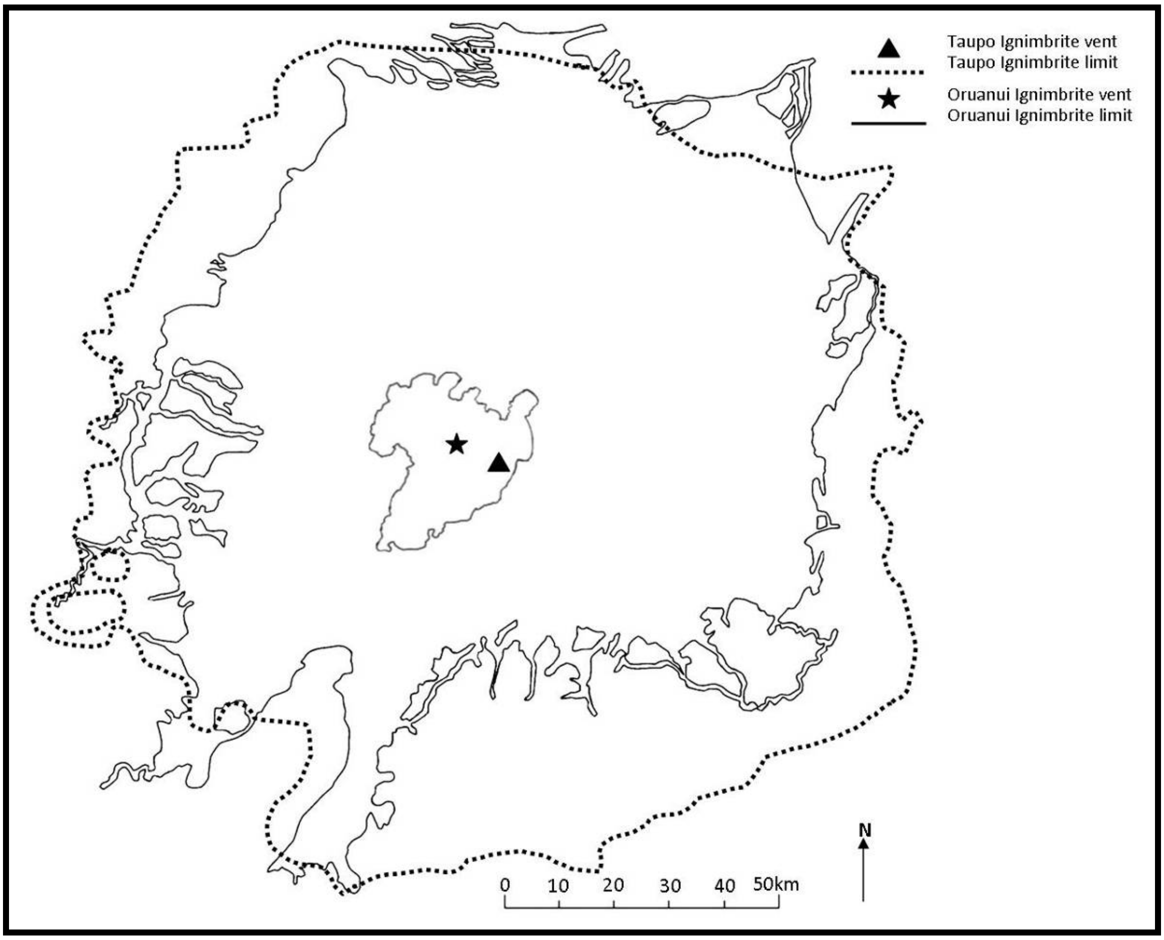


Figure 32 – Extent of ignimbrite deposits from the 1.8ka Taupo and 25.6ka Oruanui eruptions of Taupo Volcano (modified after Wilson 1985, 2001).

In the gap-analysis of monitoring benchmarks for New Zealand's volcanoes based on the NVEWS report (Appendix 3), it is evident that GNS Science places emphasis on different aspects of monitoring for different volcanoes. For example, White Island is the only New Zealand volcano with a persistent visible volcanic plume. The island, ~50 km from shore and approximately 2 x 2.4 km in size precludes any extensive seismic or GPS network but White Island is the only volcano in New Zealand to have a continuous gas network installed. Conversely, while a level 4 system is also recommended for Raoul Island (which is also considered "Frequently Active"), no regular gas monitoring is performed at all and emphasis is placed on seismic and deformation monitoring. This highlights one potential disadvantage of trying to applying a "one-size-fits-all" set of monitoring benchmarks to a range of volcanoes at different stages of "Frequently Active" activity.

As described earlier, NVEWS review was conducted with two main objectives, 1) to provide a national framework of monitoring standards and techniques, and 2) to quantify risk of volcanic hazards at each U.S. volcano.

The first objective is probably more necessary for the United States than New Zealand's where 169 volcanoes are monitored by 5 different observatories. As GNS Science monitors all of New Zealand's 12 volcanoes and volcanic complexes from the same set of offices and a unifying framework already exists from the fact that all volcanoes are monitored by the same people. However, as New Zealand is a relatively small area subject to a diverse range of volcanic hazards, a study integrating different hazards under a similar framework may be more useful.

The second objective, the quantification of risk at individual volcanoes, is a more suitable objective for a NVEWS-style review in New Zealand. The ability to quantify risk would allow GNS to provide improved support for decision making and emergency planning. While assigning figures to risk factors can be notoriously difficult, the quantification of risk to stakeholders, decision makers and funding agencies helps put abstract concepts into a relatable (and compatible) format.

The NVEWS is not the only risk review method currently underway around the world. The EXPLORIS project (Explosive Eruption Risk and Decision Support for EU Populations Threatened by Volcanoes) aims to provide detailed risk assessments of populated regions of the European Union (EU) to civil authorities for use in the construction of mitigation strategies and policy management. This is being accomplished through a series of scenario models (Spence et al. 2005; Zuccaro et al. 2008), probabilistic hazard analysis and the construction of vulnerability assessments for buildings, infrastructure and inhabitants (Spence et al. 2007).

While the NVEWS project focuses on reducing vulnerability through the quantification of volcanic risk and monitoring strategies, the EXPLORIS project revolves around the construction of scenario modelling and human-impact mitigation. The EXPLORIS project focuses mainly on areas with high-levels of urbanisation in the immediate vicinity of active or high-risk volcanoes such as Mt Vesuvius in Italy. For this reason, one of their main objectives is the creation of high-detail scenarios of all facets of volcanic activity possible at a site, at a level, probably not required in a study of New Zealand's volcanoes. However, elements of an EXPLORIS-style study could also be employed such as eruption impact assessments, vulnerability databases and the definition of potential mitigation measures.

5.4 Conclusions

The NVEWS review was not intended to be used as a comparison between the hazard posed by volcanoes the USGS monitor and other volcanoes around the world. However, it is useful as an indication of how the U.S.A. might go about monitoring New Zealand's volcanoes. It is interesting to note that, if the full hazard from New Zealand's volcanoes was included in the review (i.e. the significant hazard from silicic eruptions), they might score even higher on the rank review.

Similar scores were achieved by the NVEWS review of Yellowstone Caldera and Long Valley which could be comparable to the New Zealand silicic centres but the Ewert et al. (2005) authors had similar difficulties assessing the populations at risk from these volcanic centres. With large silicic calderas, it is difficult to quantify the hazard to populations based on a restricted distance from the centre. Depending on the size of an eruption, populations well over 30 km from the vent may be directly affected. Perhaps another exposure factor for silicic centres based on this additional exposure is warranted. However, this is hard to quantify without a rigorous statistical analysis and might not fit into a summarising table such as the Ewert et al (2005) study.

The NVEWS review was not intended to indicate any timeframe in which the volcanoes might erupt (i.e. it was not intended to imply the higher ranked volcanoes were more likely to erupt) but to provide a mini-vulnerability assessment and evaluate whether the monitoring on the volcano reflects the hazard it poses. In this way, it is a not fully quantified risk/hazard assessment with monitoring implications.

The application of a NVEWS-style review has applications to New Zealand's volcanoes but would have to be modified to account for the variety in volcanism and diverse geographic settings present between them. The NVEWS review was conducted in two parts 1) The relative threat ranking and; 2) The monitoring benchmarks recommendations. While the former has applications in New Zealand, the latter would probably not be as effective as in the U.S.

As 169 volcanoes were assessed during the Ewert et al. (2005) report it was kept intentionally general. With 169 volcanoes divided into only 4 monitoring levels, the recommendations were likewise general. For a New Zealand review, the smaller number of volcanoes would act in our favour, allowing more focussed scoring and more specialised monitoring reviews.

An integrated review where the hazard from all volcanoes is assessed under the same framework is beneficial for quantifying risk to stakeholders and funding agencies. It provides continuity in assessment and would allow comparisons across different volcanoes. However, monitoring recommendations for all volcanoes of a certain threat such as those in Moran et al. (2008) would not work in New Zealand. Reviews for each volcano should be based on their geographic setting and style of volcanism therefore potential forecast window. As the ascension rates of different types of magma can be different based on their physical properties, the potential forecast window, and precursory activity that might be detectable, will vary between types of volcanoes.

Additionally, the review may not fully reflect the risk of eruptions at different New Zealand's volcanoes. If the consequences are considered, an eruption from the AVF is more dangerous than an eruption from Ruapehu.

Recommendations based on purposes of the monitoring levels as listed for the NVEWS review in Table 6 would provide better guidelines and allow flexibility to tailor monitoring networks for the forecasting needs of the volcano. For example, as the Auckland Volcanic Field is currently inactive, it does not require the level of monitoring dictated by the monitoring benchmarks in Ewert et al. (2006: Table 7). As there is no active gas vents or suitable sites for hydrological studies, these parameters are unnecessary. However the rationale for a Level 2 monitoring system as outlined in Table 6: "*Limited Monitoring for Change Detection: Monitoring should provide the ability to detect and track activity frequently enough in near-real time to recognize that anomalous activity is occurring"* indicates that the current monitoring system is probably sufficient to accomplish this goal.

Some factors are very hard to quantify (especially the exposure factors), however, as they supply an assessment of the vulnerability of the region, they should be retained. Reworking the scoring factors in the *Exposure Factors* section to reduce ambiguity and reflect the New Zealand environment would make a review more effective.

5.5 Recommendations

If an NVEWS style review (i.e. a hazard review for monitoring purposes) was to be conducted for New Zealand's volcanoes, this author makes the following recommendations:

5.5.1 Relative Threat Ranking Review

- More emphasis on should be placed on the hazards of silicic volcanism (i.e. pumice and ash flows)
- Larger population catchments should be used when assessing silicic volcanoes
    - Alternatively, the possibility of another exposure factor reflecting the larger population risk should be assessed
- Acknowledgement of risk to ports and harbours should be included
- Rework *Exposure Factors* scoring to eliminate ambiguity (i.e. *Regional Aviation Exposure*)

5.5.2 Monitoring Recommendations Review

- Individual monitoring reviews should be undertaken on each volcano based on guidelines for the purpose of monitoring levels

- Differentiate between currently active and frequently active volcanoes (i.e. currently, the review recommends acoustic sensors in Taupo, however as Taupo is not active, nor is there a risk of imminent eruption, this is uneconomical and unnecessary)
- Review whether monitoring methods outlined in Moran et al. (2008) are suitable for application on New Zealand volcanoes i.e. InSAR,
- Acknowledgement of the differences in volcanism styles and potential forecast windows should be built into the review (i.e. magma ascension rates for basalt could provide a shorter forecast window than a large silicic eruption, monitoring should reflect this)
- Automated alert systems should be able to capture extremely short-lived precursory activity and not rely on extended accumulated patterns

6

Managing and Mitigating Blue-Sky Eruptions

New Zealand's volcanoes and geothermal areas are some of the most popular tourist destinations in the country. Tongariro National Park, which surrounds Ruapehu and Tongariro/Ngauruhoe, attracts up to one million visitors every year (Keys 2007); they come in the summer for the hiking and tramping on trails that cross the mountains and in the winter for the skiing and snow sports on Ruapehu. The Rotorua district (which includes the Okataina Volcanic Complex and geothermal regions around the city) attracts 1.6 million overnight, and 1.7 million day visitors every year(RDC 2009). This many visitors to the region indicates it is at risk from blue-sky eruptions, including the hydrothermally driven eruptions that appear to be unpredictable; effective management strategies can mitigate the risk from these volcanic hazards in lieu of effective eruption forecasting.

Since European colonisation, there have been 3 volcanic disasters that have caused multiple deaths in New Zealand. They are the 1886 eruption of Tarawera where over 130 deaths occurred, the 1914 hot avalanche on White Island which killed 11 sulphur miners and the 1953 Christmas Eve break-out lahar from Ruapehu that caused the Tangiwai train disaster which resulted in 153 deaths. Between 1953 and 2000, there were at least two significant volcanic eruptions; the 1975 eruption of Ngauruhoe and the 1995/1996 eruption of Ruapehu; neither of which resulted in any deaths of injuries even though the eruptions at Ruapehu occurred during winter ski season.

The death of Department of Conservation worker Mark Kearney during the 2006 eruption of Raoul Island was the first fatality caused directly by a volcanic eruption in New Zealand in 53 years. The following year, 6 months after the break-out lahar that partially emptied the Crater Lake, Ruapehu erupted. This is the eruption of Ruapehu that coined the term "blue-sky eruption", and created a lahar that directly hit Dome Shelter where William Pike and a fellow climber were overnighting. Mr. Pike lost his leg after being partially buried in the debris. These two incidents, both of which are classed as BSEs in this thesis, along with international case studies such as the deaths that occurred at Agua Shuca and the parallels that can be drawn to geothermal areas such as Kuirau Park in Rotorua, highlight the danger that exists in New Zealand from BSEs.

As discussed in §4.4.1, there are some international differences in the definition of a "precursor" to a volcanic eruption (Marzocchi et al. 2007). Whether a precursory signal can be defined as deterministic, statistically probable or only identifiable in retrospect is not a matter of semantics, it affects the way in which the volcanic hazard is managed. In the first two definitions, as described in Chapter 4, monitoring networks can assist in precursor detection and eruption forecasting. However, in BSEs we must assume that no eruption forecast is possible as no definitive precursor has been detected. In these cases, the effective management of the crisis becomes the mitigation of the risk. There are a number of ways this can be achieved.

6.1 Mitigating the Hazard of Blue-Sky Eruptions

For the purposes of this section, the hazard posed to New Zealand from BSEs will be limited to the magmatically-driven eruptions of Ruapehu and the hydrothermally-driven eruptions from the central North Island, because case study analysis has shown there is a real possibility of these styles of eruption occurring without prediction.

Arguably, the most extensive work on mitigating volcanic hazards to vulnerable populations has been carried out in Italy. Work done during the EXPLORIS project, which has been described earlier in this thesis, has shown that early evacuation should not be the sole mitigation measure relied upon by emergency managers and decision makers (Baxter et al. 2008b). Additionally, the unexpected lateral blast in the 1980 eruption of Mt St. Helens and subsequent volcanic crises have underlined the need for establishing mitigation measures well in advance of the renewal of activity at a volcano (Baxter et al. 2008a).

6.1.1 Limiting Access to Dangerous Areas

Following volcanic crises early this decade, the local Civil Protection authority of the island of Stromboli (an island volcano that is an extremely popular tourist destination in Italy) modified the rules governing access to the summit region of the volcano (Bertolaso et al. 2009). New rules limited the number of people able to visit the summit regions at one time and insisted groups (of no more than 20 individuals) be accompanied by a volcanological guide at all times. The role of the guides was to report the position of the group continuously to a command post and to facilitate emergency procedures if an eruption was to occur or the hazard to increase. Shelters were also constructed on the volcano to protect visitors from flying rocks during eruptions. Visitors to the summit are also required to read and sign a form which outlines the specific volcanological hazards of the region.

Visitors to Stromboli come with the express wish to climb an active volcano. While the same might be true for White Island, other volcanic regions of the country draw visitors for reasons such as skiing, hiking, appreciating geothermal phenomena and other outdoor pursuits (as previously discussed). As Stromboli is one of the most active volcanoes in Europe (Speranza et al. 2008), it is perhaps unreasonable to impose that level of restriction on New Zealand's volcanoes, other than on White Island, which has a similar policy in place already. However, on Ruapehu and Tongariro/Ngauruhoe making rules regarding the length of time visitors may spend at the summit or in other high-risk areas may provide a reduction in the number of visitors at risk during an eruption event, whether it is forecast or not.

In the geothermal regions of the central North Island (which include the Taupo and Okataina regions), there is a fine balance between allowing access to locations of interest for tourists and providing for their safety. As seen in §3.2, hydrothermally driven BSEs appear to have no detectable precursors at all and can occur at any time. In these cases, apart from preventing access altogether from these areas (which would remove a large portion of the local economy which is based on tourism), there is little that can be done other than employ and enforce reasonable set-back distances from existing features and rely on other means of hazard mitigation such as those described below.

6.1.2 Land-Use Planning

Even when accurate hazard maps showing the extent of areas at potential risk are produced and circulated, economic and developmental concerns of both individuals and local authorities tend to override the warnings given. The potential for a reawakening of a volcano within an individual's lifetime is considered a low probability by the individual, especially if the volcano has been in a quiescent state for a long period of time (Bertolaso et al. 2009).

After the eruption at Agua Shuca in El Salvador (§3.2.2), an area with a radius of 200m surrounding the geothermal area was deemed to have a high potential risk and an area with a 300m radius a low potential risk (Handal & Barrios 2004). Similar risk zones were designated around other hydrothermal areas in the area following this eruption. However, as no law limiting building in these areas existed, these designations were meaningless. In New Zealand, the Resource Management Act (1991) and the Building Act (1991) give responsibilities for the control of the use of land for the purposes of the avoidance and mitigation of natural hazards to both regional and territorial authorities. The Rotorua District Council has clauses built into its District Plan where conditions may be imposed on development or activity in an effort to avoid or mitigate natural hazards (RDC 1996). The Taupo District Council District Plan contains an entire section on the management of natural hazards and unstable ground (TDC 2007).

The Civil Defence and Emergency Management Act 2002 states that all regional councils must have a CDEM group responsible for the identification, assessment and management of all natural hazards in their region. Once a hazard has been identified, it the responsibility of the council to take all reasonable steps to protect the people and property at risk from the hazard and achieve a reasonable level of risk. The Resource Management Act (RMA) 1991 states it is the responsibility of the Regional Councils to control land use for the purpose of the avoidance or mitigation of natural hazards. They can enforce this by withholding resource consents for building in high-risk areas based on legislation in the Building Act 1991. However, the legislation cannot be applied retrospectively, meaning that structures already built in dangerous zones cannot be removed. District Plans can be altered to discourage further development in high risk areas such as in and around the Okataina Volcanic Centre but considering the size of the eruptions possible from the area, the hazard may preclude any development in the TVZ whatsoever.

With low probability/high effect eruptions such as those from Taupo and Okataina, there is typically resistance to the restriction of development based on their threat. This is especially the case in New Zealand where written records and European colonisation date back approximately 175 years and the oral history of the Maori regarding some volcanic events has been lost. It can be difficult for current residents to appreciate the risk based on events that occurred such a long time ago. The last major silicic eruption in the TVZ was the ~AD 1314 Kaharoa eruption (Lowe et al. 2008) which resulted in the production of approximately 4 km^3 of rhyolitic lavas (Sherburn & Nairn 2004). It has been estimated that pyroclastic flows and surges from any future Kaharoa-style event could result in deaths up to 20 km from the source (Blumenthal 2003).

6.1.3 Resource Management

Browne et al. (2001) noted that hydrothermal eruptions can occur as part of the natural evolution of a geothermal field and as a result of exploitation of the field's resources. The natural evolution of a geothermal field can produce much larger eruptions with deeper foci while eruptions in exploited fields tend to be smaller in magnitude. Managing the geothermal system effectively so as not to too greatly disturb the regional hydrology, e.g. through mass withdrawal and so forth, can reduce the hazard of hydrothermally driven BSEs.

This is best illustrated in Rotorua. Exploitation of the Rotorua geothermal field was initially encouraged, however, once its effects were realised, the management strategies introduced have encouraged the recovery of the resource and resulted in an overall decrease in small hydrothermal eruptions in the area (Figure 22) (Scott & Cody 2000).

6.1.4 Effective Hazard Communication and Education

In a phone interview with William Pike, who lost his leg during the September 2007 eruption of Ruapehu, the issue of communication was discussed. Mr Pike noted that while he was aware that Ruapehu was a volcano, he saw no acknowledgement or information regarding the risk of a volcanic eruption. During the preparations he and his climbing partner made prior to their ascent of the mountain, he observed no information on the volcanic hazard present at the summit either on the Department of Conservation website or at the visitor centres where they filed their intentions in the log book. As an experienced mountain climber, Mr Pike said he knew that overnighting at the summit of the volcano was not advised, but there was an opinion within the climbing community that the risk was exaggerated and although there were no facilities inside the shelter at the summit to encourage climbers to overnight there, “everyone did”. This opinion appeared to be confirmed by Mr Pike when he noted the large number of holes caused by ice crampons in the Dome Shelter where he and his companion decided to sleep the night of the eruption.

When accessed on 10/06/2009, the DoC website made no mention of volcanological hazard in its “Plan and Prepare” section of the National Park pages, other than the graphic for the button used to navigate to the page. Similarly, information on the “Safety” pages was limited to warnings about packing adequate gear, avalanches and wildfires but there was no mention of volcanic hazards. Warnings of the possibility of volcanic activity were provided in downloadable brochures (that are also presumably available at information centres) advising people to check the status of volcanoes at the GeoNet website before they set out and briefly outlining what should be done in the case of an eruption. However, this information is only available on specific walks pages and not generally in the Tongariro National Park information pages. This may preclude many day visitors (i.e. skiers, general visitors) not undertaking specific hikes from being fully informed of the hazard. This author remembers hiking or taking the chairlift to the upper skifield many times as a teenager and participation in a specific tour was not needed, nor was filing intentions with the visitors centre. This puts pressure on the operators on the mountain to protect visitors through staff training and emergency procedures (Christianson 2006).

Some might argue that too much information on hazards might be viewed as negative and discourage people from visiting the mountain. However, this author feels certain visitors to the mountains, particularly those intending to spend a long time at the summit or in other high-risk areas, are familiar the concepts of personal acceptable risk and would not be discouraged from visiting the mountain. When asked whether the presence of any hazard information at the "intentions book" would have altered his climbing plans, Mr Pike responded that they would not have. He and his friend were experienced climbers and that he felt the odds were still likely to have been in his favour, but he would have been more aware of the possible dangers.

In a similar way to communication, hazard education of those at risk of volcanic hazards can help mitigate the hazard posed by BSEs. Low levels of perceived risk through inadequate understanding of the hazard can be dangerous during times of volcanic crisis as it may cause individuals to respond inappropriately to the danger (Carlino et al. 2008). Effective and ongoing education programmes through schools, media and local authorities can reduce a community's exposure to volcanic hazards (Lavigne et al. 2008).

Acceptable Risk

Newhall and Hoblitt (2002) noted that a person's level of acceptable risk in regard to being killed or injured during a volcanic eruption depends on the benefits and losses experienced in undertaking the process that would put them in danger. There is a trade-off between risk and pay-off. For example, a person might be more likely to work near a volcano because their job requires it and they might lose pay or employment if they refuse. They noted that volcanologists might be motivated by a different trade-off and find a high level of personal risk acceptable if their work might reduce risk to others.

Because of the unpredictable nature of BSEs, where other planning and restriction initiatives are impractical, the only mitigation possible may be to provide the individual with all pertinent information and allow them to decide whether the situation exceeds their personal acceptable limits. This would require, however, that the person must have an understanding of the hazard posed by BSEs and have had the risk communicated effectively in order to make a sound judgement.

6.2 Response to BSEs

If eruption forecasts cannot predict BSEs, after then attempting to mitigate the hazard posed by these eruptions and events, planning should turn to creating an effective response to a BSE. As these events would most likely be unexpected focus the initial response would most likely need search and rescue planning in both urban and rural settings (Baxter et al. 2008b). Following the January 1993 eruption of Galeras in Colombia, emergency crews descended into the volcano to search for survivors almost immediately after the eruption had abated, in spite of the serious risk of further explosions (Williams & Montaigne 2001).

One of the main purposes of the Civil Defence and Emergency Management Act 2002 is to provide for planning and preparation for emergencies and for response and recovery in the event of an emergency. It places the responsibility on the regional Civil Defence and Emergency Management groups to prepare response and recovery plans for all natural disasters including volcanic eruptions. The Bay of Plenty Regional Council (responsible for responding to threats from the OVC and Taupo area), Horizons Regional Council (responsible for Ruapehu and Tongariro/Ngauruhoe) and the Auckland Regional Council all have response and recovery plans ready for implementation following a natural disaster. On a smaller scale, Ruapehu has a professionally trained search and rescue unit called the Ruapehu Alpine Rescue Organisation (RARO) which has been called into action in both alpine and volcanological (the 2007 eruption of Ruapehu) emergencies.

The evacuation of a large city such as Auckland would be particularly problematic. As an isthmus, there are only two main route exiting the city, one north and one south, both State Highway 1. As these routes regularly clog due to long weekend or vacation traffic, the evacuation of the city (whether planned or spontaneous) would be a very difficult. The Auckland Regional Council (ARC) advises on its Civil Defence pages that residents should not evacuate unless requested to during an emergency and the current “Get Ready, Get Thru” media campaign by Civil Defence also advises people to stay at home unless otherwise instructed. However, if only a small percentage of the population decide to self-evacuate, this could cause major problems for organised response efforts and this message needs to be reinforced.

6.3 Recommendations

Both general and location-specific recommendations are made in this section for the mitigation and management of blue-sky eruptions.

6.3.1 General Recommendations

- Ensure all regions that are at risk from blue-sky eruptions have sufficient response and recovery plans and that they are suitable for implementation in a volcanic event
- The CDEM plans should be updated to acknowledge the risk of volcanic eruptions that occur without warning and appropriate response plans developed

6.3.2 Tongariro National Park

- Hazard information on the website under planning and safety headings should include volcanological hazard as well as other regional hazards
- Department of Conservation material should acknowledge the risk of blue-sky eruptions (i.e. eruptions that might not have any precursory warnings given on the GeoNet website), particularly from Ruapehu
- Information on volcanic (and other) hazards should be provided at the registration of intentions book at the Whakapapa Visitors Centre.
    - Additionally, a section of the entry could request a signature acknowledging the person has read and understands the hazard information given
- Visitors who intend an extended stay in the park are expressly told not to overnight at the summit or in any high-risk areas
    - Additionally, danger areas should be outlined to summit visitors, and they should be told to minimise time in these areas
- Shelters for visitors protecting them from ejecta or flying rocks should located at intervals on the Tongariro Crossing

6.3.3 Okataina Volcanic Centre

- Ensure the District Plan discourages building in high-risk areas in and around the OVC
- Assess the safe distances from existing features at geothermal attractions and install barriers
- Require geothermal attractions to have their own emergency contingency plans to deal with blue-sky eruptions
- Ensure the hydrothermal resource is managed effectively to prevent instability in the hydrothermal field

7

Summary of Conclusions and Recommendations

7.1 Summary of Conclusions

7.1.1 Blue-Sky Eruptions

- Blue-sky eruptions do exist and the term can be used to describe eruptions both within New Zealand and internationally
    - o They are diverse in character, occurring as both small, localised events that would probably not be represented in the geological record and large plinian eruptions that have resulted in widespread deposits and many deaths
- BSEs can be a product of physical triggers, social triggers or a combination of the two
    - o Physical BSEs either show no pre-eruptive activity (hydrothermally driven BSEs) or an increase in activity at a single parameter (magmatically driven BSEs)
    - o Social BSEs are a result of ineffective (or absent) monitoring networks or a poor understanding of the eruption model
    - o Mixed-cause BSEs are a result of both a poor understanding of the eruption model and inadequate monitoring networks
- BSEs are important as they require different management and monitoring strategies than other eruptions
- BSEs produce both direct and indirect hazards
- The main difference between blue-sky eruptions and blue-sky events is that blue-sky eruptions are unexpected in their occurrence, while blue-sky events are unexpected in their behaviour.

7.1.2 Monitoring and Forecasting BSEs

- In the absence of site specific eruption models, general models should not be employed in eruption forecasting
    - Number and style of historical eruptions is low and skewed (i.e. there has been only a single rhyolitic eruption captured in historical records; Chaitén, 2008) that general models do not have enough data to be accurate
    - The nature of BSEs means they may not be fully represented in the historical record so any evidence-based (probabilistic) models may not be fully effective
- Monitoring should be undertaken in real time to detect small changes in the state of activity at a site
- Monitoring should be undertaken at times of both heightened activity and quiescence
    - Monitoring in both situations should be used for the construction of an effective eruption model and eruption forecasting (if an effective eruption model is already available)
- Even a small network monitoring two or more parameters (which could include phenomenology through a network of informed locals i.e. Nyiragongo) would reduce the risk of social BSEs
    - Remote sensing can provide monitoring where funding or site access is restricted
- A single monitoring parameter is insufficient to rely on for the purposes of eruption forecasting
    - A combination of seismology and gas emissions monitoring could be most effective; deformation does not appear to be a precursory feature of physical BSEs
- BSEs have no single eruption style and represent a diverse set of hazards
    - This diversity means there is no “quick fix” for being able to forecast all BSEs

- Detection of precursory phenomena preceding some magmatically driven physical BSEs may be possible with the construction of effective, site-specific, eruption models and technological advances
  - Magmatically driven physical BSEs may be able to be fully forecast in time
- Hydrothermally driven BSEs show no evidence of precursory phenomena, do not require the input (of mass of energy) of magma and may not produce any phenomena that will be able to be detected
  - The mitigation of the risk from this style of BSE may only be possible through effective management procedures

7.1.3 A NVEWS-style Monitoring Review for New Zealand

- A hazard and monitoring review of New Zealand's volcanoes would have benefits but the NVEWS hazard scoring system has issues in its direct application to a New Zealand setting
  - The NVEWS review may not fully portray the risk from New Zealand's silicic calderas and the Auckland Volcanic Field
- Using this system, it appears some of New Zealand's volcanoes are under-monitored (such as White Island and Tongariro/Ngauruhoe) while others (such as Ruapehu and the silicic calderas) are reasonably well monitored
  - The monitoring benchmarks in the NVEWS review are a "one-size-fits-all" system which does not fit well to all volcanoes in the threat group (i.e. there is no differentiation between high-risk active and non-active centres such as Ruapehu and Taupo)

7.1.4 Managing and Mitigating BSEs

- Effective management and mitigation strategies can reduce the risk of BSEs where forecasting is not achievable
- Limiting access, land use planning, resource management and response strategies can be effective mitigation measures for both magmatic and hydrothermal BSEs

7.2 Summary of Recommendations

7.2.1 Monitoring BSEs

- Real-time seismic monitoring can provide the basis for an effective monitoring network
- Seismic monitoring can be supplemented with gas emissions or other monitoring methods (e.g. phenomenology or remote sensing)
- Ensure monitoring is undertaken in real-time
- Ensure alert protocols are capable of capturing extremely short duration precursory patterns

7.2.2 NVEWS-style Monitoring Review for New Zealand's Volcanoes

- More emphasis on should be placed on the hazards of silicic volcanism (e.g. pyroclastic density currents)
- Larger population catchments should be used when assessing silicic volcanoes
    - o Alternatively, the possibility of another exposure factor reflecting the larger population risk should be assessed
- Acknowledgement of risk to ports and harbours should be included
- Rework *Exposure Factors* scoring to eliminate ambiguity (i.e. *Regional Aviation Exposure*)

7.2.3 Monitoring Recommendations Review

- Individual monitoring reviews should be undertaken on each volcano based on guidelines for the purpose of monitoring levels
- Differentiate between currently active and frequently active volcanoes (i.e. currently, the review recommends acoustic sensors in Taupo, however as Taupo is not active, nor is there a risk of imminent eruption, this is uneconomical and unnecessary)
- Review whether monitoring methods outlined in Moran et al. (2008) are suitable for application on New Zealand volcanoes e.g. InSAR,
- Acknowledgement of the differences in volcanism styles and potential forecast windows should be built into the review (i.e. magma ascension rates for basalt

could provide a shorter forecast window than a large silicic eruption, monitoring should reflect this)

- Automated alert systems should be able to capture extremely short-lived precursory activity and not rely on extended accumulated patterns

7.2.4 Management and Mitigation of BSEs

General Recommendations

- Ensure all regions that are at risk from blue-sky eruptions have sufficient response and recovery plans and that they are suitable for implementation in a volcanic event
- The CDEM plans should be updated to acknowledge the risk of volcanic eruptions that occur without warning and appropriate response plans developed

Tongariro National Park

- Hazard information on website under planning and safety headings should include volcanological hazard as well as other regional hazards
- Department of Conservation material should acknowledge the risk of blue-sky eruptions (i.e. eruptions that might not have any precursory warnings given on the GeoNet website), particularly from Ruapehu
- Information on volcanic (and other) hazards should be provided at the registration of intentions book at the Whakapapa Visitors Centre.
    - Additionally, a section of the entry could request a signature acknowledging the person has read and understands the hazard information given
- Visitors who intend an extended stay in the park are expressly told not to overnight at the summit or in any high-risk areas
    - Additionally, danger areas should be outlined to summit visitors and they should be told to minimise time in these areas
- Shelters for visitors protecting them from ejecta or flying rocks should located at intervals on the Tongariro Crossing

Okataina Volcanic Centre

- Ensure the District Plan discourages building in high-risk areas in and around the OVC
- Assess the safe distances from existing features at geothermal attractions and install barriers
- Require geothermal attractions to have their own emergency contingency plans to deal with blue-sky eruptions
- Ensure all hydrothermal resources are managed effectively to prevent instability in the hydrothermal field

References

Allen SR, Smith IEM 1994. Eruption styles and volcanic hazard in the Auckland Volcanic Field, New Zealand. Geoscience Reports Shizuoka University 20: 5–14.

Andrews P 2001. New Zealand: hydrothermal blowout. Geology Today 17(1/2): 10–11.

Auckland Regional Council 2007. Rangitoto: Te Rangi-i-totongia-a-Tama-te-kapua. Retrieved 14/06/2009 http://www.arc.govt.nz/environment/volcanoes-of-auckland/rangitoto.cfm

Aspinall WP, Woo G, Voight B, Baxter PJ 2003. Evidence-based volcanology: application to eruption crises. Journal of Volcanology and Geothermal Research 128(1–3): 273–285.

Avolio MV, Crisci GM, Di Gregorio S, Rongo R, Spataro W, D'Ambrosio D 2006a. Pyroclastic flows modelling using cellular automata Computers and Geosciences 32(7): 897–911.

Avolio MV, Crisci GM, Di Gregorio S, Rongo R, Spataro W, Trunfio GA 2006b. SCIARA γ2: An improved cellular automata model for lava flows and applications to the 2002 Etnean crisis Computers and Geosciences 32(7): 876–889.

Baher S, Thurber C, Roberts K, Rowe C 2003. Relocation of seismicity preceding the 1984 eruption of Mauna Loa Volcano, Hawaii: Delineation of a possible failed rift. Journal of Volcanology and Geothermal Research 128(4): 327–339.

Barberi F, Martini M, Rosi M 1990. Nevado del Ruiz volcano (Columbia): pre-eruption observations and the November 13, 1985 catastrophic event. Journal of Volcanology and Geothermal Research 42: 1–12.

Barberi F, Bertagnini A, Landi P, Principe C 1992. A review on phreatic eruptions and their precursors. Journal of Volcanology and Geothermal Research 52: 231–246.

Barnard ST 2003. Potential physical effects of any future 1886 type eruption from Tarawera Volcano on the Bay of Plenty region. Unpublished thesis, University of Canterbury, Christchurch. 146 p.

Battaglia M, Segall P, Murray J, Cervelli P, Langbein J 2003. The mechanics of unrest at long Valley caldera, California: 1. Modelling the geometry of the source using GPS, levelling and two-colour EDM data. Journal of Volcanology and Geothermal Research 127: 195–217.

Baxter PJ, Gresham A 1997. Deaths and injuries in the eruption of Galeras Volcano, Columbia, 14 January 1993. Journal of Volcanology and Geothermal Research 77: 325–338.

Baxter PJ, Neri A, Blong R 2008a. Evaluating Explosive Eruption Risk at European Volcanoes Preface. Journal of Volcanology and Geothermal Research 178(3): V–Ix.

Baxter PJ, Aspinall WP, Neri A, Zuccaro G, Spence RJS, Cioni R, Woo G 2008b. Emergency planning and mitigation at Vesuvius: A new evidence-based approach. Journal of Volcanology and Geothermal Research 178(3): 454–473.

Belousov A, Voight B, Bleousova M 2007. Directed blasts and blast-generated pyroclastic density currents: a comparison of the Bezymianny 1956, Mount St Helens 1980, and Soufrière Hills, Montserrat 1997 eruptions and deposits. Bulletin of Volcanology 69: 701–740.

Bertolaso G, De Bernardinis B, Bosi V, Cardaci C, Ciolli S, Colozza R, Cristiani C, Mangione D, Ricciardi A, Rosi M and others 2009. Civil protection preparedness and response to the 2007 eruptive crisis of Stromboli volcano, Italy. Journal of Volcanology and Geothermal Research 182(3–4): 269–277.

Bland L, Tresch S 2007. GeoNET: Monitoring New Zealand's natural hazards. In: Mortimer N, Wallace LM ed. Geological Society of New Zealand & New Zealand Geophysical Society Joint Annual Conference: launching International Year of Planet Earth, 26–29 November 2007: programme and abstracts: 15.

Blumenthal EC 2003. Evacuation planning needed for any future rhyolite eruption from Tarawera Volcano : a thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Geology, Department of Geological Sciences, University of Canterbury. Unpublished Thesis (M Sc) thesis, University of Canterbury, 2003. 186 p.

Bluth GJS, Shannon JM, Watson IM, Prata AJ, Realmuto VJ 2007. Development of an ultra-violet digital camera for volcanic SO2 imaging. Journal of Volcanology and Geothermal Research 161(1–2): 47–56.

Bogoyavlenskaya GE, Braitseva OA, Melekestsev IV, V.Y. K, Dan Miller C 1985. Catastrophic eruptions of the directed-blast type at Mount St. Helens, Bezymianny and Shiveluch volcanoes Journal of Geodynamics 3(3–4): 189–218.

Brantley SR 1997. Volcanoes of the United States: United States Geological Survey Interest Publication. Retrieved 13/04/2009 http://pubs.usgs.gov/gip/volcus/index.html

Brothers RN, Golsons J 1959. Geological and archaeological interpretation of a section in Rangitoto ash on Motutapu Island, Auckland. New Zealand Journal of Geology and Geophysics 2: 569–577.

Browne PRL, Lawless JV 2001. Characteristics of hydrothermal eruptions, with examples from New Zealand and elsewhere. Earth-Science Reviews 52: 299–331.

Bulletin of the Global Volcanism Programme 1990a. 11/1990 (BVGN 15:11): October explosion deaths to rise to 26; new crater described. Retrieved 13/04/2009 http://www.volcano.si.edu/world/volcano.cfm?vnum=1403-01=&volpage=var

Bulletin of the Global Volcanism Programme 1990b. 09/1990 (BVGN 15:09): Phreatic blast at hot springs ; 14 people dead. Retrieved 12/04/2009 http://www.volcano.si.edu/world/volcano.cfm?vnum=1403-01=&volpage=var

Burlini L, Vinciguerra S, Di Toro G, De Natale G, Meredith P, Burg JP 2007. Seismicity preceding volcanic eruptions: New experimental insights. Geology 35(2): 183–186.

Canul RF, Rocha VL 1981. A geological report on the geothermal area of El Chichonal Chiapas (Spanish). Comision Federal de Electricidad; Morelia, Michoacán, México Internal Report. Pp. 38.

Carlino S, Somma R, Mayberry GC 2008. Volcanic risk perception of young people in the urban areas of Vesuvius: Comparisons with other volcanic areas and implications for emergency management. Journal of Volcanology and Geothermal Research 172(3–4): 229–243.

Carn SA, Krueger AJ, Arellano S, Krotkov NA, Yang K 2008. Daily monitoring of Ecuadorian volcanic degassing from space. Journal of Volcanology and Geothermal Research 176(1): 141–150.

Carrivick JL, Manville V, Cronin SJ 2009. A fluid dynamics approach to modelling the 18th March 2007 lahar at Mt. Ruapehu, New Zealand. Bulletin of Volcanology 71(2): 153–169.

Cas RAF, Wright JV 1993. Volcanic successions: modern and ancient. London, Chapman and Hall. 528 p.

Cashman KV, Sturtevant B, Papale P, Navon O 2000. Magma fragmentation. In: Sigurdsson H ed. Encyclopedia of Volcanoes. San Diego, Academic Press. Pp. 421–430.

Chirico GD, Favalli M, Papale P, Boschi E, Pareschi MT, Mamou-Mani A 2009. Lava flow hazard at Nyiragongo Volcano D.R.C.: 2. Hazard reduction in urban areas. Bulletin of Volcanology 71: 375–387.

Christenson BW, Werner CA, Reyes AG, Sherburn S, Scott BJ, Miller C, Rosenberg MD, Hurst AW, Britten KA 2007. Hazards from hydrothermally sealed volcanic conduits,. Eos Transactions of the AGU 88(5): 53–55.

Christianson AN 2006. Assessing and improving the effectiveness of staff training and warning system response at Whakapapa and Turoa ski areas, Mt. Ruapehu : a thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Hazard Management at the University of Canterbury. Unpublished Thesis (M Sc) thesis, University of Canterbury, 2006. 186 p.

Coetzee D 2004. National contingency plan for volcanic eruption. Tephra 21: 24–25.

Cole JW 1970. Structure and eruptive history of the Tarawera volcanic complex. New Zealand Journal of Geology and Geophysics 13(4): 879–902.

Cole JW, Cowan HA, Webb TA 2006. The 2006 Raoul Island Eruption–a Review of GNS Science's Actions. GNS Science Report 2006/7 38.

Cortes GP, Raigosa J 1997. A synthesis of the recent activity of Galeras volcano, Colombia: Seven years of continuous surveillance, 1989–1995. Journal of Volcanology and Geothermal Research 77(1–4): 101–114.

Crisci GM, Rongo R, Di Gregorio S, Spataro W 2004. The simulation model SCIARA: the 1991 and 2001 lava flows at Mount Etna. Journal of Volcanology and Geothermal Research 132(2–3): 253–267.

Cronin SJ, Hedley MJ, Neall VE, Smith RG 1998. Agronomic impact of tephra fallout from the 1995 and 1996 Ruapehu Volcano eruptions, New Zealand. Environmental Geology 34(1): 21–30.

De la Cruz-Reyna S, Martin Del Pozzo AL 2009. The 1982 eruption of El Chicon volcano, Mexico: eyewitness of the disaster. Geofísica Internacional 48(1): 21–31.

Dean KG, Dehn J, Papp KR, Smith S, Izbekov P, Peterson R, Kearney C, Steffke A 2004. Integrated satellite observations of the 2001 eruption of Mt. Cleveland, Alaska. Journal of Volcanology and Geothermal Research 135(1–2): 51–73.

Dehn J, Dean KG, Engle K, Izbekov P 2002. Thermal precursors in satellite images of the 1999 eruption of Shishaldin Volcano. Bulletin of Volcanology 64(8): 525–534.

Del Negro C, Fortuna L, Vicari A 2005. Modelling lava flows by Cellular Nonlinear Networks (CNN): preliminary results. Nonlinear Processes in Geophysics 12: 505–513.

Denlinger RP, Hoblitt RP 1999. Cyclic eruptive behavior of silicic volcanoes. Geology 27(5): 459–462.

Diaz JA, Giese CF, Gentry WR 2002. Mass spectrometry for *in-situ* volcanic gas monitoring. Trac-Trends in Analytical Chemistry 21(8): 498–514.

Doherty AL 2008. White Island MiniDOAS: A brief review July 2006–December 21007, GNS Science Internal Report 2008/2. 18 p.

Donegan SJ, Flynn LP 2004. Comparison of the response of the landsat 7 enhanced thematic mapper plus and the earth observing-1 advanced land imager over active lava flows. Journal of Volcanology and Geothermal Research 135(1–2): 105–126.

Edmonds M, Herd RA 2005. Inland-directed base surge generated by the explosive interaction of pyroclastic flows and seawater at Soufrière Hills volcano, Montserrat. Geology 33: 245–248.

Edmonds M, Herd RA, Galle B, Oppenheimer CM 2003. Automated, high time-resolution measurements of SO2 flux at Soufriere Hills Volcano, Montserrat. Bulletin of Volcanology 65(8): 578–586.

Elias T, Sutton AJ, Oppenheimer C, Horton KA, Garbeil H, Tsanev V, McGonigle AJS, Williams-Jones G 2006. Comparison of COSPEC and two miniature ultraviolet spectrometer systems for SO2 measurements using scattered sunlight. Bulletin of Volcanology 68(4): 313–322.

Eppler DB 1987. The May 1915 eruptions of Lassen Peak, II: May 22 volcanic blast effects, sedimentology and stratigraphy of deposits, and characteristics of the blast cloud. Journal of Volcanology and Geothermal Research 31: 65–85.

Espindola JM, Macias JL, Tilling RI, Sheridan MF 2000a. Volcanic history of El Chichón Volcano (Chiapas, Mexico) during the Holocene, and it's impacts on human activity. Bulletin of Volcanology 62: 90–104.

Espindola JM, Macias JL, Tilling RI, Sheridan MF 2000b. Volcanic history of El Chichón Volcano (Chiapas, Mexico) during the Holocene, and its impact on human activity. Bulletin of Volcanology 62: 90–104.

Ewert J, Guffanti MC, Murray TL 2005. An assessment of volcanic threat and monitoring capabilities in the United States: framework for a National Volcano Early Warning System. USGS Open-File Report 2005–1164. 62 p.

Favalli M, Chirico GD, Papale P, Pareschi MT, Boschi E 2009. Lava flow hazard at Nyiragongo volcano, D.R.C.: 1. Model calibration and hazards mapping. Bulletin of Volcanology 71: 363–374.

Felpeto A, Arana V, Ortiz R, Astiz M, Garcia A 2001. Assessment and modelling of lava flow hazard on Lanzarote (Canary Islands). Natural Hazards 23: 247–257.

Ferrucci F 1995. Seismic monitoring at active volcanoes. In: McGuire WJ, Kilburn CRJ, Murray J ed. Monitoring Active Volcanoes. London, UCL Press Ltd. Pp. 60–92.

Fisher RV 1995. Decoupling of pyroclastic density currents: hazard assessments. Journal of Volcanology and Geothermal Research 66: 257–263.

Flynn L, Wright R, Garbeil H, Harris A, Pilger E 2002. A Global Thermal Alert System Using MODIS: Initial Results from 2000–2001. Advances in Environmental Monitoring and Modelling 1(1): 37–69.

Fournier T, Freymueller J, Cervelli P 2009. Tracking magma volume recovery at okmok volcano using GPS and an unscented kalman filter. Journal of Geophysical Research B: Solid Earth 114(2).

Foxworthy BL, Hill M 1982. Volcanic eruptions of 1980 at Mount St. Helens: the first 100 days. Geological Survey professional paper ; 1249: 125 p.

Francis P, Oppenheimer C 2004. Volcanoes. 2nd ed. New York, Oxford University Press. 521 p.

Francis P, Horrocks L, Oppenheimer C 2000. Monitoring gases from andesite volcanoes. Philosophical Transactions of the Royal Society of London Series A-Mathematical Physical and Engineering Sciences 358(1770): 1567-1584.

Fujii T, Nakada S 1999. The 15 September 1991 pyroclastic flows at Unzen Volcano (Japan): a flow model for associated ash-cloud surges. Journal of Volcanology and Geothermal Research 89: 159–172.

Galle B, Oppenheimer C, Geyer A, McGonigle AJS, Edmonds M, Horrocks L 2003. A miniaturised ultraviolet spectrometer for remote sensing of SO2 fluxes: a new tool for volcano surveillance. Journal of Volcanology and Geothermal Research 119(1–4): 241–254.

Galley I, Leonard G, Johnston D 2004. The Ruapehu lahar emergency response plan development process: an analysis. The Australasian Journal of Disaster and Trauma Studies 2004–1.

Gardner CA, Guffanti MC 2006. U.S. Geological Survey's Alert Notification System for Volcanic Activity. U.S.G.S. Fact Sheet 2006–3139. 4 p.

GeoNet 2009. GeoNet. Retrieved 28/09/2008 http://www.geonet.org.nz

GNS Science 2009. GNS Science. Retrieved 31/03/2009 www.gns.cri.nz

Granieri D, Chiodini G, Marzocchi W, Avino R 2003. Continuous monitoring of CO2 soil diffue degassing at Phlegraen Fields (Italy): influence of environmental and volcanic parameters. Earth and Planetary Science Letters 212: 167–179.

Guffanti MC, Scott WE, Driedger CL, Ewert J 2006. Summary of the Stakeholders Workshop to develop a National Volcano Early Warning System (NVEWS) USGS Open-File Report 2006–1224. 17 p.

Halbwachs M 2007. Degassing the "killer lakes"; an experimental venture Retrieved 05/05/2009 http://pagesperso-orange.fr/mhalb/nyos/project/indexproj.htm

Hall ML 1990. Chronology of the principal scientific and governmental actions leading up to the November 13, 1985 eruption of Nevado del Ruiz, Columbia. Journal of Volcanology and Geothermal Research 42: 101–115.

Hamaguchi H, Nishimura T, Zana N 1991. Process of the 1977 Nyiragongo eruption inferred from the analysis of long-period earthquakes and volcanic tremors. Tectonophysics 209(209): 241–254.

Handal S, Barrios LA 2004. Hydrothermal eruptions in El Salvador: A review. In: Rose WI, Bommer JJ, Lopez DL, Carr MJ, Major JJ ed. Natural hazards in El Salvador. Boulder, Colorado, Geological Society of America Special Paper 375. Pp. 245–255.

Hansell A, Oppenheiner C 2004. Health hazards from volcanic gases: a systematic literature review. Archives of Environmental Health 59(12): 628–639.

Harris AJL, Flynn LP, Dean K, Pilger E, Wooster M, Okubo C, Mouginis-Mark P, Garbeil H, Thornber C, De la Cruz-Reyna S and others 2000. Real-time satellite monitoring of volcanic hot spots. Remote Sensing of Active Volcanism 116: 139–159.

Herd DG, Vulcanologicos CdE 1986. The 1985 Ruiz volcano disaster. Transactions of the American Geophysical Union 67(19): 457–460.

Hillger DW, Schmit TS, Daniels J ed. 2003. Imager and sounder radiance and product validations for the GOES-12 science test, *NOAA Tech. Rep. 115*. Washington, D.C., U.S. Department of Commerce.

Hirn B, Bartola CD, Ferrucci F In press. Combined Use of SEVIRI and MODIS for detecting, measuring, and monitoring active lava flows at erupting volcanoes. IEEE Transactions on Geoscience and Remote Sensing.

Houghton BF, Bonadonna C, Gregg CE, Johnston DM, Cousins WJ, Cole JW, Del Carlo P 2006. Proximal tephra hazards: Recent eruption studies applied to volcanic risk in the Auckland volcanic field, New Zealand. Journal of Volcanology and Geothermal Research 155(1–2): 138–149.

Hawaii Volcano Observatory 2007. Eruption history of Kilauea Volcano, Hawai'i http://hvo.wr.usgs.gov/kilauea/history/main.html

Jaupart C 2000. Magma ascent at shallow levels. In: Sigurdsson H ed. Encyclopedia of volcanoes. San Diego, Academic Press. Pp. 237–245.

Jimenez Z, Espindola VH, Espindola JM 1999. Evolution of the seismic activity from the 1982 eruption of El Chichón Volcano, Chiapas, Mexico. Bulletin of Volcanology 61: 411–422.

Jonsson VK, Matthiasson M 1997. Lava-Cooling Operations During the 1973 Eruption of Eldfell Volcano, Heimaey, Vestmannaeyjar, Iceland. U.S. Geological Survey Open–File Report 97–724.

Joyce KE, Samsonov S, Manville V, Jongens R, Graettinger A, Cronin SJ 2009. Remote sensing data types and techniques for lahar path detection: A case study at Mt Ruapehu, New Zealand. Remote Sensing of Environment 113(8): 1778–1786.

Keam RF 1988. Tarawera: The volcanic eruption of 10 June 1886. Auckland, R. F. Keam. 472 p.

Keller SAC ed. 1986. Mount St. Helens: Five years later. Cheney, WA, Eastern Washington University Press. 441 p.

Keys H 2007. Lahars of Ruapehu Volcano, New Zealand: risk mitigation. Annals of Glacialology 45: 155–162.

Keys H, Green P 2004. Mt Ruapehu Crater Lake Lahar Threat Response - Crater Lake issue - a management dilemma. Retrieved 08/06/2009 http://www.doc.govt.nz/publications/about-doc/news/issues/mt-ruapehu-crater-lake-lahar-threat-response/crater-lake-issue-a-management-dilemma/

Kilburn CRJ 2003. Multiscale fracturing as a key to forecasting volcanic eruptions. Journal of Volcanology and Geothermal Research 125(3–4): 271–289.

Kling GW, Clark MA, Compton HR, Devine JD, Evans WC, Humphrey AM, Koenigsberg EJ, Lockwood JP, Tuttle ML, Wagner GN 1987. The 1986 Lake Nyos Gas Disaster in Cameroon, West Africa Science 236(4798): 169–175.

Komorowski JC, Tedesco D, Kasereka M, Allard P, Papale P, Vaselli O, Durieux J, Baxter PJ, Halbwachs M, Akumbe M and others 2002. The January 2002 flank eruption of Nyiragongo volcano (Democratic Republic of Congo): chronology, evidence for tectonic rift trigger, and impact of lava flows on the city of Goma. Acta Vulcanologica 14(1–2): 27–61.

Krueger A, Krotkov N, Carn S 2008. El Chichón: The genesis of volcanic sulphur dioxide monitoring from space. Journal of Volcanology and Geothermal Research 175: 408–414.

Larsen J, Neal C, Webley P, Freymueller J, Haney M, McNutt SR, Schneider DJ, Prejean S, Schaefer J, Wessels R 2009. Eruption of Alaska volcano breaks historic pattern. Eos Transactions of the AGU 90(20): 173–174.

Latter JH 1992. Volcanic hazards in the Kermadec Islands, and at submarine volcanoes between southern Tonga and New Zealand, Ministry of Civil Defence. 42 p.

Lavigne F, De Coster B, Juvin N, Flohic F, Gaillard JC, Texier P, Morin J, Sartohadi J 2008. People's behaviour in the face of volcanic hazards: Perspectives from Javanese communities, Indonesia. Journal of Volcanology and Geothermal Research 172(3–4): 273–287.

Leonard GS, Johnston DM, Paton D, Christianson A, Becker J, Keys H 2008. Developing effective warning systems: Ongoing research at Ruapehu volcano, New Zealand Journal of Volcanology and Geothermal Research 172(3–4): 199–215.

Levelt PF, Hilsenrath E, Leppelmeier GW, van den Oord GHJ, Bhartia PK, Tamminen J, de Haan JF, Veefkind JP 2006. Science Objectives of the Ozone Monitoring Instrument. IEEE Transactions on Geoscience and Remote Sensing 44(5): 1199–1208.

Lipman PW, Mullineaux DR ed. 1981. The 1980 eruptions of Mount St. Helens, Washington, US Geological Survey Professional Paper 1250. 844 p.

Lowe D, Keam RF, Lee D 2001. How many deaths were caused by the Tarawera eruption? Geological Society of New Zealand Newsletter No. 126.

Lowe DJ, Shane PAR, Alloway BV, Newnham RM 2008. Fingerprints and age models for widespread New Zealand tephra marker beds erupted since 30,000 years ago: a framework for NZ-INTIMATE. Quaternary Science Reviews 27(1–2): 95–126.

Macias JL, Sheridan MF, Espindola JM 1997. Reappraisal of the 1982 eruptions of El Chichón Volcano, Chiapas, Mexico: new data from proximal deposits. Bulletin of Volcanology 58: 459–471.

Magill C, Blong R 2005. Volcanic risk ranking for Auckland, New Zealand. II: Hazard consequences and risk calculation. Bulletin of Volcanology 67(4): 340–349.

Magill CR, McAneney KJ, Smith IEM 2005. Probabilistic assessment of vent locations for the next Auckland volcanic field event. Mathematical Geology 37(3): 227–242.

Magill CR, Hurst AW, Hunter LJ, Blong RJ 2006. Probabilistic tephra fall simulation for the Auckland region, New Zealand. Journal of Volcanology and Geothermal Research 153(3–4): 370–386.

Mahmood A, Giugni LP 2001. Mapping recent lava flows with RADARSAT-1 imagery. Igarss 2001: Scanning the Present and Resolving the Future, Vols 1–7, Proceedings: 482–484.

Manville V, Hodgson KA, Nairn IA 2007. A review of break-out floods from volcanogenic lakes in New Zealand. New Zealand Journal of Geology and Geophysics 50(2): 131–150.

Manville V, Segschneider B, Newton E, White JDL, Houghton BF, Wilson CJN In press. Environmental impact of the 1.8 ka Taupo eruption, New Zealand: Landscape responses to a large-scale explosive rhyolite eruption. Sedimentary Geology.

Marti J, Spence R, Calogero E, Ordonez A, Felpeto A, Baxter PJ 2008. Estimating building exposure and impact to volcanic hazards in Icod de los Vinos, Tenerife (Canary Islands). Journal of Volcanology and Geothermal Research 178(3): 553–561.

Martinelli B 1990. Analysis of seismic patterns observed at Nevado del Ruiz volcano, Columbia during August–September 1985. Journal of Volcanology and Geothermal Research 41: 297–314.

Marzocchi W, Zaccarelli L 2006. A quantitative model for the time-size distribution of eruptions. Journal of Geophysical Research–Solid Earth 111(B4).

Marzocchi W, Woo G 2007. Probabilistic eruption forecasting and the call for evacuation. Geophysical Research Letters 34: L22310.

Marzocchi W, Zaccarelli L, Boschi E 2004. Phenomenological evidence in favor of a remote seismic coupling for large volcanic eruptions. Geophysical Research Letters 31(4): L04601 1–5.

Marzocchi W, Sandri L, Selva J 2008. BET_EF: a probabilistic tool for long- and short-term eruption forecasting. Bulletin of Volcanology 70(5): 623–632.

Marzocchi W, Neri A, Newhall CG, Papale P 2006. Quantifying long- and short-term volcanic hazard: Building up a common strategy for Italian volcanoes. International School of Geophysics 27th Workshop. Pp. 7.

Marzocchi W, Neri A, Newhall CG, Papale P 2007. Probabilistic volcanic hazard and risk assessment. Eos Transactions of the AGU 88(32): 318.

McGuire B 1995a. Monitoring active volcanoes : strategies, procedures and techniques. London ; Bristol, Pa., UCL Press. 421 p.

McGuire WJ 1995b. Monitoring active volcanoes–an introduction. In: McGuire WJ, Kilburn CRJ, Murray J ed. Monitoring active volcanoes. London, UCL Press. Pp. 421.

Mckee CO, Johnson RW, Lowenstein PL, Riley SJ, Blong RJ, Desaintours P, Talai B 1985. Rabaul Caldera, Papua-New-Guinea–Volcanic Hazards, Surveillance, and Eruption Contingency Planning. Journal of Volcanology and Geothermal Research 23(3–4): 195–237.

McNutt SR 2000. Seismic monitoring. In: Sigurdsson H ed. Encyclopedia of Volcanoes. San Diego, Academic Press. Pp. 1095–1119.

McNutt SR, Rymer H, Stix J 2000. Sythesis of volcano monitoring. In: Sigurdsson H ed. Encyclopedia of Volcanoes. San Diego, Academic Press. Pp. 1165–1183.

Menand T, Tait SR 2001. A phenomenological model for precursor volcanic eruptions. Nature 411(6838): 678–680.

Miller TP, Casadevall TJ 2000. Volcanic ash hazards to aviation. In: Sigurdsson H ed. Encyclopedia of Volcanoes. San Diego, Academic Press. Pp. 915–930.

Miller TP, McGimsey RG, Richter DH, Riehle JR, Nye CJ, Yount ME, Dumoulin JA 1998. Catalog of the historically active volcanoes of Alaska. USGS Open–File Report 1998–582: 104.

Mojica J, Colmenares F, Villarroel C, Macia C, Moreno M 1985. Characteristicas de flujo de lodo ocurrido el 13 de Noviembre de 1985 en el valle de Armero (Tolima, Columbia). Historia y comentarios de los flujos de 1595 y 1845. Geol Columb 14: 107–140.

Monro IF 1975 NZ532 – North Island East Coast aproaches to Auckland. Map (1 sheet) and notes. Auckalnd, New Zealand, Hydrographic Office of the Royal New Zealand Navy.

Moran SC, Freymueller JT, LaHusen RG, McGee KA, Poland MP, Power JA, Schmidt DA, Schneider DJ, Stephens G, Werner CA and others 2008. Instrumentation recommendations for volcano monitoring at U.S. volcanoes under the National Volcano Early Warning System. U.S. Geological Survey Scientific Investigations Report 2008–5114. 47 p.

Morrissey MM, Mastin LG 2000. Vulcanian eruptions. In: Sigurdsson H ed. Encyclopedia of Volcanoes. San Diego, Academic Press. Pp. 463–475.

Murray J, Rymer H, Locke CA 2000. Ground deformation, gravity and magnetics. In: Sigurdsson H ed. Encyclopedia of Volcanoes. San Diego, Academic Press. Pp. 1121–1140.

Montserrat Volcano Observatory 2009. Montserrat Volcanic Observatory. Retrieved 31/03/2009 www.mvo.ms

Nairn IA 1989 V16AC: 55—Mount Tarawera. Map (1 sheet) and notes. Wellington, New Zealand, Department of Scientific and Industrial Research.

Nairn IA, Houghton BF, Cole JW 1996. Volcanic Hazards at White Island. 2 ed. Palmerston North, Ministry of Civil Defence. 27 p.

Nakada S 2000. Hazards from pyroclastic flows and surges. In: Sigurdsson H ed. Encyclopedia of Volcanoes. San Diego, Academic Press. Pp. 945–955.

Narvaez L, Torres RA, Gomez DM, Cortes GP, Cepeda H, Stix J 1997. 'Tornillo'-type seismic signals at Galeras volcano, Columbia, 1992–1993. Journal of Volcanology and Geothermal Research 77: 159–171.

Neal VE, Houghton BF, Cronin SJ, Donoghue SL, Hodgson KA, Johnston DM, Lecointre JA, Mitchel AR 1996. Volcanic hazards at Ruapehu Volcano. 34 p.

Neri A, Aspinall WP, Cioni R, Bertagnini A, Baxter PJ, Zuccaro G, Andronico D, Barsotti S, Cole PD, Ongaro TE and others 2008. Developing an Event Tree for probabilistic hazard and risk assessment at Vesuvius. Journal of Volcanology and Geothermal Research 178(3): 397–415.

Newhall CG, Self S 1982. The Volcanic Explosivity Index (Vei)–an Estimate of Explosive Magnitude for Historical Volcanism. Journal of Geophysical Research–Oceans and Atmospheres 87(Nc2): 1231–1238.

Newhall CG, Hoblitt RP 2002. Constructing event trees for volcanic crises. Bulletin of Volcanology 64(1): 3–20.

Nichol R 1982. Fossilised human footprints in Rangitoto Ash on Motutapu Island. Geological Society of New Zealand Newsletter 51: 11–13.

National Park Service 2009. NPS: Nature & Science>> Air Resources Division–Hawai'i Volcanoes NP Current Sulfur Dioxide Conditions. Retrieved 21/06/2009 http://volcano.wr.usgs.gov/hvo/so2/havoalert.php

Oswalt JS, Nichols W, O'Hara JF 1996. Meteorological observations of the 1991 Mount Pinatubo eruption. In: Newhall CG, Punongbayan RS ed. Fire and mud : eruptions and lahars of Mount Pinatubo, Philippines Seattle, University of Washington Press.

Parfitt EA, Wilson L 2008. Fundamentals of physical volcanology. Malden, MA, Blackwell Publishing. 230 p.

Patrick MR, Dehn J, Dean K 2005. Numerical modelling of lava flow cooling applied to the 1997 Okmok eruption: Comparison with advanced very high resolution radiometer thermal imagery. Journal of Geophysical Research B: Solid Earth 110(2): 1–9.

Pergola N, Pietrapertosa C, Lacava T, Tramutoli V 2001. Robust satellite techniques for monitoring volcanic eruptions. Annali Di Geofisica 44(2): 167–177.

Pergola N, D'Angelo G, Lisi M, Marchese F, Mazzeo G, Tramutoli V 2009. Time domain analysis of robust satellite techniques (RST) for near real-time monitoring of active volcanoes and thermal precursor identification. Physics and Chemistry of the Earth 34(6–7): 380–385.

Peterson D 1986. Mount St. Helens and the science of volcanology: a five-year perspective. In: Keller SAC ed. Mount St. Helens: Five years later. Cheney, WA, Eastern Washington University Press.

Peterson D, Tilling RI 2000. Lava flow hazards. In: Sigurdsson H ed. Encyclopedia of volcanoes. San Diego, Academic Press.

Pieri D, Abrams M 2005. ASTER observations of thermal anomalies preceding the April 2003 eruption of Chikurachki volcano, Kurile Islands, Russia Remote Sensing of Environment 99(1–2): 84–94.

Pierson TC, Janda RJ, Thouret JC, Borrero CA 1990. Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow, and deposition of lahars. Journal of Volcanology and Geothermal Research 41: 17–66.

Pierson TC, Daag AS, Delos Reyes PJ, Regalado MTM, Solidium RU, Tubianosa BS 1996. Flow and deposition of posteruption hot lahars on the east side of Mount Pinatubo, July–October 1991. In: Newhall CG, Punongbayan RS ed. Fire and mud : eruptions and lahars of Mount Pinatubo, Philippines Seattle, University of Washington Press.

Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat 2008. World Population Prospects: The 2008 Revision. Retrieved 28/03/2009 http://esa.un.org/unpp

Punongbayan RS, Newhall CG, Bautista MLP, Garcia D, Harlow DH, Hoblitt RP, Sabit JP, Solidium RU 1996. Eruption hazard assessment and warnings. In: Newhall CG, Punongbayan RS ed. Fire and mud : eruptions and lahars of Mount Pinatubo, Philippines. Seattle University of Washington Press.

Robock A 2002. Volcanic Eruption, El Chichón. In: MacCracken MC, Perry JS ed. The Earth system: physical and chemical dimensions of global environmental change. Chichester, John Wiley and Sons. Pp. 736–736.

Rodolfo KS 2000. The hazards from lahars and jokulhlaups. In: Sigurdsson H ed. Encyclopedia of volcanoes. San Diego, Academic Press. Pp. 973–995.

Rosenberg MD, Wilson CJN, Gravley DM, Rotella M, Borella MW 2007. Insights into the 2006 Raoul Island eruption from deposit characteristics and eruption effects. In: Mortimer N, Wallace LM ed. Geological Society of New Zealand & New Zealand Geophysical Society Joint Annual Conference: launching International Year of Planet Earth, 26–29 November 2007: programme and abstracts.

Rotorua District Council 1996. Proposed District Plan. Rotorua, Rotorua District Council.

Rotorua District Counicil 2009. Major industries in Rotorua: Destination Rotorua economic development. Retrieved 12/06/2009 http://www.rotorua-business.com/Investing/industries.asp

Rowlands DP, White RS, Haines AJ 2005. Seismic tomography of the Tongariro Volcanic Centre, New Zealand. Geophysical Journal International 163: 1180–1194.

Saucedo R, Macias JL, Sheridan MF, Bursik MI, Komorowski JC 2005. Modelling of pyroclastic flows of Colima Volcano, Mexico: implications for hazard assessment Journal of Volcanology and Geothermal Research 139(1–2): 103–115.

Scarpa R, Gasparini P 1996. A review of volcano geophysics and volcano-monitoring methods. In: Scarpa R, Tilling RI ed. Monitoring and mitigation of volcano hazards. Berlin, Sringer-Verlag.

Scarpa R, Tilling RI 1996. Monitoring and mitigation of volcano hazards. New York, Springer. 841 p.

Schwandner FM, Selva J, Ueda H, Venezky DY, Cervelli P, Weertman B, Stroker K, Malone SD, Fujita E, Marzocchi W and others 2007. WOVOdat: The World Organization of Volcano Observatories Database of Volcanic Unrest. Cities on Volcanoes 5. Shimabara, Japan

Scott BJ 2001. Alert bulletin: Jan 26 2001–Rotorua Volcanic Centre: Science Alert Bulletin ROT-01/01 – Eruption at Kuirau Park, Rotorua. Retrieved 12/04/2009 http://www.geonet.org.nz/volcano/alert-bulletins/archives/2001/alert-bulletin-eruption-at-kuirau-park-rotorua-26-january-2001.html

Scott BJ, Cody AD 2000. Response of the Rotorua geothermal system to exploitation and varying management regimes. Geothermics 29: 573–592.

Scott BJ, Travers J In press. Volcano monitoring in NZ and links to SW Pacific via the Wellington VAAC. Natural Hazards.

Scott WE, Hoblitt RP, Torres C. RA, Self S, Martinez ML, Nillos T 1996. Pyroclastic flows of the June 15, 1991, climactic eruption of Mount Pinatubo. In: Newhall CG, Punongbayan RS ed. Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines Seattle, Washington University Press.

National Park Service 2009. Hawai`i Volcanoes National Park current sulfur dioxide (SO2) conditions Retrieved 05/05/2009 http://www.nature.nps.gov/air/webcams/parks/havoso2alert/havoalert.cfm

Sherburn S, Bryan CJ 1999. The Eruption Detection System: Mt Ruapehu, New Zealand. Seismological Research Letters 70(5): 505–511.

Sherburn S, Nairn IA 2004. Modelling geophysical precursors to the prehistoric c. AD1305 Kaharoa rhyolite eruption of Tarawera volcano, New Zealand. Natural Hazards 32(1): 37–58.

Siebert L, Simkin T 2002. Volcanoes of the world: an illustrated catalog of Holocene volcanoes and their eruptions. Retrieved 31/03/1981 http://www.volcano.si.edu/world/

Sigurdsson H ed. 2000a. Encyclopedia of Volcanoes. San Diego, Academic Press. 1389 p.

Sigurdsson H 2000b. Encyclopedia of volcanoes. San Diego, Academic Press. xxiv, 1417 p. , [8] of plates p.

Sigurdsson H, Carey SN, Espindola JM 1984. The 1982 eruption of El Chichón Volcano, Mexico: stratigraphy of pyroclastic deposits. Journal of Volcanology and Geothermal Research 23: 11–37.

Smith RT 1998. Eruptive and depositional models for units 3 and 4 of the 1.85 ka Taupo eruption : implications for the nature of large-scale "wet" eruptions : a thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Geology in the University of Canterbury. Unpublished Thesis (Ph D) thesis, University of Canterbury, 1998. 336 p.

Smith SP 1887. The eruption of Tarawera: a report to the Surveyor-General. Wellington, George Disdsbury, Government Printer. 84 p.

Sparks SJR 2003. Forecasting volcanic eruptions. Earth and Planetary Science Letters 210: 1–15.

Spence R, Kelman I, Brown A, Toyos G, Purser D, Baxter P 2007. Residential building and occupant vulnerability to pyroclastic density currents in explosive eruptions. Natural Hazards and Earth System Sciences 7(2): 219–230.

Spence RJS, Kelman I, Calogero E, Toyos G, Baxter PJ, Komorowski JC 2005. Modelling expected physical impacts and human casualties from explosive volcanic eruptions. Natural Hazards and Earth System Sciences 5(6): 1003–1015.

Speranza F, Pompilio M, Caracciolo FD, Sagnotti L 2008. Holocene eruptive history of the Stromboli volcano: Constraints from paleomagnetic dating. Journal of Geophysical Research–Solid Earth 113(B9).

Statistics New Zealand 2008a. Statistics New Zealand. Retrieved 28/05/2008 http://www.stats.govt.nz/

Statistics New Zealand 2008b. Tourism and Migration 2007. Retrieved 28/05/2008 http://www.stats.govt.nz/tables/tourism-and-migration-2007.htm

Stevens NF, Garbeil H, Mouginis-Mark PJ 2004. NASA EOS Terra ASTER: Volcanic topographic mapping and capability. Remote Sensing of Environment 90(3): 405–414.

Stix J, Gaonac'h H 2000. Gas, plume and thermal monitoring. In: Sigurdsson H ed. Encyclopedia of Volcanoes. San Diego, Academic Press. Pp. 1141–1163.

Stix J, Calvache V ML, Williams S 1997a. Galeras volcano, Columbia: Interdisciplinary study of a Decade Volcano. Journal of Volcanology and Geothermal Research 77: 1–4.

Stix J, Torres C. RA, Narvaez M. L, Cortes J. GP, Raigosa A. J, Gomez M. DM, Castonguay R 1997b. A model of vulcanian eruptions at Galeras volcano, Columbia. Journal of Volcanology and Geothermal Research 77: 285–303.

Stoiber RE, Malinconico Jr. LL, Williams SN 1983. Use of correlation spectrometer at volcanoes. In: Tazieff H, Sabroux JC ed. Forecasting volcanic events. Amsterdam – New York, Elsevier. Pp. 425–444.

Takada A 1997. Cyclic flank-vent and central-vent eruption patterns. Bulletin of Volcanology 58(7): 539–556.

Takahashi T, Tsujimoto H 2000. A mechanical model for Merapi-type pyroclastic flow. Journal of Volcanology and Geothermal Research 98(1–4): 91–115.

Taupo District Council 2007. Taupo District Council District Plan. Taupo, Taupo District Council.

Tazieff H 1977. An exceptional eruption: Mt Nyiragongo, Jan 10th 1977. Bulletin of Volcanology 30: 189–200.

Tazieff H, Sabroux JC 1983. Forecasting volcanic events. Amsterdam ; New York, Elsevier. 635 p.

Tedesco D, Vaselli O, Papale P, Carn SA, Voltaggio M, Sawyer GM, Durieux J, Kasereka M, Tassi F 2007. January 2002 volcano-tectonic eruption of Nyiragongo volcano, Democratic Republic of Congp. Journal of Geophysical Research 112. B09202.

Tepley III FJ, Davidson JP, Tilling RI, Arth JG 2000. Magma mixing, recharge and eruption histories recorded in plagioclase phenocrysts from El Chichón volcano, Mexico. Journal of Petrology 41(9): 1397–1411.

Tiedemann H 1992. Earthquakes and volcanic eruptions: A handbook on risk assessment. Zurich, Swiss Reinsurance Company. 951 p.

Tilling RI 2003. Volcano monitoring and eruption warnings. In: Zschau J, Kueppers AN ed. Early Warning Systems for Natural Disaster Reduction. Berlin, Springer.

Tilling RI 2008. The critical role of volcano monitoring in risk reduction. Advances in Geosciences 14: 3–11.

Tilling RI, Topinka L, Swanson DA 1990. Eruptions of Mount St Helens: past, present and future, US Geological Survey Special Interest Publication. 56 p.

Trunk L, Bernard A 2008. Investigating crater lake warming using ASTER thermal imagery: Case studies at Ruapehu, Poas, Kawah Ijen, and Copahue Volcanoes. Journal of Volcanology and Geothermal Research 178(2): 259–270.

U.S. Geological Survey 2006. U.S. Geological Survey's Alert Notification System for Volcanic Activity, United Stated Geological Survey Fact Sheet 2006–3139. 4 p.

U.S. Geological Survey 2009. Types of Volcano Hazards Retrieved 13/04/2009 http://volcanoes.usgs.gov/hazards/

U.S. Geological Survey: Cascades Volcano Observatory 2004. Mount St. Helens, Washington May 18, 1980 eruption summary Retrieved 13/04/2009 http://vulcan.wr.usgs.gov/Volcanoes/MSH/May18/summary_may18_eruption.html

Wellington Volcanic Air Advisory Centre 2009. Wellington Volcanic Ash Advisory Centre. Retrieved 24/04/2009 http://vaac.metservice.com/vaac/index.php

Vallance JW 2000. Lahars. In: Sigurdsson H ed. Encyclopedia of volcanoes. San Diego, Academic Press. Pp. 601–616.

van Wyk de Vries B, Self S, Francis P, Keszthelyi L 2001. A gravitational spreading origin for the Socompa debris avalanche. Journal of Volcanology and Geothermal Research 105: 225–247.

Vassilopoulou S, Hurni L, Dietrich V, Baltsavias E, Pateraki M, Lagios E, Parcharidis I 2002. Orthophoto generation using IKONOS imagery and high-resolution DEM: a case study on volcanic hazard monitoring of Nisyros Island (Greece). Isprs Journal of Photogrammetry and Remote Sensing 57(1–2): 24–38.

Vicari A, Ciraudo A, Del Negro C, Herault A, Fortuna L In press. Lava flow simulations using discharge rates from thermal infrared satellite imagery during the 2006 Etna eruption. Natural Hazards.

Voight B 1990. The 1985 Nevado del Ruiz volcanic catastrophe: anatomy and retrospection. Journal of Volcanology and Geothermal Research 42: 151–188.

Voight B, Cornelius RR 1991. Prospects for eruption prediction in near real-time. Nature 350(6320): 695–698.

Wadge G, Jackson P, Bower SM 1998. Computer simulations of pyroclastic flows from dome collapse. Geophysical Research Letters 25(19): 3677–3680.

Walker GPL, Self S, Wilson L 1984. Tarawera 1886, New Zealand–A basaltic plinian fissure eruption. Journal of Volcanology and Geothermal Research 21: 61–78.

Williams S, Montaigne F 2001. Surviving Galeras. Boston, Houghton Mifflin Company. 270 p.

Wilson CJN 1985. The Taupo Eruption, New Zealand .2. The Taupo Ignimbrite. Philosophical Transactions of the Royal Society of London Series a–Mathematical Physical and Engineering Sciences 314(1529): 229.

Wilson CJN 1993. Stratigraphy, Chronology, Styles and Dynamics of Late Quaternary Eruptions from Taupo Volcano, New Zealand. Philosophical Transactions of the Royal Society of London Series a–Mathematical Physical and Engineering Sciences 343(1668): 205–306.

Wilson CJN 2001. The 26.5 ka Oruanui eruption, New Zealand: an introduction and overview. Journal of Volcanology and Geothermal Research 112(1–4): 133–174.

Wilson CJN, Houghton BF, Institute of Geological & Nuclear Sciences Limited. 2004. Taupo the eruption. Lower Hutt, N.Z., Institute of Geological & Nuclear Sciences. 1 p.

Witham CS 2005. Volcanic disasters and incidents: A new database. Journal of Volcanology and Geothermal Research 148: 191–233.

Woo G 1999. The mathematics of natural catastrophes. London, Imperial College Press. 292 p.

Woo G 2008. Probabilistic criteria for volcano evacuation decisions. Natural Hazards 45(1): 87–97.

Wood CP 1992. Geology of the Rotorua geothermal system. Geothermics 21(1/2): 25–41.

Zeilinga de Boer J, Sanders DT 2002. Volcanoes in human history: the far reaching effects of major eruptions. Princeton, Princeton University Press. 295 p.

Zuccaro G, Cacace F, Spence RJS, Baxter PJ 2008. Impact of explosive eruption scenarios at Vesuvius. Journal of Volcanology and Geothermal Research 178(3): 416–453.

Appendix 1 – NVEWS Threat Scoring System

From Ewert et al. (2005).

Hazard and exposure factors used in threat assessment of U.S. volcanoes for the National Volcano Early Warning System.	
Hazard Factors	**Score**
Volcano type If volcano type is cinder cone, basaltic field, small shield, or fissure vents: Score = 0 If volcano type is stratocone, lava domes, complex volcano, maar or caldera: Score = 1	
Maximum Volcano Explosivity Index (VEI) If maximum known VEI ≤ 2: Score = 0 If maximum known VEI = 3 or 4: Score = 1 If maximum known VEI = 5 or 6: Score = 2 If maximum known VEI ≥ 7: Score = *3* If no maximum VEI is listed by GVP and if volcano type = 0: Score = 0 If no maximum VEI is listed by GVP but volcano type = 1: Score = 1 If no known Holocene eruptions and the volcano is *not* a silicic caldera system: Score = 0	
Explosive activity If explosive activity (VEI ≥ 3) within the last 500 years: Score = 1	
Major explosive activity If major explosive activity (VEI ≥ 4) within last 5000 years: Score = 1	
Eruption recurrence If eruption interval is 1–99 years: Score = 4 If eruption interval is 100–1,000 years: Score = 3 If eruption interval is 1,000 to several thousand years: Score =2 If eruption interval is 5,000–10,000 years, or if no Holocene eruptions but it is a large-volume restless silicic system that has erupted in the last 100,000 years: Score = 1 If no known Holocene eruption: Score = 0	
Holocene pyroclastic flows? If yes: Score = 1	
Holocene lava flows? If Holocene lava flows have travelled beyond the immediate eruption site or flanks and reached populated areas: Score =1	
Holocene lahars? If Holocene lahars have travelled beyond the flanks and reached populated areas: Score =1	
Holocene tsunami(s)? Has it produced a tsunami within the Holocene? If yes: Score = 1	
Hydrothermal explosion potential? If the volcano has had Holocene phreatic explosive activity, and/or the volcano has thermal features that are extensive enough to pose a potential for explosive activity: Score =1	
Sector collapse potential? If the volcano has produced a sector collapse in Quaternary-Holocene time *and* has re-built its edifice, *or*, has high relief, steep flanks and demonstrated or inferred alteration: Score = 1	
Primary lahar source? If volcano has a source of permanent water/ice on edifice, water volume > 10^6 m^3: Score = 1	
Historical Unrest Factors	
Observed seismic unrest Since the last eruption, in the absence of eruptive activity, within 20 km of the volcanic edifice? If yes: Score = 1	

Observed ground deformation Since the last eruption, in the absence of eruptive activity, inflation or other evidence of magma injection? If yes: Score = 1	
Observed fumarolic or magmatic degassing Since the last eruption, in the absence of eruptive activity, either heat source or magmatic gases? If yes: Score = 1	
Total of Hazard Factors	
Exposure Factors	
Log_{10} of Volcano Population Index (VPI) at 30 km Calculated with LandScan population database. Visitor statistics for volcanoes in National Parks and other destination recreation areas are added to the VPI factor where available. Score = 0–x	
Log_{10} of approximate population downstream or downslope (0–x) Population outside the 30 km VPI circle included within the extent of Holocene flow deposits or reasonable inundation modelling. This factor to be used only with volcanoes that have a primary lahar hazard (e.g. Cascade stratovolcanoes) or significant lava flow hazard (e.g. Mauna Loa). Score = 0–x	
Historical fatalities? If yes, and a permanent population is still present: Score = 1	
Historical evacuations? If yes, and a permanent population is still present: Score = 1	
Local aviation exposure If any type volcano is within 50 km of a jet-service airport, score = 1; if a *Type 1* volcano is within 300 km of a jet-service airport, score = 1; if a *Type 1* volcano is within 300 km of a major international airport, score = 2; if none of these criteria are met, score = 0.	
Regional aviation exposure This score is based on the log_{10} of approximate daily passenger traffic in each region. At present, in the U.S., this score ranges from 4 to 5.15. The regional risk code is applied only to *type 1* volcanoes and those *type 0* volcanoes that have produced explosive eruptions. Score 0–x	
Power infrastructure Is there power infrastructure (e.g., power generation/transmission/distribution for electricity, oil, or gas) within flowage hazard zones or in an area frequently downwind of the volcano and close enough to be considered at some risk? If yes, score =1	
Transportation infrastructure Is there transportation infrastructure (e.g. port facilities, rail lines, major roads) within flowage hazard zones, or in an area frequently downwind of the volcano and close enough to be considered at some risk? If yes, score = 1	
Major development or sensitive areas Are there major developments or sensitive areas threatened (e.g., National Park facilities, flood control projects, government facilities, developed tourist/recreation facilities, manufacturing or other significant economic activity)? If yes, score =1	
Volcano is a significant part of a populated island Holocene volcanic deposits cover >25% of land mass. If yes, score = 1	
Total of Exposure Factors	
Sum of all hazard factors x Sum of all exposure factors = Relative Threat Ranking	

Appendix 2 – U.S. and New Zealand Case Studies with NVEWS Ranking, Monitoring and Threat Levels

From Ewert et al. (2005).

Note: VH = Very high threat, H = High threat, M = Moderate threat, L = Low threat and VL = Very low threat.

Rank	*Volcano*	*State*	*Hazard Factor Score*	*Exposure Factor Score*	*Threat Score*	*Required Monitoring Level*	*Current Monitoring Level*	*Threat Level*
1	Kilauea	HI	16	20.3	324	4	4	VH
2	St. Helens	WA	15	17.8	267	4	4	VH
3	Rainier	WA	13	18.8	244	4	2	VH
4	**Okataina/ Tarawera**	**NZ**	**13**	**16.5**	**215**	**4**	**3**	**VH**
5	Hood	OR	12	17.8	213	4	2	VH
6	Shasta	CA	13	16.2	210	4	2	VH
7	**Ruapehu**	**NZ**	**14**	**14.6**	**204**	**4**	**3**	VH
8	South Sister	OR	12	16.2	194	4	2	VH
9	Lassen Volcanic Center	CA	13	14.3	186	4	2	VH
10	**Taupo**	**NZ**	**13**	**13.2**	**171.6**	**4**	**3**	**VH**
11	Mauna Loa	HI	11	15.4	170	4	3	VH
12	Redoubt	AK	14	11.7	164	4	3	VH
13	**Tongariro/ Ngauruhoe**	**NZ**	**12**	**13.6**	**163.2**	**4**	**2**	**VH**
14	Crater Lake	OR	10	16.1	161	4	1	VH
15	Baker	WA	9	17.4	156	4	2	VH
16	Glacier Peak	WA	11	14.1	155	4	1	VH
17	Makushin	AK	16	9.5	152	4	3	VH
18	Akutan	AK	16	8.8	140	4	3	VH
19	Spurr	AK	14	9.3	130	4	3	VH
20	Long Valley Caldera	CA	9	14.3	128	4	4	VH
21	Newberry Volcano	OR	9	14	126	4	2	VH
22	Augustine	AK	14	8.8	123	4	3	VH
23	Adams	WA	7	16.1	113	4	2	H
24	Veniaminof	AK	14	7.8	109	4	3	H
25	Yellowstone	WY	9	11.9	107	4	3	H
26	Iliamna	AK	12	8.8	106	4	3	H

Contd.

Rank	Volcano	State	Hazard Factor Score	Exposure Factor Score	Threat Score	Required Monitoring Level	Current Monitoring Level	Threat Level
27	Inyo Craters	CA	8	13.3	106	4	2	H
28	Shishaldin	AK	14	7.4	104	4	3	H
29	Kanaga	AK	13	7.9	102	4	3	H
30	Wrangell	AK	12	8.3	100	4	2	H
31	Mono Craters	CA	8	12.2	98	4	1	H
32	Pavlof	AK	13	7.3	95	4	3	H
33	Ugashik-Peulik	AK	14	6.6	93	4	3	H
34	Hualalai	HI	6	15.4	92	4	2	H
35	Medicine Lake	CA	7	13.1	92	4	2	H
36	**White Island**	**NZ**	**12**	**7.6**	**91**	**4**	**2**	**H**
37	Pagan	CNMI	13	7	91	4	0	H
38	Trident	AK	12	7.5	90	4	3	H
39	Katmai	AK	12	7.5	90	4	3	H
40	Great Sitkin	AK	13	6.9	90	4	3	H
41	Clear Lake	CA	6	14.8	89	4	1	H
42	Aniakchak	AK	13	6.7	88	4	3	H
43	Churchill	AK	10	8.3	83	4	1	H
44	**Kermadec Is./ Raoul Is.**	**NZ**	**13**	**6.4**	**83.2**	**3**	**2**	**H**
45	Gareloi	AK	13	6.3	82	4	3	H
46	Anatahan	CNMI	9	9	81	4	2	H
47	Agrigan	CNMI	11	7	77	4	0	H
48	Martin	AK	10	7.5	75	4	3	H
49	Mageik	AK	10	7.5	75	4	3	H
50	Novarupta	AK	10	7.5	75	4	3	H
51	Griggs	AK	10	7.5	75	4	3	H
52	Hayes	AK	9	8.3	75	4	1	H
53	Dutton	AK	9	8.3	74	4	2	H
54	Westdahl	AK	14	5.3	74	4	3	H
55	Alamagan	CNMI	9	8	72	4	0	H

Contd.

Rank	Volcano	State	Hazard Factor Score	Exposure Factor Score	Threat Score	Required Monitoring Level	Current Monitoring Level	Threat Level
56	Atka	AK	10	7.1	71	4	3	H
57	Semisopochnoi	AK	11	6.3	69	4	0	H
58	Okmok	AK	16	4.3	69	4	3	H
59	Kaguyak	AK	9	7.5	68	4	2	H
60	Pavlof Sister	AK	9	7.4	66	4	3	H
61	Seguam	AK	12	5.3	64	4	0	H
62	Chiginagak	AK	10	6.3	63	3	1	M
63	Steamboat Springs	NV	4	15.6	62	3	2	M
64	Snowy Mountain	AK	8	7.5	60	3	3	M
65	Dana	AK	8	7.4	59	3	1	M
66	Kiska	AK	11	5.3	58	3	0	M
67	Roundtop	AK	8	7.3	58	3	1	M
68	Tanaga	AK	9	6.3	57	3	3	M
69	Vsevidof	AK	10	5.6	56	3	0	M
70	Mono Lake Volcanic Field	CA	5	11	55	3	1	M
71	Valles Caldera	NM	5	11	55	3	2	M
72	Kupreanof	AK	8	6.8	55	3	1	M
73	North Sister Field	OR	4	13.5	54	3	1	M
74	Edgecumbe	AK	6	8.9	53	3	1	M
75	Coso Volcanic Field	CA	5	10.6	53	3	2	M
76	Douglas	AK	7	7.5	53	3	1	M
77	Yantarni	AK	9	5.8	52	3	0	M
78	Frosty	AK	7	7.4	52	3	2	M
79	Ukinrek Maars	AK	8	6.5	52	3	3	M
80	Guguan	CNMI	8	6	48	3	0	M
81	Sarigan	CNMI	6	8	48	3	1	M
82	Little Sitkin	AK	9	5.3	48	3	0	M
83	Fisher	AK	9	5.3	48	3	3	M
84	Recheschnoi	AK	8	5.9	47	3	0	M

Contd.

Rank	Volcano	State	Hazard Factor Score	Exposure Factor Score	Threat Score	Required Monitoring Level	Current Monitoring Level	Threat Level
85	Ubehebe Craters	CA	4	11.6	46	3	1	M
86	Black Peak	AK	7	6.5	45	3	1	M
87	Dotsero	CO	4	11.3	45	3	0	M
88	Kukak	AK	6	7.5	45	3	2	M
89	**Auckland Volcanic Field**	**NZ**	**3**	**14.7**	**44**	**2**	**2**	**M**
90	Haleakala	HI	5	8.8	44	3	2	M
91	Cleveland	AK	10	4.3	43	3	0	M
92	Emmons Lake	AK	6	7.1	43	3	2	M
93	Bachelor	OR	3	14.1	42	3	2	M
94	Moffett	AK	5	7.7	38	3	2	M
95	Adagdak	AK	5	7.7	38	3	2	M
96	Denison	AK	5	7.5	38	3	2	M
97	Steller	AK	5	7.5	38	3	2	M
98	Red Cones	CA	5	7.1	36	3	3	M
99	Amukta	AK	8	4.3	34	3	0	M
100	Bogoslof	AK	8	4.3	34	3	0	M
101	Kialagvik	AK	5	6.8	34	3	0	M
102	Amak	AK	5	6.7	33	3	0	M
103	Sanford	AK	4	8.3	33	3	1	M
104	Mauna Kea	HI	3	11.1	33	3	2	M
105	Farallon de Pajaros	CNMI	8	4	32	3	0	M
106	Asuncion	CNMI	8	4	32	3	0	M
107	Sunset Crater	AZ	3	10.7	32	3	2	M
108	Kasatochi	AK	6	5.3	32	3	0	M
109	Black Rock Desert	UT	3	10.5	32	3	1	M
110	Yunaska	AK	7	4.3	30	3	0	M
111	Carlisle	AK	7	4.3	30	2	0	L
112	Fourpeaked	AK	4	7.5	30	2	2	L
113	Isanotski	AK	4	7.2	29	2	3	L

Contd.

Rank	Volcano	State	Hazard Factor Score	Exposure Factor Score	Threat Score	Required Monitoring Level	Current Monitoring Level	Threat Level
114	Kagamil	AK	6	4.3	26	2	0	L
115	Takawangha	AK	4	6.3	25	2	3	L
116	Bobrof	AK	3	8	24	2	2	L
117	St. Michael	AK	3	7.7	23	2	0	L
118	Segula	AK	4	5.3	21	2	0	L
119	Blue Lake Crater	OR	2	10.5	21	2	1	L
120	Ingakslugwat Hills	AK	3	6	18	2	0	L
121	Nunivak Island	AK	3	5.9	18	2	0	L
122	Maug Islands	CNMI	4	4	16	2	0	L
123	Koniuji	AK	3	5.3	16	2	0	L
124	Sergief	AK	3	5.3	16	2	0	L
125	Hell's Half Acre	ID	2	6.8	14	2	1	L
126	Stepovak	AK	6	2.3	14	2	0	L
127	Buldir	AK	3	4.3	13	2	0	L
128	Chagulak	AK	3	4.3	13	2	0	L
129	Herbert	AK	3	4.3	13	2	0	L
130	Uliaga	AK	3	4.3	13	2	0	L
131	Craters of the Moon	ID	3	4.1	12	2	2	L
132	Unnamed	AK	2	5.9	12	2	0	L
133	Indian Heaven	WA	2	5.7	11	2	1	L
134	Davidof	AK	2	5.3	11	2	0	L
135	West Crater	WA	2	5	10	2	1	L
136	Markagunt Plateau	UT	1	9.8	10	2	1	L
137	Shoshone Lava Field	ID	2	4.8	10	2	1	L
138	Belknap	OR	2	4.4	9	2	1	L
139	Table Top-Wide Bay	AK	2	4	8	2	0	L
140	Wapi Lava Field	ID	2	4	8	2	1	L
141	Duncan Canal	AK	2	3.5	7	2	0	L
142	Buzzard Creek	AK	3	2.3	7	2	1	L

Contd.

Rank	Volcano	State	Hazard Factor Score	Exposure Factor Score	Threat Score	Required Monitoring Level	Current Monitoring Level	Threat Level
143	Ruby	CNMI	6	1	6	2	1	L
144	Esmeralda Bank	CNMI	6	1	6	2	1	L
145	Carrizozo	NM	2	2.8	6	1	0	VL
146	Zuni-Bandera	NM	2	2.8	6	1	0	VL
147	Santa Clara	UT	1	4.7	5	1	1	VL
148	Jordan Craters	OR	2	2.2	4	1	0	VL
149	Gordon	AK	2	2	4	1	0	VL
150	Eagle Lake Field	CA	1	3.8	4	1	1	VL
151	Big Cave	CA	1	3.8	4	1	1	VL
152	Twin Buttes	CA	1	3.7	4	1	1	VL
153	Davis Lake	OR	1	3.7	4	1	1	VL
154	Tumble Buttes	CA	1	3.7	4	1	1	VL
155	Lavic Lake	CA	1	3.6	4	1	1	VL
156	Brushy Butte	CA	1	3.5	4	1	1	VL
157	Washington	OR	1	3.4	3	1	1	VL
158	Amboy	CA	1	3.4	3	1	0	VL
159	Sand Mountain Field	OR	1	3.2	3	1	1	VL
160	Jefferson	OR	1	3	3	1	1	VL
161	Bald Knoll	UT	1	3	3	1	1	VL
162	Cinnamon Butte	OR	1	3	3	1	1	VL
163	Uinkaret Field	AZ	1	3	3	1	1	VL
164	St. Paul Island	AK	1	2.9	3	1	1	VL
165	Tlevak Strait-Suemez Is.	AK	1	2.8	3	1	1	VL
166	Four Craters Lava Field	OR	1	2.7	3	1	1	VL
167	Imuruk Lake	AK	2	1.4	3	1	1	VL
168	Lava Mountain	OR	1	2.7	3	1	1	VL
169	Devils Garden	OR	1	2.5	3	1	1	VL
170	Diamond Craters	OR	1	2.2	2	1	1	VL
171	Jackies Butte	OR	1	2.2	2	1	0	VL

Contd.

Rank	Volcano	State	Hazard Factor Score	Exposure Factor Score	Threat Score	Required Monitoring Level	Current Monitoring Level	Threat Level
172	Golden Trout Creek	CA	1	2.2	2	1	1	VL
173	Kookooligit Mountains	AK	1	2.1	2	1	0	VL
174	Behm Canal-Rudyerd Bay	AK	0	1	0	1	0	VL
175	Ahyi	CNMI	4	0	0	1	0	VL
176	Supply Reef	CNMI	4	0	0	1	0	VL

Appendix 3 – Monitoring Gap Analysis of New Zealand's Volcanoes

Gap analysis of New Zealand's volcanoes based on the monitoring benchmarks described in Ewert et al. (2005) (after G. Jolly pers. comm., 2009). Ratings range from 0 (no monitoring) to 4 (well monitored), see Table 7 for explanations.

Volcano	***Current Rating***						***Comment***
	Seismic	***Deformation***	***Hydrology***	***Remote Sensing***	***Gas Emissions***	***Overall Monitoring Rating***	
Ruapehu	4	3	2–4	4	4	4	Overall good coverage but weak on deformation
Tongariro/ Ngauruhoe	3/4	0/1	1/2	0	2	2	Seismic good but needs more broadband sensors of Tongariro; weak in all other areas
White Island	2	1/2	2	0	4	2	Comprehensive gas monitoring; all other areas weak
Raoul Island	2	1	2	3	0	2	Difficult to maintain due to distance; hard to adequately monitor due to small size
Taupo	3	3	1/2	2	0	3	Some methods not applicable e.g. Gas emissions monitoring
Okataina Volcanic Centre	3	3	1/2	2	0	3	Some methods not applicable e.g. gas emissions monitoring
Auckland Volcanic Field	2	1	0	2	0	2	Size of volcanic field makes methods other than seismic monitoring hard to justify and implement