COMMUNICATING THE STATUS OF VOLCANIC ACTIVITY IN NEW ZEALAND, WITH SPECIFIC APPLICATION TO CALDERA UNREST

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ABSTRACT

Volcanic eruptions can negatively impact social, economic, built, and natural environments. Volcanic unrest is the key indicator of an impending eruption, enabling warnings to be disseminated, and risk to be reduced. This research focuses on recognising changes at a caldera volcano when it begins to show signs of unrest, and the communication of this information using the Volcanic Alert Level (VAL) system.

New Zealand's existing VAL system is explored, and influences on the determination of the VAL and potential foundations of VAL systems are identified. For the first time globally, a qualitative ethnographic methodology is used to develop a new VAL system, involving interviews, document analysis, and observations over three years at GNS Science (New Zealand's official provider of science advice for geological hazards). The new VAL system developed in this research is being actively used in New Zealand from July 2014.

To assist with distinguishing 'unrest' from 'background' activity at volcanoes, a new, innovative tool called the Volcanic Unrest Index (VUI) has been developed. The VUI integrates multi-parameter qualitative and quantitative data, enabling a world-first comparison of the intensity of unrest. It contributes towards probabilistic decision-making tools by defining unrest. The VUI provides a simple way to communicate the status of any volcano with non-scientists. The frequency and intensity of historical caldera unrest was investigated at Taupo Volcanic Centre (TVC), New Zealand. Through the use of the VUI, 16 episodes of unrest were identified, many more than had previously been recognised. Socio-economic impacts have resulted from several of these unrest episodes. The recurrence rate of unrest between 1872 and 2011 is one episode every nine years, and the median duration of unrest is slightly less than five months.

The findings suggest that the VAL could have been raised during past unrest at TVC, including in 2008–10. However, influences on the decision to change the VAL, including potential socio-economic impacts, may cause a delay in raising the VAL during future unrest. These findings contribute towards more effective communication of the status of volcanoes in New Zealand in the future, particularly at calderas.

DON’T PANIC

- Douglas Adams, *The Hitchhiker’s Guide to the Galaxy*

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CHAPTER ONE

INTRODUCTION

1 INTRODUCTION

When a caldera volcano starts showing signs of unrest, at what point should the Volcanic Alert Level be raised?

This was a practical question asked by volcanologists at GNS Science (New Zealand's equivalent to a Geological Survey), following an episode of caldera unrest that occurred in 2008 at Taupo Volcanic Centre (TVC), a large rhyolitic caldera volcano in the North Island of New Zealand. It is the guiding question for this research. To explore the context in which such decisions are made, a transdisciplinary research framework is needed. First, the content and nature of New Zealand's Volcano Early Warning System (VEWS) need to be established. Decisions made within the VEWS, including the determination of threat and whether to alert, require exploration. The Volcanic Alert Level (VAL) system, a communication tool within the VEWS, needs to be examined to identify aspects which could contribute towards a more effective VEWS. The history of caldera unrest at TVC needs to be catalogued to ascertain the intensity of past activity. A key requirement for a decision to change the VAL is understanding at what level complex, multi-parameter volcanic phenomena constitute 'unrest'. A method to combine complex, multi-parameter unrest phenomena into a comparable format would be beneficial to ascertain relative levels of the intensity of unrest over time, and between volcanoes. The integration of these aspects will enable the research question to be answered, and will contribute towards a more effective VEWS for New Zealand.

This chapter introduces the field of research by discussing aspects of the impact of volcanoes on society, and the role of volcanic unrest phenomena in forecasting eruptions. An overview of Early Warning Systems (EWSs) is also provided, particularly for volcanology, including aspects of decision-making and communication tools used. Caldera unrest is recognised as a type of volcanic crisis situation requiring careful management in the future. Gaps in knowledge are identified, together with a description of the structure of the thesis and the research aims. A list of acronyms and abbreviations mentioned in this thesis is provided in Appendix 1.

1.1 Volcanoes and society

Many of the world's population live in close proximity to an active volcano. As the world's population drifts to fertile volcanic soils, an increasing number of humans are settling closer to volcanoes, particularly in developing countries. More than 260,000 people have been killed by volcanic hazards since 1600 AD (Tilling, 2003). Hazards caused by the interaction between volcanic phenomena and society have been well documented (e.g., Blong, 1984; Crandell et al., 1984; Baxter et al., 1990; Casadevall, 1994; Blong & McKee, 1995; Sigurdsson et al., 2000; Hansell et al., 2006; Wilson et al., 2012). Volcanic hazards include pyroclastic density currents, lava flows, debris avalanches, lateral blasts, phreatic eruptions, lahars, jökulhlaups, tephra, earthquakes, lightning, and volcanic gases. Tephra includes a range of particle sizes, from ballistics close to the vent, to finer ash, which may impact a wide area downwind of the volcano disrupting air traffic, as occurred during the 2010 Eyjafjllajökull (Iceland) and 2011 Puyehue Cordón Caulle (Chile) eruptions (e.g., Lechner, 2012). Secondary hazards that may result from volcanic eruptions include tsunami, crop damage leading to famine and disease, acid rain, wildfires, pumice rafts, and rain-triggered lahars, which can alter drainage channels and cause flooding and erosion for years after the conclusion of an eruption. Many of these hazards cause fatalities and injuries to nearby populations. Unsuspecting distal populations are also vulnerable to mobile volcanic hazards such as ashfall, tsunami, and lahars due to their lack of natural warnings (seeing, hearing or feeling the volcano erupt). For example, a lahar destroyed the town of Armero, Colombia, in 1985 causing over 22,000 deaths following the eruption of an up-river volcano, Nevado del Ruiz (Voight, 1990). Large volcanic eruptions, which may form calderas, can also cause atmospheric effects and global climate change (Lipman, 2000).

Volcanoes generally exhibit precursory phenomena prior to eruptions, enabling the potential for forecasts of eruptions to be disseminated by scientists. The phenomena may include seismicity, ground deformation, geothermal system changes, and degassing, all of which can be hazardous, irrespective of any resulting eruption. The interpretation and integration of this information is key to eruption forecasting, because it can indicate magma movement or the possibility of an imminent eruption (e.g., Sparks, 2003). However, more often than not, volcanoes show signs of unrest without resulting in an eruption, particularly long-quiet silicic caldera volcanoes (Newhall & Dzurisin, 1988). Some unrest episodes are caused by the injection of magma into shallow depths without it reaching the surface, sometimes referred to as ‘failed eruptions’ (e.g., Moran et al., 2011). Co-existing tectonic faults, regional tectonic processes, and numerous geothermal fields also produce similar phenomena without involvement of magma, resulting in difficulties for eruption forecasting. Determining the point at which the background level of activity increases and becomes considered as unrest is a major challenge due to the differences in behaviour and characteristics of each volcano. These factors create high levels of uncertainty among scientists about the genesis of unrest, determination of threat, and at what stage to warn end-users. In this thesis, ‘end-users’ refers to anyone receiving scientific advice, including but not limited to civil protection officers (referred to as civil defence and emergency management officials in New Zealand), the Ministry of Civil Defence and Emergency Management (MCDEM), local authorities, response agencies, lifeline utilities, major land managers, tourist operators, media, and the public.

Caldera unrest is an example of a volcanic "crisis", defined by Tilling (1989, p. 241) as:

> "a situation during which a volcano shows signs of instability or unrest interpreted to augur impending eruptive activity and associated hazards. A crisis may or may not culminate in a dangerous eruption, but it always causes anxiety and/or socio-economic disruption among the populace affected."

Caldera unrest crises have occurred a number of times in recent decades, including at Long Valley (U.S., 1982–84, e.g., Mader & Blair, 1987; Hill, 1998), Campi Flegrei (Italy, 1970s and 1980s, e.g., Barberi et al., 1984), Rabaul (Papua New Guinea, 1983–85, e.g., Lowenstein, 1988), and Santorini (Greece, 2011–12, e.g., Newman et al., 2012). The effect of these unrest situations and eruption hazards on the population can vary widely depending on factors such as magma chemistry and type; occurrence, duration and location of the unrest and eruption; characteristics of the hazards; the location, density, preparedness, beliefs, and resilience of the population; resilience of the infrastructure and economy; geographical features of the landscape; and the weather conditions at the time of the eruption (influencing ash dispersal and severity of hazards). Populations are particularly vulnerable at volcanoes with long periods of quiescence, such as TVC, due to the perception that the volcano is extinct (Crandell et al., 1984).

TVC has undergone a number of episodes of unrest during recorded history, which have impacted the local community without resulting in an eruption (e.g., Johnston et al., 2002). A thorough and systematic search of historical information relating to unrest at this volcano has not previously been compiled, providing an inadequate basis for understanding the associated risk. For the purposes of this thesis, the definition of risk used is the 'likelihood and consequences of a natural hazard' occurring, as stated in New Zealand's Civil Defence Emergency Management (CDEM) Act 2002.

Relatively few of the world's volcanoes are adequately monitored or have well-defined eruptive histories which contribute towards the knowledge-base of a volcano's capabilities (Tilling, 1989; McGuire & Kilburn, 1997). Yet a plethora of research states that risk assessments, hazard monitoring, land use and emergency planning, and public education must take place before a volcanic crisis develops (e.g., Crandell et al., 1984; Peterson & Tilling, 1993; Paton et al., 1998a; Frenzen & Matarrese, 2008; MCDEM, 2008). The rapid development of scientific knowledge of volcanic systems and processes has contributed towards improving mitigation of volcanic hazards, but there is still a long way to go, in part due to the inherent complexity of nature, and the lack of resources in many parts of the world. These preparations contribute to EWSs, which act to decrease the vulnerability of society in volcanic areas.

1.2 Early Warning Systems (EWSs)

EWSs are used in many disciplines, and can be defined in the field of hazards and disasters as:

> “the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss” (UN/ISDR, 2009, p. 12).

The Hyogo Framework was established by the United Nations International Strategy for Disaster Reduction (UN/ISDR) in 2005 to promote disaster risk reduction. One of the priorities recognised in this Framework (p. 6) is to “identify, assess and monitor disaster risks and enhance early warning”. This is to be done through risk assessments, developing people-centred EWSs within a local context, increasing capacity to reduce risk through research and communication of information, and the assessment of regional (cross-boundary) risks (UN/ISDR, 2005).

Conferences on early warnings have been held by UN/ISDR to contribute towards meeting the goals of the Hyogo Framework (e.g., UN/ISDR, 2006; UN/ISDR PPEW, 2006). An output of the 2006 conference held in Bonn, Germany, was a checklist for developing EWSs by the Platform for the Promotion of Early Warnings (UN/ISDR PPEW, 2006). This checklist defines four elements required for developing effective people-centred warning systems (Figure 1.1).

Establishing effective warning systems for volcanic events (typically termed VEWSs) is important for the mitigation of volcanic risk, aiding decision-making by end-users (Newhall & Punongbayan, 1996b; Hall, 2007). There are many other models relating to EWSs, and overviews of the mitigation of volcanic risk in the literature (including Sorensen & Mileti, 1987;

Tilling, 1989; Mileti & Sorensen, 1990; Twigg, 2004; Glantz, 2009; and Fearnley, 2011, among others), as well as models depicting the flow of scientific information between organisations during a specific volcanic crisis (e.g., Peterson, 1986; Punongbayan et al., 1996), and factors influencing the cognitive processes involved in public response (such as the Protective Action Decision Model by Lindell & Perry, 2012). These models are in general agreement with Figure 1.1, with many including the need for an initial assessment of hazard and risk, shaping the monitoring programme (and other risk-reduction activities), the collection and interpretation of information contributing towards the formulation of a warning (usually by science organisations), the dissemination and communication of that warning, and the response by the decision-making emergency management officials and subsequently, the public. While some people consider the technological hardware as the extent of a warning system (also noted by Leonard et al., 2008), this research takes the more commonly accepted view that an EWS encompasses the entire process from development of risk knowledge and monitoring capabilities, to the public's capability to respond.

Figure 1.1. Elements of people-centred Early Warning Systems. From UN/ISDR PPEW (2006, p. 2).

Leonard et al. (2008) provide the only overview of a generic EWS in New Zealand in the literature; their model is reproduced in Figure 1.2. These authors suggest following a practical five-step process to establish an effective EWS, consisting of the development of early warning hardware, planning, communication, education and exercises. Research and scientific advice contribute to these steps, and the model includes the need to regularly evaluate the EWS. Leonard et al.'s model is differently structured to the UN/ISDR PPEW model shown in Figure 1.1. Leonard et al.'s model is focussed on the emergency management and response organisation sector factors involved in an EWS, without inclusion of most scientific processes.

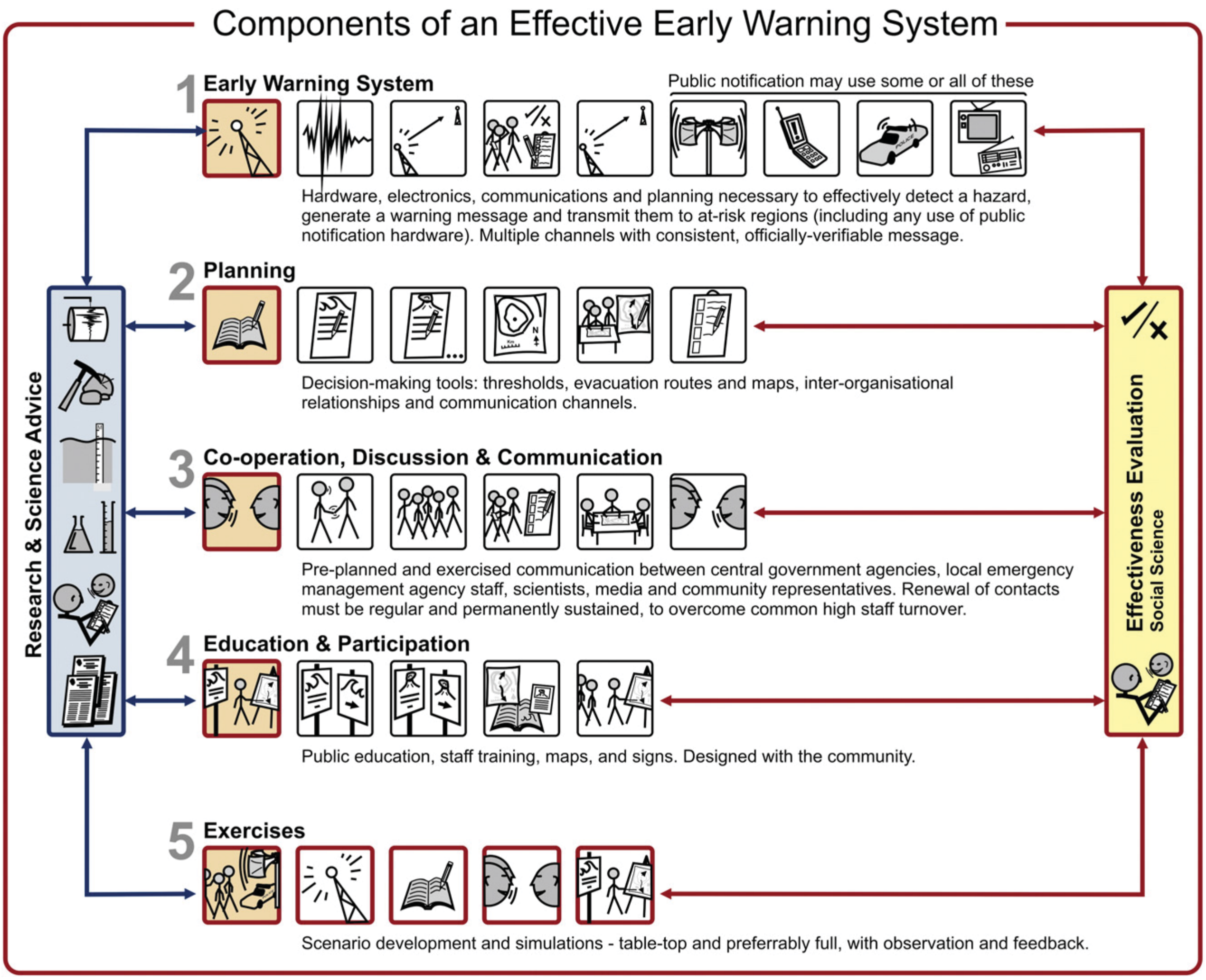


Figure 1.2. Early Warning System model for New Zealand, from Leonard et al. (2008, p. 204).

Each step or element in an EWS is a complex subsystem, with multiple linkages integrating the elements for effective disaster risk reduction, set in a context of societal, political, economic, and organisational factors (Mileti & Sorensen, 1990; Basher, 2006; UN/ISDR, 2006; Fearnley, 2011; Garcia & Fearnley, 2012). Each subsystem involves decision-making under uncertainty and complexity, with potentially high impact consequences (e.g., Fearnley, 2011).

1.2.1 Decision-making under uncertainty in EWSs

The determination of the threat of a natural hazard and the decision to alert end-users are complicated by the inherent complexity of these events. Volcanoes, their products, and hazards differ according to a vast array of factors including the tectonic setting, magma chemistry, subsurface processes, involvement of water, and societal factors. The random nature of these systems involve aleatoric (or stochastic) uncertainty, which is irreducible; and incomplete scientific knowledge or lack of data, which results in epistemic uncertainty (e.g., Woo, 1999). Successful scientific forecasts of hazardous events at volcanoes have been rare (and include to a certain extent Mount St Helens in the 1980s (Swanson et al., 1983) and Pinatubo in 1991 (Punongbayan et al., 1996), with others listed in McNutt (2000, p. 1097)), mainly due to the characteristic differences and the complex nature of volcanoes. Predictions provide information of what event is expected, in a specific location at a specified time, whereas a forecast is comparatively less precise, consisting of possible scenarios or events which may occur, often within a time window (Newhall, 2000). Both forecasting and predictions are still relatively rare in volcanology. Once volcanoes show signs of unrest, the outcome is highly uncertain causing significant challenges in communicating predictions (Swanson et al., 1985). Long-dormant calderas in particular often exhibit signs of unrest without resulting in an eruption (Newhall & Dzurisin, 1988). Based on observations and monitoring data, with consideration of the past behaviour of the volcano (and analogues), scientists must determine the threat of an eruption within this highly complex and uncertain environment. Uncertainty in the context of decision-making “is a sense of doubt that blocks or delays action” (Lipshitz & Strauss, 1997, p. 50).

One of the criteria identified by Quarantelli (1997, p. 46) for good management during a disaster is to “permit the proper exercise of decision-making”. Decisions are made at multiple stages in an EWS, by organisations with different roles. The major organisational decision-making points are shown in Sorensen and Mileti’s (1987) model in Figure 1.3. Scientists and responding organisations determine when and where there is a threat, and in what form, and decide if and when to warn, who to warn, and how (Sorensen & Mileti, 1987; Mileti & Sorensen, 1990). The three boxes on the left side of Figure 1.3 predominantly relate to science organisations with a monitoring function. These scientific decisions have come under scrutiny within volcanology in recent decades, with formalised methods of ascertaining expert judgement becoming more common. Methods include weighted expert elicitation (Aspinall & Cooke, 1998), the use of Bayesian Belief Networks (Aspinall et al., 2003; Aspinall, 2006; Hincks, 2006), and the construction of event trees (e.g., Newhall & Hoblitt, 2002; Marzocchi et al., 2004; Marzocchi et al., 2008). However, the final interpretation and resulting decision-making is usually qualitative, unstructured, and subjective (Barclay et al., 2008). This is largely due to the complexity of the natural and political settings, and the need to rapidly make a decision using multiple inputs. These types of decisions made by a group are known to be subject to influences and biases (e.g., Asch, 1952; Stoner, 1961; Janis, 1982). The development of critical thresholds at which to alert end-users is a key challenge in effective EWSs (Birkmann et al., 2013).

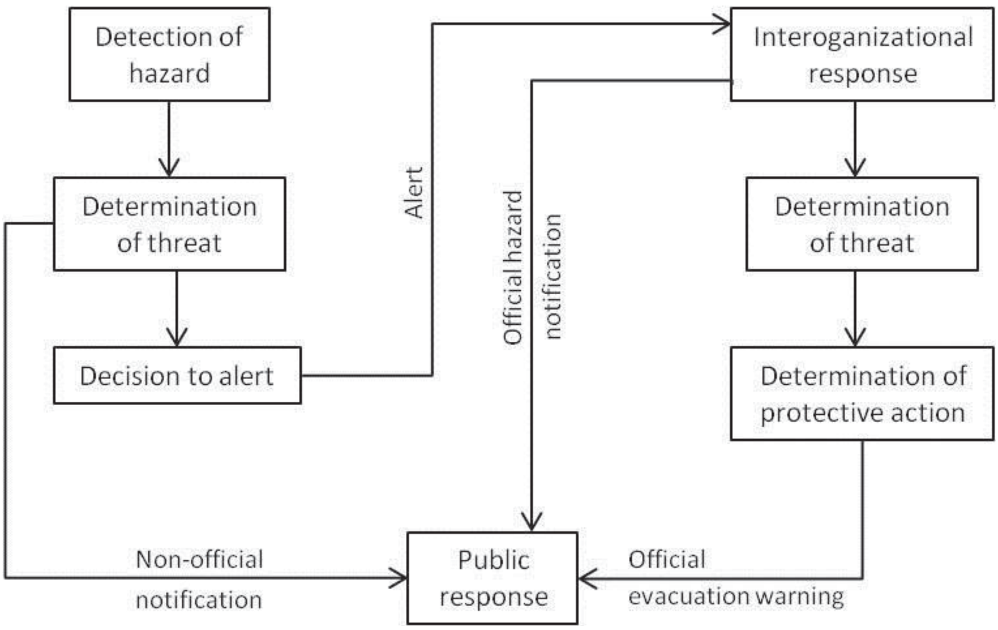


Figure 1.3. Organisational decision-making points in warning systems. Reproduced from Sorensen and Mileti (1987, p. 38).

An alert is communicated to end-users, which contributes towards their decision-making (described in the three boxes on the right side of Figure 1.3) relating to, for example, the safety of the public, and the reduction of risk to infrastructure and the economy. These end-user decision-makers must understand the hazards, consequences, and likelihoods of the hazard occurring to the extent that robust decisions relating to the level of risk can be made. This understanding is reliant on factors such as on-going education, situational awareness, and the effectiveness of interagency communication. The determination of protective action can then be made, and an official warning with response advice disseminated to the media and public.

Sorensen and Mileti's model does not recognise a repetition of this process (receipt of information, determination of threat, and decision to act) at the level of the public. The cognitive processes involved in a response to a hazardous event include pre-decisional processes (such as the exposure to the information, attention paid, and the ability to interpret it), core perceptions of the environmental threat, alternative protective actions and factors relating to stakeholders, as well as multiple stages within the protective action decision-making process (Lindell & Perry, 2012). The major decision points within an EWS for natural hazards have not been investigated in New Zealand. Probabilistic decision-making models are a focus in the international eruption forecasting literature, yet very few publications have identified the major decision-making points involved in a volcanic unrest crisis.

As well as interpretation of scientific data, many factors influence scientists' decisions relating to the 'determination of threat' and 'decision to alert' within an EWS. These include politics, economics, institutional and user protocols, the desire to make defensible decisions, and the perceived actions of the end-users associated with the alert (Fearnley, 2011). Risk is also considered, which is shaped by experience, beliefs, societal dynamics, the local context, and personal feelings and values (Fearnley, 2011; Eiser et al., 2012). The influences on scientific decisions within EWSs relating to the determination of threat and decision to alert have not previously been explored in New Zealand. Internationally, no long-term immersion within a volcanic observatory group (or, quite possibly, any scientific natural hazard decision-making group) has been undertaken with the purpose of understanding the culture of the group processes and factors influencing decisions made.

1.2.2 Scientific information communication

The communication of a warning relating to an impending hazardous event provides the opportunity for an appropriate response to minimise losses (e.g., Newhall, 2000). End-users receive information from a variety of sources on a range of topics preceding, throughout, and following a volcanic crisis. Volcanologists are just one source of information, with others including meteorologists and social scientists, as well as liaison with mental health, welfare, and insurance agencies (Paton et al., 1998b). The processing of scientific information by emergency management decision-makers can cause unnecessary delays in responding, prompting the need for an analysis of their specific information needs (Paton et al., 1998b). The effectiveness of a warning in promoting the appropriate response is dependent on a number of factors. Mileti and Sorensen (1990) describe five topics important to include in a warning message:

1) Hazard – a description of the event and the ways in which it may affect people
2) Guidance – instructions on what people should do to minimise the impact of the hazard
3) Location – where the places of risk are
4) Time – the expected time of the hazardous event
5) Source – the agency issuing the warning.

Additionally, the warning should be specific, consistent, accurate, certain, clear and understandable, and widely dispersed in a timely fashion (Mileti & Sorensen, 1990; Newhall, 2000). The information source requires credibility (Newhall, 2000).

Miscommunication and misunderstanding of scientific information during a volcanic crisis can result in detrimental effects (e.g., Paton & Flin, 1999), as has been seen at Soufrière de la Guadeloupe in 1976 (Fiske, 1984), and Nevado del Ruiz, Colombia in 1985 (Voight, 1990). This was also the case at Long Valley Caldera (U.S.) during the 1982–1984 unrest episode, when a Notice of Potential Volcanic Hazard was issued by U.S. Geological Survey (USGS) following signs of unrest (Mader & Blair, 1987). The Notice was published by the media the day before it was to be communicated directly to those affected, which exacerbated the impact that the unrest was already having on the tourism community. Due to the high level of uncertainty and potential consequences associated with caldera unrest, communication strategies need to be particularly well planned and inter-organisational relationships established in advance to enable an effective response by scientific and end-user groups (e.g., Ronan et al., 2000).

The effective communication and availability of scientific information impacts end-user decision-making (Paton et al., 1998a; Solana et al., 2008), and is provided by science organisations using a range of methods and tools.

1.2.2.1 Overview of volcanic information communication tools

Information relating to volcanoes can be communicated via a wide range of media and resources, as well as person-to-person. Prior to a volcanic crisis, long-range forecasts and hazard maps, based on the past eruptive activity at a volcano, indicate potential future hazards for planning purposes (Newhall, 2000). During a volcanic crisis, warnings may take the form of a factual statement, which "describes current conditions but does not anticipate future events" (Swanson et al., 1985, p. 397); forecasts (as described in section 1.2.1); and/or probabilities of several scenarios or outcomes within a specified time frame (Newhall, 2000).

Expert elicitation has been applied at Montserrat Volcano Observatory, West Indies, to ascertain the probabilities of scenarios for volcanic activity at Soufrière Hills Volcano (Aspinall & Cooke, 1998). This technique also allows the communication of the uncertainties involved. Volcanic warnings are becoming increasingly quantitative (Sparks, 2003), yet it is recognised that probabilities can be confusing for end-users to understand (e.g., Doyle et al., 2011; Newhall, 2000).

Rapid hazard detection systems are a tool used to communicate short-range warnings of volcanic hazards. These are triggered by events such as eruption acoustic waves, tremor, and lahar vibrations, allowing immediate warning to people within the most hazardous areas and bypassing the scientific and response organisation decision-making and alert processes. Examples of these systems in New Zealand are Mt Ruapehu's Eruption Detection System (EDS), which provides a warning of lahars on the Whakapapa ski area (Sherburn & Bryan, 1999), and the Eastern Ruapehu Lahar Alarm & Warning System (ERLAWS), which communicates lahar warnings in the Whangaehu River channel (Leonard et al., 2008).

Volcanic monitoring information and alerts in New Zealand are communicated by GNS Science to the Ministry of Civil Defence and Emergency Management (MCDEM), as described in Appendix 1 of the National CDEM Plan Order 2005 (MCDEM, 2005) and the Guide to the National CDEM Plan (MCDEM, 2006). Formal information relating to currently occurring events are primarily communicated in Volcanic Alert Bulletins (VABs). MCDEM receives this information from GNS Science, and adapts and disseminates the message through the National Warning System (NWS) to various levels of CDEM (i.e. Civil Defence personnel at local and regional levels), local authorities, lifeline utilities, police, certain government departments, and media broadcasters, among others (MCDEM, 2005).

In accordance with procedures recommended by the International Civil Aviation Organisation (ICAO), and as part of the International Airways Volcano Watch system, New Zealand also uses the International Aviation Colour Code (ACC) (Lechner, 2012). The ACC is intended for "aviation information only and does not determine any action or obligation in the New Zealand civil aviation system" (Lechner, 2009, p. 6). GNS Science determines the ACC, communicating it within VABs and in a Volcano Observatory Notice for Aviation (VONA). Notifications of Volcanic Alert Levels (VALs) are also disseminated by GNS Science within VABs and both ACC and VALs are displayed on the GNS Science GeoNet monitoring project website (geonet.org.nz/volcano).

1.2.2.2 Volcanic Alert Levels

Volcanic Alert Levels are a communication tool within a VEWS, which simplify the communication of volcanologists' interpretation of data (Newhall, 2000). The VAL is disseminated with supporting information, which provides more specific details and local context to enable responding agencies, the public, and other stakeholders to make informed decisions (Fearnley, 2011). The levels can be labelled using words, numbers, colours, and/or symbols, and summarise information from 'background' activity (no unrest), through to the highest level of activity (usually a large eruption) (Newhall, 2000; Fearnley, 2011).

The use of a VAL system must be carefully managed to provide adequate warnings of impending eruptions, without resulting in too many 'false alarms'. False alarms can cause unnecessary evacuations and an associated economic and psychosocial impact, and can result in mistrust of the scientists and therefore the potential for future warnings to be ignored. Scientists must be willing to freely move the VAL depending on the volcano's activity, without being influenced by political pressure (Newhall, 2000).

In New Zealand, the VAL system consists of a numerical scale from zero (low) to five (high), with different meanings applied to these numbers according to whether the volcano is a 'frequently active cone' or is 'reawakening' (this system is described further in Chapter 2). As stated in the previous section, GNS Science determines the VALs and communicates this information to MCDEM, as mandated in the Guide to the National CDEM Plan (MCDEM, 2006). New Zealand's current VAL system was formed in the early stages of the 1995 Ruapehu eruption, and so has been in use for 19 years to date, without an assessment of its effectiveness. No previous research has been conducted on any aspect of New Zealand's VAL system. Determining the point at which 'background' activity (level zero) becomes 'unrest' (level one) is seen as an issue (*pers. comm*. from GNS staff), particularly in the case of a volcanic crisis that is likely to result in significant societal impacts, such as caldera unrest (e.g., TVC in 2008), or unrest at Auckland Volcanic Field (AVF), New Zealand, which underlies a city of 1.4 million people. Concern has also been stated that the current VAL system does not allow for the recognition of heightened unrest, particularly at volcanoes that constantly show a level of minor unrest, because there is only one level representing unrest. For example, Ruapehu is predominantly in a state of unrest (VAL 1); when indicators of heightened unrest are identified, the VAL is not raised to 2 (minor eruptive activity) until the volcano is actually erupting.

In her PhD thesis, Carina Fearnley focussed on the standardisation of the USGS VAL system using a multi-sited ethnographic method, with a total of 18 weeks spent at USGS, spread between five observatories (Fearnley, 2011). This research provided an insight into the different cultures and processes relating to the multiple volcano observatories in the U.S., particularly the VAL system. However no volcanic crises were observed during her research, and due to the breadth of her study, she was unable to get into any great depth at each observatory. No in-depth investigations of volcano observatory practices over an extended time period have occurred globally, and no research on VALs during a volcanic crisis has been found.

In summary, the interaction of volcanoes and their products with society cause hazards, requiring careful management and effective communication. Caldera unrest in particular involves high levels of complexity and uncertainty in the outcome. Little is known about the intensity and impacts of past caldera unrest episodes in New Zealand. The point at which 'background' levels of activity are considered as 'unrest' is difficult to ascertain, and is not currently transferable between volcanoes. A VEWS encompasses the entire process of alerting people at risk to a potential threat. It includes an initial risk assessment; monitoring; data interpretation; the determination of the eruption threat; the decision to alert end-users; communication of the information; education of end-users; end-users' decisions to act and communicate warnings to the public, media and other stakeholders; further interpretation and decision-making process at the level of the public; and evaluation of the system through feedback. Little research has been conducted on New Zealand's VEWS, and none on the VAL system, which needs to be reviewed. Very little research has investigated influences on the decisions relating to the VAL system, and no research relating to VALs during a volcanic crisis has occurred globally.

1.3 Research Aims

1.3.1 Research objectives and questions

This research addresses gaps in our knowledge by aiming to:

1) Establish the context of New Zealand's Volcano Early Warning System
2) Explore New Zealand's VAL system, and how it is used
3) Identify ways to make New Zealand's VAL system more effective
4) Document the intensity and frequency of historical caldera unrest episodes at TVC

5) Ascertain the point at which the background level of multi-parameter activity at TVC becomes considered as volcanic unrest, using a method which can be applied to any volcano and tectonic setting.

These aims are guided by the initial research question posed of:

When a caldera volcano starts showing signs of unrest, at what point should the Volcanic Alert Level be raised?

Specific questions directing the research are:

a) How is volcano-related information communicated between scientists, the end-users, and the public in New Zealand?
b) What are the opinions of the research participants of New Zealand's VAL system?
c) What is the purpose of the VAL system?
d) How is the VAL system in New Zealand currently used by scientists and end-users?
e) What are the decisions involved in a VEWS?
f) What are the influences on the decision to determine the VAL?
g) Which aspects (if any) of New Zealand's VAL system can be improved, and how?
h) What are possible foundations of VAL systems?
i) How frequently and at what intensity has Taupo Volcanic Centre exhibited caldera unrest during historical times?
j) What constitutes volcanic 'unrest'?
k) How can the intensity of complex, multi-parameter volcanic unrest episodes easily be compared and communicated to non-scientists as a basis for their decision-making?

1.3.2 Outline of approach

The transdisciplinary nature of the management of a volcanic crisis and communication of complex volcanic information promotes a mixture of research frameworks and methods. A qualitative long-term ethnographic approach to investigating New Zealand's VEWS and VAL system allows an in-depth understanding of the culture of GNS Science and meanings placed on the systems. A historical chronology enables the past unrest activity at TVC to be explored, to assist with understanding future episodes. A literature review, complemented by discussions with a range of international scientists, allows the current state of knowledge of unrest precursors to be ascertained for the investigation of what constitutes 'unrest'. The creation of an innovative semi-quantitative tool based on that understanding enables a transferable method of assessing the intensity and frequency of volcanic unrest at any volcano. The integration of the findings of this research contributes towards a more effective VEWS for New Zealand, particularly for the scientific management of a caldera unrest crisis.

1.4 Structure of thesis

This chapter has provided an overview of the interaction between volcanoes and society, and factors contributing towards the effective management of volcanic crises to reduce deleterious impacts. Caldera unrest is identified as an example of a potential future volcanic crisis in New Zealand. Gaps in our knowledge are identified, and how this research can help fill those gaps is discussed, contributing to the effective management and communication of a volcanic crisis in New Zealand.

Chapter 2 reviews existing research relating to this topic in more detail. Context is provided on New Zealand's VEWS, structured according to risk knowledge, including New Zealand's volcanoes and caldera unrest (with further information in Appendix 2); New Zealand's volcano monitoring networks, including a description of New Zealand's government science organisation; dissemination and communication of warnings, including effective decision-making and VALs; and response capabilities, including a description of New Zealand's CDEM structure.

Chapter 3 provides the background and details on the methods used for the VAL investigation in this research, including why those methods were chosen. Chapter 4 presents the results of the exploration of New Zealand's VAL system. Chapters 5 and 6 describe the development of the Volcanic Unrest Index (VUI), and TVC's unrest history, respectively. These two chapters have been submitted to international journals for publication, and so are 'self-contained'. Therefore, some concepts and background information have necessarily been repeated. Statements describing the proportion of authors' contributions for Chapters 5 and 6 and Appendix 2 are included in Appendix 3.

Chapter 7 concludes this thesis by integrating the discussions, positioning the findings in the literature, and providing a conceptual framework for decision-making in EWSs based on the findings of this research. Finally, the major findings of this research and the potential implications are summarised.

CHAPTER TWO

NEW ZEALAND'S VOLCANO EARLY WARNING SYSTEM

2 NEW ZEALAND'S VOLCANO EARLY WARNING SYSTEM

2.1 Introduction

Chapter 1 provided an overview of the interaction between volcanoes and society, and the need for an effective VEWS. The communication of scientific information was acknowledged as a key component of warning populations about hazardous volcanic activity. Tools to communicate volcanic information were introduced, including VALs. It was recognised that New Zealand's VAL system is in need of review, and that there is currently limited knowledge about influences on VAL decisions. Volcanic unrest at caldera volcanoes was identified as an example of a volcanic crisis which will require careful management in the future. Chapter 1 also included the acknowledgement that it is difficult to distinguish volcanic unrest from normal, background activity at a volcano, and subsequently communicate this information to end-users. Gaps in our knowledge which were identified in Chapter 1 are discussed in Chapter 2, as is a description on how this research can help fill those gaps, contributing to effective communication and management of a volcanic crisis in New Zealand.

This chapter builds on the overview of EWSs provided in the previous chapter. An EWS can be described as having four elements, each with a two-way interaction with the other elements (Basher, 2006). These four elements (from UN/ISDR PPEW, 2006) are:

1) Risk knowledge
2) Technical monitoring and warning service
3) Communication and dissemination of warnings
4) Response capability.

This chapter is structured in alignment with these four elements (however the 'technical monitoring and warning service' section is referred to as 'GNS Science and volcano monitoring', as this is more consistent with New Zealand terminology). The volcanic hazardscape within New Zealand, including TVC and caldera unrest hazards, is discussed along with the potential impacts as the framework for risk knowledge. The evolution of the scientific agency with the responsibility to monitor and warn about geological hazards in New Zealand is described. Methods of communication and dissemination of warnings used in New Zealand are outlined, including aspects of effective decision-making and an overview of the VAL system.

The current CDEM organisational structure in New Zealand is described in alignment with ascertaining response capabilities.

2.2 Risk knowledge

Knowledge of hazards, likelihoods, consequences, and vulnerabilities combine in risk assessments to help prioritise the focus of EWSs. Increasing risk knowledge contributes towards the reduction of epistemic uncertainty (Marzocchi et al., 2012). To develop effective risk knowledge, it has been suggested by UN/ISDR PPEW (2006) that natural hazards be identified and assessed through systematic collection and analysis of data, including historical data. Potential consequences and vulnerabilities should be assessed, based on identified hazards. Roles and responsibilities of organisations need to be established (discussed further in sections 2.3 and 2.5), and information made accessible (UN/ISDR PPEW, 2006).

Through increasing risk knowledge, methods can be established to reduce those risks. Risk reduction is the process of "identifying and analysing long-term risks to human life and property from hazards; taking steps to eliminate these risks if practicable, and, if not, reducing the magnitude of their impact and the likelihood of their (sic) occurring" (MCDEM, 2007, p. 5).

The focus of this thesis is on the communication of volcano-related information in New Zealand. To set the context, the next section is an overview of New Zealand's volcanic hazardscape.

2.2.1 New Zealand's volcanic hazardscape

The North Island of New Zealand is situated on a tectonic plate boundary with the Pacific Plate in the east subducting beneath the Australian Plate in the west (Figure 2.1). This causes an area of back-arc rifting, with extension occurring at an average rate of 8 ± 2 mm/yr (Darby et al., 2000). This area of thin crust with magmatic upwelling is more susceptible to large scale volcanism, and is termed the Taupo Volcanic Zone (TVZ; Figure 2.2). The TVZ is up to 60 km in width and approximately 300 km in length, stretching from Ruapehu in the southwest to White Island in the northeast. The TVZ contains most of New Zealand's active volcanoes, which have a range in magma chemistry, past magnitude and frequency of eruptions, and eruptive styles.

The southernmost volcanic complex of the TVZ is the Tongariro Volcanic Centre, which includes the frequently active andesitic Ruapehu and Ngauruhoe/Tongariro stratocone volcanoes. New Zealand's worst railway disaster occurred in 1953 when 151 people were killed when a lahar from the Ruapehu Crater Lake destroyed a rail bridge as the Wellington to Auckland express train arrived, causing it to plunge into the Whangaehu River (Board of Inquiry, 1954). Lahars have frequently occurred, causing a hazard at various parts of the volcano (e.g., Leonard et al., 2008). Ruapehu hosts popular ski fields, and last erupted with vigour in 1995–96. The eruptions at this time resulted in a total volume ejected in the order of 0.1 km^3 (Hurst & McGinty, 1999). Small eruptions with short durations also occurred in October 2006 and September 2007; volcanic unrest is on-going.

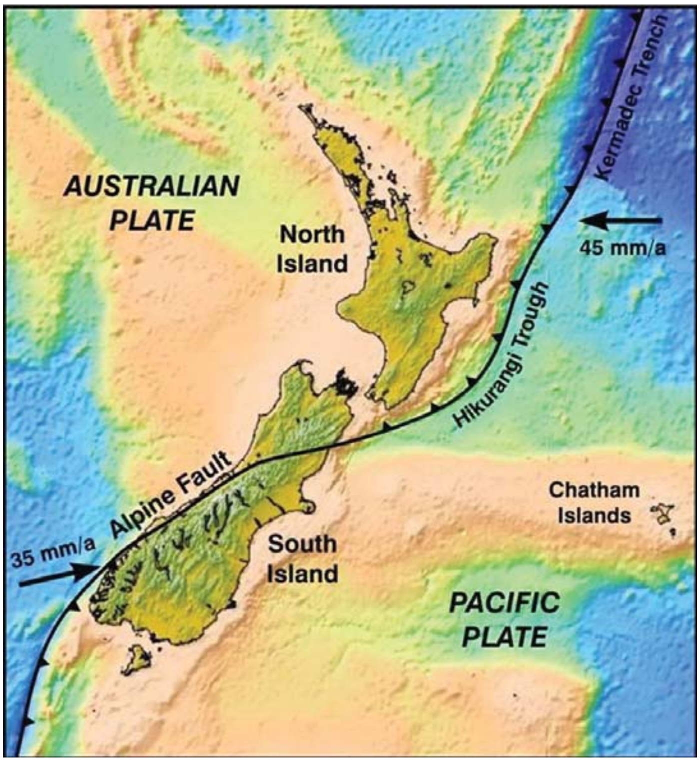


Figure 2.1. Tectonic setting of New Zealand. Convergence rates assume fixed opposing plates. Source: GNS Science.

Ngauruhoe is the most frequently active vent of the Tongariro massif, displaying regular eruptions until 1977 (Scott, 1978), and none since. Te Maari Crater and Red Crater on northern Tongariro were active in the late 19th Century, with frequent eruptions in 1896–97 (Scott & Potter, 2014). After less than one month of minor unrest, Te Maari Crater was the source of two small, short-lived phreatic eruptions on 6 August and 21 November 2012 (Figure 2.3). There were no casualties, however the tourism industry was impacted due to the closure of a popular walking track (the Tongariro Alpine Crossing) by the Department of Conservation (DoC), which manages the National Park.

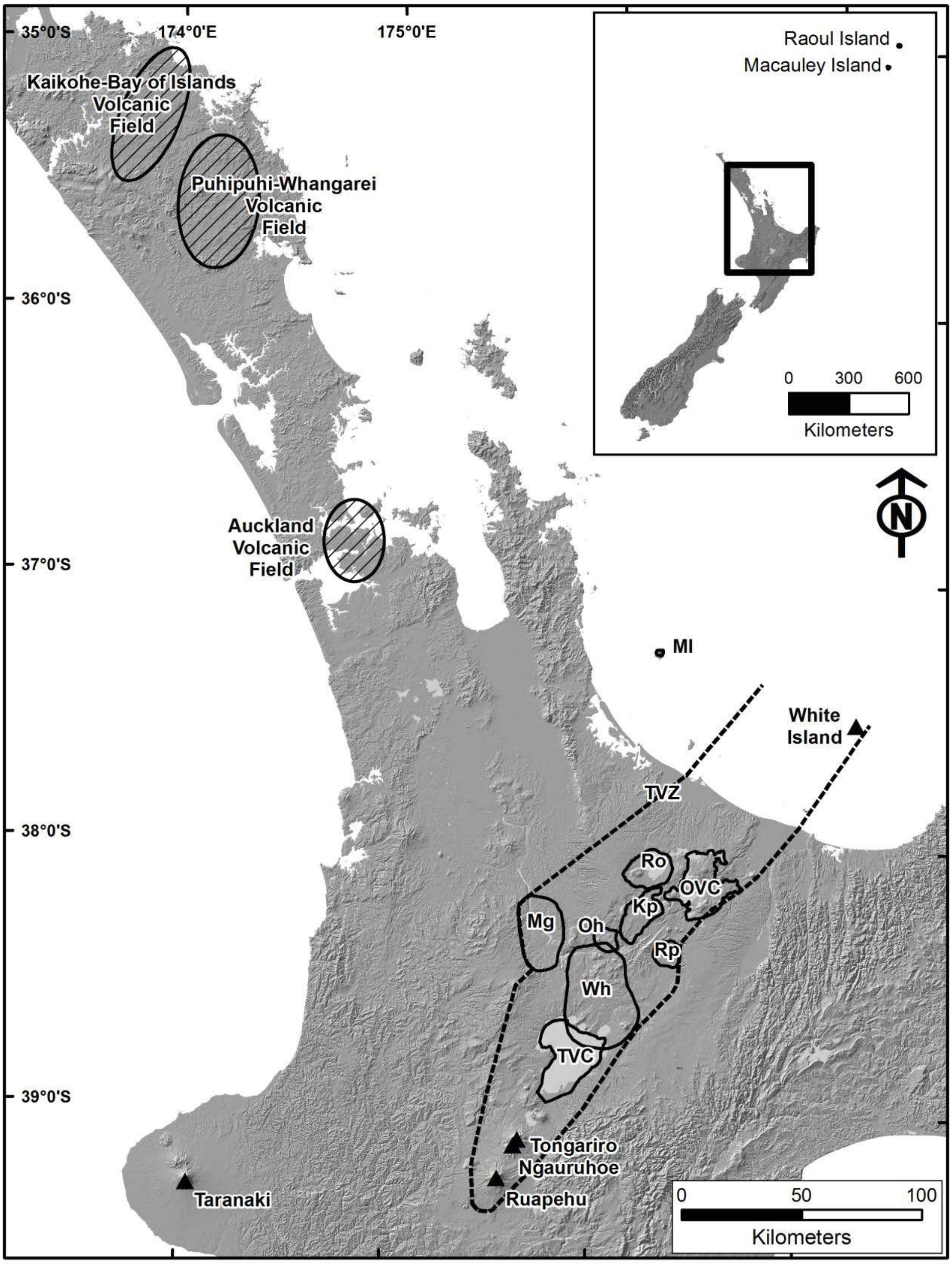


Figure 2.2. Map of New Zealand's potentially active volcanoes, based on Smith et al. (1993), Nairn (2002), Wilson et al. (2009), and Lindsay et al. (2010). The Taupo Volcanic Zone (TVZ; depicted as a dashed line) envelops the majority of the volcanoes. The calderas (polygons) are MI = Mayor Island; Ro = Rotorua; OVC = Okataina Volcanic Centre; Kp = Kapenga; Rp = Reporoa; Oh = Ohakuri; Mg = Mangakino; Wh = Whakamaru; and TVC = Taupo Volcanic Centre. The volcanic fields are indicated by ovals with diagonal lines. The inset map of New Zealand shows the location of Raoul and Macauley Calderas in the Kermadecs, and the box indicates the extent of the main map.

Figure 2.3. Eruption at Te Maari Crater, Tongariro, on 21 November 2012, captured by the GeoNet Te Maari Crater web camera. The eruption plume had a height of 3 to 4 km. Source: GeoNet, GNS Science.

There are eight caldera volcanoes in the central TVZ (Figure 2.2). Calderas are formed by overlying rock and eruption deposits collapsing into an evacuated magma chamber forming a depression many times greater than the size of individual vents (Lipman, 2000). Calderas can be created at a volcano with any type of magma, from basaltic volcanoes such as Kilauea (Hawaii, U.S.) to rhyolitic volcanoes such as TVC (Lipman, 2000). The size and geometry of calderas largely depends on the pre-existing host rock types, tectonic influences, magma chamber properties (such as size and shape), and the volume of material erupted (Lipman, 2000). Although calderas are usually formed from one or two very large eruptions, their magma system can also be the source of many smaller eruptions. The calderas in the TVZ have erupted almost exclusively rhyolitic material in at least 25 caldera-forming eruptions in the last 1.6 million years (Wilson et al., 1984; Wilson et al., 2009). Only <0.1% of the volume of deposits in all of the TVZ are from basaltic eruptions (Wilson et al., 1995).

The southernmost caldera of the TVZ is Taupo Volcanic Centre (TVC), source of the world's most recent 'super-eruption' (Self, 2006). Large calderas were formed at TVC 25,360 ±160 cal. years before present, during the 530 km^3 'Oruanui eruption'; (Wilson, 2001; Wilson et al., 2006; Vandergoes et al., 2013), and during the most recent eruption in 232 ±5 AD, during the 35 km^3 'Taupo eruption' (Wilson, 1993; Davy & Caldwell, 1998; Hogg et al., 2012). The explosive Taupo eruption devastated a significant portion of the central North Island in widespread pyroclastic density currents (Wilson & Walker, 1985). However 26 of the 29 eruptions at TVC in the past 26,000 years have been much smaller than the most recent eruption (Wilson et al., 2009). Therefore it is unknown whether future eruptions at TVC will be relatively small, as has been the case most frequently, or devastatingly large, as was the case with the most recent eruption. Because of this risk, Tilling (1989, p. 262) stated that "an important adjunct to hazards mitigation research is the better characterization of unrest at dormant calderas and its bearing on the probability of renewed caldera-forming eruptions." This characterisation of unrest at TVC is addressed in Chapter 6. Taupo township is situation on the north-eastern shore of Lake Taupo, which fills TVC. It currently has a population of approximately 22,000 people.

Of the eight calderas in the TVZ, Okataina Volcanic Centre (OVC) erupted most recently. OVC has been the source of multiple, mostly rhyolitic eruptions for over 550,000 years (Cole et al., 2010; Leonard et al., 2010). The 1314 AD Kaharoa eruption formed large lava domes and caused block-and-ash flows, erupting 4 km^3 of material over a period of about four years (Leonard et al., 2010). This was the largest eruption in New Zealand in the past 1,000 years, and is the most recent rhyolitic eruption (Johnston et al., 2004; Leonard et al., 2010). The most recent eruption from OVC was a basaltic rift eruption in June 1886 AD at Tarawera. The eruption occurred from a 17 km vent lineation (Nairn, 1991), and killed 108 people (e.g., Scott & Travers, 2009). This is the largest eruption to have occurred in New Zealand's recorded history. The nearby Waimangu hydrothermal area was the location of four deaths in 1903, and two in 1917 from hydrothermal eruptions (Scott & Travers, 2009). New Zealand's other calderas, including Rotorua Caldera with its proximal Rotorua city, are described in Appendix 2.

The north-eastern extremity of the TVZ contains White Island (Whakaari), a privately owned andesitic stratocone located 50 km from the Bay of Plenty coastline. It is New Zealand's most frequently active volcano, and a popular tourist destination with approximately 25,000 tourists and tourist operators visiting the island per year. Frequent eruptive sequences have been documented since written records began in 1826, with constant unrest and intermittent eruptive episodes (Nairn et al., 1991). The only known casualties at White Island resulted from a large landslide, which reached a sulphur factory situated within the breached crater area, killing 10 workers in 1914 (Scott & Travers, 2009). Following a period of relative quiescence lasting over a decade, White Island is the site of the most recent eruptive episode in New Zealand (at the time of writing, October 2013), which began in August 2012 and continued throughout 2013. Heightened levels of unrest occurred prior to and throughout this eruptive episode, often including high levels of tremor and vigorous steam activity. Minor to moderate explosive phreatomagmatic eruptions (Figure 2.4) and the extrusion of a lava dome in the crater occurred. This eruptive episode, along with the recent Tongariro eruptions, provided an opportunity for observations to take place on how the VAL system was being used by monitoring scientists at GNS Science. White Island activity also provided the context to observe the range in scientists' perceptions of what constitutes background and unrest activity at a volcano which is far from dormant.

Figure 2.4. Eruption at White Island on 20 August 2013, captured by the GeoNet Crater Rim web camera. The eruption plume had a height of about 4 km. Source: GeoNet, GNS Science.

A number of other volcanoes lie beyond the TVZ. Mayor Island is the upper portion of a rhyolitic shield volcano with a summit caldera, situated offshore in the Bay of Plenty (Figure 2.2), and was last active about 1000 years before present (Buck, 1985; Houghton & Wilson, 1986; Houghton et al., 1995b). The Kermadec Islands (including Raoul and Macauley Calderas) host a chain of mainly submerged volcanoes 750–1000 km to the northeast of New Zealand (see inset map of Figure 2.2). Raoul Island is the site of the most recent eruption from a caldera within New Zealand's territory, with a small phreatic eruption occurring in March 2006, unfortunately killing a DoC worker who was collecting water samples from a crater lake. This eruption was preceded by minor unrest, similar in intensity to multiple other episodes of unrest at the volcano, which had not resulted in an eruption (Cole et al., 2006).

Taranaki/Egmont Volcano is a stratocone located in the west of the North Island (Figure 2.2). The steep-sided cone began forming more than 130,000 years before present (Neall, 2003). It has a history of explosive eruptions and sector collapses. In approximately 1650 AD eruption deposits covered Maori ovens (umu), demonstrating an interaction with the early native population (Druce, 1966). Taranaki/Egmont is thought to have last erupted in 1755 AD (Druce, 1966), but it may have subsequently extruded lava, forming a dome after this date (Platz, 2007). It is capable of fairly large eruptions, and has a history of sector collapse (e.g., Neall, 2003). Taranaki/Egmont Volcano is surrounded by productive agricultural land and is in a major hydrocarbon (gas and oil) production region. There is a regional population of just over 100,000 people, most of whom live in the city of New Plymouth (Statistics NZ website[1]).

The intraplate Puhipuhi-Whangarei and Kaikohe-Bay of Islands Volcanic Fields (note that sometimes these are collectively referred to as Northland Volcanic Field), and Auckland Volcanic Field (AVF) are in northern New Zealand. Puhipuhi-Whangarei Volcanic Field is thought to have been active as recently as 0.26 Ma (K-Ar dates), while dating of the Kaikohe-Bay of Islands Volcanic Field indicates an eruption occurred in 0.06 Ma (Smith et al., 1993), or perhaps as recently as in 200–500 AD (Kear & Thompson, 1964). AVF has had more than 50 basaltic eruptions from different vents, most recently approximately 600 years ago (e.g., Needham et al., 2011). Auckland city hosts a third of New Zealand's population with 1.4 million residents, and is sited directly on top of AVF. A nation-wide exercise called Exercise Ruaumoko took place in 2008 focussing on the build-up to an eruption at AVF (Lindsay et al., 2010). The scientific details for the scenario were created by a volcanologist from GNS Science, and presented for discussion to the Auckland Volcanic Science Advisory Group (AVSAG), which has members from multiple scientific agencies. After discussion of the data, scientists from GNS Science determined the VALs and scientific information was disseminated in VABs to Auckland city CDEM personnel, national governmental decision-makers at MCDEM, and responders from many other regions and fields. End-users coordinated response actions including a hypothetical evacuation, and the exercise ceased at the point of eruption (Lindsay et al., 2010).

Eruption hazards specifically associated with New Zealand's volcanoes are outlined in the Ministry of Civil Defence *Volcanic Hazard Information Series* (also known as the Yellow Book

[1] www.stats.govt.nz, accessed on 28 October 2013

series; e.g., Froggatt, 1997), which are targeted at end-users. Eruptions from most of New Zealand's volcanoes are likely to impact infrastructure of national importance, including many State Highways and road networks, electricity lines and hydropower stations, train lines, water supplies, and sewage facilities (Wilson et al., 2012). Additionally, industries important to the local, regional, and national economies may be threatened during future eruptions, including the tourism, agricultural, forestry, and hydrocarbon industries.

2.2.2 Caldera unrest

Volcanic unrest is caused by the interaction of magma and/or its fluids and gases with surrounding existing rock and any fluid it contains (e.g., geothermal systems and groundwater). Unrest manifests as seismicity, ground deformation, degassing, and geothermal system changes. Unrest phenomena may be detected by monitoring techniques, and they may be severe enough to be observed by nearby residents and visitors, to the point where the unrest can be hazardous. Ground shaking, ground deformation, poisonous gas emissions, and geothermal system activity are examples are unrest hazards. It has been identified that caldera unrest is a significant component of New Zealand's hazardscape (Johnston et al., 2002). Many calderas worldwide are located amid densely populated regions, creating the potential for hazards relating to unrest to eventuate. For example, Campi Flegrei Caldera in Italy is situated on the outer metropolitan area of Naples, which has a population of 3.8 million people. Campi Flegrei has undergone frequent and intense episodes of unrest in the past few centuries (particularly since 1970), some of which have prompted mass evacuations, but the volcano has not erupted since 1538 AD (e.g., Di Vito et al., 1999). As another example, Rabaul Caldera, located on the eastern end of New Britain Island, Papua New Guinea, was home to 70,000 people when it experienced intense episodes of unrest in 1983–84 without resulting in an eruption (e.g., McKee et al., 1985). Ten years later, in 1994–95, two reasonably small eruptions within the caldera occurred (Davies, 1995a).

Understanding the hazards posed by caldera unrest contributes towards an assessment of risk. A gap in the knowledge-base is details about the potential impact on New Zealand society resulting from caldera unrest, and the intensity and frequency of past unrest episodes. The latter knowledge gap is addressed in Chapter 6, with an assessment of the unrest which has been observed at TVC. An overview of the hazards of caldera unrest and potential consequences on vulnerable communities, as has been observed internationally, is discussed in the present section. Much of this information, in addition to mitigation strategies and information on significant international unrest episodes, is included and elaborated on in

Appendix 2 (including a world map of locations of calderas mentioned in the text of this thesis – see Figure 11 of Appendix 2). Appendix 2 is a direct copy of GNS Science Report: 2012/12 by Potter, Scott and Jolly (2012), entitled 'Caldera unrest management sourcebook', and is also available on the GNS Science publications website (http://www.gns.cri.nz/Home/Products/Publications, as accessed on 28 October 2013). The vast majority of that sourcebook, which is written for end-users and other non-scientists, was written by me during my literature review for this thesis (see attached statement of contribution in Appendix 3). It includes information that cannot be incorporated here due to word limit constraints on this thesis.

2.2.2.1 Physical hazards resulting from caldera unrest

Volcanic unrest can be hazardous even if no eruption occurs. Injuries and fatalities have occurred at calderas around the world during unrest episodes, as well as during periods of quiescence. The physical hazards described below are no different to those seen at other types of volcanoes during unrest. Information relating to caldera unrest hazards needs to be communicated before and during unrest episodes. A combination of the following unrest phenomena may occur at varying levels of severity and frequency.

Ground shaking

Earthquakes are the most common expression of volcanic unrest and eruptive activity (Newhall & Dzurisin, 1988). Volcanic processes generate a wide variety of seismicity. These may be reflecting sub-surface processes such as the movement of magma and/or related fluids and gases, eruptive activity, or post-eruption readjustment (McNutt, 2000). Earthquakes near volcanoes are termed 'volcanic earthquakes' and can have the same impacts on society as tectonic earthquakes. In some cases seismicity is only detected if monitoring is adequate, while in other cases it will be felt locally and may cause alarm. Earthquakes can occur in swarms, which are defined by McNutt (2000, p. 1095) as "a group of many earthquakes of similar size occurring closely clustered in space and time with no dominant main shock"; or they can be isolated events, affecting localised areas.

Volcanogenic earthquakes are thought to predominantly occur at a magnitude of two to three, and rarely exceed magnitude five (Richter scale). Larger earthquakes can also occur during unrest; for example, multiple magnitude six earthquakes occurred during a caldera unrest episode at Long Valley Caldera, California, U.S., in 1980 (Mader & Blair, 1987). Long Valley Caldera contains the small ski resort town of Mammoth Lakes, which is the tourism base for the popular ski field on Mammoth Mountain. Mammoth Lakes experienced three magnitude six earthquakes within one day in May 1980, causing scientific concern of volcanic unrest (Hill, 1998). Following years of continued unrest and perceived impacts on the business and tourist industry (discussed further below), a particularly intense seismic swarm caused power outages in 1983. While there were no reported casualties, these earthquakes prompted volcano-related emergency plans to be made and an alternative road to be built for potential future evacuations (Mader & Blair, 1987; Hill, 1998).

Earthquakes during eruptions have caused deaths at volcanoes due to building collapse (or partial collapse; Blong, 1984), and they can cause structural and infrastructure damage (Johnston, 1997; Zobin, 2001). Collapsing brick chimneys can fall through building roofs; the rupturing of gas lines and electrical circuits may lead to fire; and broken water pipes can cause flooding (Blong, 1984). Liquefaction can occur in areas with sand and gravel substrates, especially near low gradient waterways, if the earthquakes are of sufficient magnitude. Fissures can be formed on the ground surface, potentially causing damage to roads and destruction of buildings and underground services.

Ground deformation

Ground deformation at volcanic centres can take place as a result of magmatic processes, such as subterranean magma movements, occurring before, during, and after eruptions (e.g., Murray et al., 2000). As volcanoes, particularly large caldera systems, tend to lie in active tectonic environments they may also be influenced by regional deformation, such as rifting. Horizontal and vertical deformation can cause damage to buildings and infrastructure but are not usually directly life threatening. The deformation can range from millimetres to metres, can affect a wide area, and may cause fissures (e.g., Murray et al., 2000). Uplift and subsidence can cause flooding through altered water courses, or from ground subsidence below the water level (as seen at TVC in 1922 (Morgan, 1923), and in Pozzuoli, Campi Flegrei over a number of centuries (e.g., Dvorak & Mastrolorenzo, 1991; Bellucci et al., 2006)).

Uplift was observed during unrest at Rabaul Caldera, as described by McKee et al. (1985), when the rate increased from a background level of 8 mm per month in the 1970's to an average rate of 50 mm per month from November 1983 until May 1984. The maximum amount of uplift during an individual crisis was 100 mm, while the total amount of uplift between 1971 and 1984 was 3.5 m (McKee et al., 1985). Occasional episodes of increased seismicity and deformation were observed over the next decade, and the 1994 eruption was preceded by 6 m of uplift in a space of a few hours (Nairn & Scott, 1995). This example demonstrates the potential rate of deformation and total uplift which may be seen during unrest at calderas.

Poisonous gas emissions

Volcanic gases are commonly emitted at volcanoes and geothermal areas through fumaroles, hot springs, and other areas of the ground surface (Stix & Gaonac'h, 2000). Volcanic gases include carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrochloric acid (HCl), hydrofluoric acid (HF), hydrogen sulphide (H_2S), and radon (Rn), as well as heavy metals and water (H_2O) (Stix & Gaonac'h, 2000). Interpretation of geochemical data from monitoring volcanic fluids and gases can indicate the source and movement of magma, interactions with hydrothermal and meteorological fluids, and types of potential eruptions (Stix & Gaonac'h, 2000).

Documented health effects of volcanic gases include discomfort and/or asphyxiation due to the accumulation of gases in topographic lows; respiratory effects (and occasionally deaths) from exposure to acidic sulphate aerosols formed from sulphur dioxide, primarily in geothermal areas; as well as long-term health effects (e.g., Blong, 1984; Hansell & Oppenheimer, 2004). Many casualties caused by volcanic gas exposure were effected during volcanic unrest, rather than eruptions (Blong, 1984).

High levels of gas in soil during unrest can cause areas of vegetation to die, and can impact animal life. This has been observed during unrest at Mammoth Mountain (e.g., Sorey et al., 2000; Hill, 2006); Rotorua Caldera (Durand, 2007); Furnas Volcano (Azores, Fructuoso, 1583, cited in Baxter et al., 1999); and Rabaul Caldera (Fisher, 1939, cited in McKee et al., 1985).

Approximately 70,000 people reside on an active geothermal field at Rotorua Caldera, New Zealand. Potentially dangerous and damaging levels of gas are emitted in parts of Rotorua city, discharged from cracks in paving, waste water drains, in low and narrow spaces, and inside buildings (Durand & Scott, 2005). 14 people have been killed in Rotorua by H_2S and CO_2 gas poisoning or asphyxiation in the past century (Durand & Scott, 2005). These casualties have occurred in small, low, contained spaces such as natural hot spa baths.

In Cameroon, 1986, approximately 1700 people were killed by volcanic gas when a build-up of CO_2 was released suddenly from the waters of Lake Nyos (at the summit of a volcano) and flowed down the slopes to a nearby town (Baxter et al., 1989). While there is a Crater Lake at Ruapehu, based on data from 1991, Christenson (1994) found that a Lake Nyos-type gas release is unlikely at that volcano. At Rabaul in 1990, CO_2 gas killed six people who were collecting eggs in a small depression (Rabaul Volcano Observatory, 1990). At Mammoth Mountain, three members of a ski patrol died from toxic levels of CO_2 in 2006 after falling into a snow cave melted by a fumarole (Cantrell & Young, 2009).

Further information on health hazards resulting from volcanic gases is provided by Hansell and Oppenheimer (2004) and the International Volcanic Health Hazard Network (www.ivhhn.org).

Geothermal system changes

A magma body may provide additional heat, gas, and fluids, which interact with the overlying geothermal system during volcanic unrest. This can result in changes to the flow, temperature, and/or chemistry of fumaroles and springs. Ground shaking (from tectonic or volcanic processes) can also alter underground cracks and pressure systems, resulting in hydrothermal changes (Vandemeulebrouck et al., 2008). As the temperature and/or pressure of the geothermal system increases, activity at surface features and gas emissions can increase, and potentially result in hydrothermal explosions (Browne & Lawless, 2001). No magma is erupted in a hydrothermal eruption, by definition (Nairn, 2002; Nairn et al., 2005), however they can still be very dangerous, as demonstrated by the prehistoric hydrothermal eruption from Rotokawa (approx. 10 km northeast of Taupo township, and TVC) 6060 ± 60 years ago, which deposited ejecta over an area with a diameter of 4 km (Browne & Lawless, 2001). Many of the casualties from the 1886 Tarawera rift eruption in OVC were caused by a large magmatic-hydrothermal eruption at Lake Rotomahana (Nairn, 1979; Simmons et al., 1993; Browne & Lawless, 2001).

As a complication for volcanic eruption forecasting, hydrothermal explosions can also occur without the influence of magma, from changes in rainfall, barometric pressure, landslides, earthquakes, or due to exploitation (e.g., drilling and fluid extraction) (Bromley & Mongillo, 1994). Additionally, inadequate borehole maintenance can cause failure of the casing and the leaking of hot fluids, resulting in hydrothermal eruptions in residential areas, as occasionally occur in Rotorua city.

2.2.2.2 Socioeconomic impacts of caldera unrest

Societal and political impacts

Social impacts of unrest may include a decline in the tourism industry; impacts on the national, regional, and local economies; media speculation and misreporting; self-evacuations; and temporary psychological distress, particularly from frequent earthquakes (Johnston et al., 2002). Initial reactions to a volcanic unrest episode are likely to include fear, confusion, and denial, as seen at the town of Mammoth Lakes in Long Valley Caldera in 1982 (Mader & Blair, 1987), and in Pozzuoli (near the centre of Campi Flegrei Caldera) during unrest in 1970 when an evacuation order for 3,000 people was issued (Barberi et al., 1984). Repeated earthquakes can have a detrimental effect on nearby communities, leaving the population on edge and waiting for the seismic swarm to cease so they can respond to damage. Unrest may cause a heightened feeling of uncertainty in the community as it is unknown whether the unrest will escalate to culminate in an eruption or die away. This may prevent life from being lived as it normally would be for potentially long periods of time. Education institutes may close, and some members of the community may leave town to gain a sense of normalcy elsewhere. This decreases the workforce, potentially having a flow-on effect on businesses and the local economy (Johnston et al., 2002).

Perceived effects of unrest on the community and economy can tempt public officials and politicians to put pressure on scientists to lower VALs, or remove the label of 'volcanic unrest' from the situation. Tensions between the two groups can heighten until there is a sense of mistrust, in part due to high levels of uncertainty and the lack of timely information. Mader and Blair (1987) describe how these consequences of unrest occurred at Mammoth Lakes during the 1979–84 unrest episode at Long Valley Caldera, when a few of the officials and local business owners attempted to lessen the impact on the tourism and local investment industries. Mistrust between scientists, public officials, and the public can also influence elections and result in delays in actions (for example, evacuations). The outcome of the local elections at Mono County (the area which includes Long Valley Caldera and Mammoth Lakes) in 1983 may have been affected by the coinciding caldera unrest (Mader & Blair, 1987). While not a large, rhyolitic caldera, similar societal and political effects from a VAL change were experienced at Quito (Ecuador), due to unrest at the neighbouring Guagua Pichincha volcano in 1998 (Metzger et al., 1999). Here, pressure was laid on scientists by the tourism industry to lower the VAL (Metzger et al., 1999). A high level of interagency communication and public information management is required during volcanic unrest to minimise the potential for these issues to occur.

The public and media are likely to demand information from public officials and scientists during unrest episodes, as seen during the 1983–85 unrest episode at Rabaul Caldera (Lowenstein, 1988). Special arrangements had to be made, including establishing a regular newsletter and a Public Information Unit to fulfil this need. Similarly, daily information meetings were well attended by the public during the 1983 seismic swarm at Long Valley (Mader & Blair, 1987). In these situations, information relating to caldera unrest needs to be communicated effectively for it to be understood by those who need it (e.g., Mileti & Sorensen, 1990).

Economic impacts

The economic effects of a long period of unrest are varied, and depend on factors such as the duration; magnitude of activity; type, strength and flexibility of businesses; and degree of uncertainty (Johnston et. al., 2002).

Local tourist and real estate industries may be adversely affected, as experienced at Taupo township during and immediately after the 1963–64 episode of unrest at TVC (Johnston et al., 2002), and in the ski-season of 1982–83 at Mammoth Lakes, Long Valley Caldera (Mader & Blair, 1987). However in the latter example, the effect of unrest on the tourism industry, while easily blamed on volcanic unrest, is hard to prove or measure due to contributing circumstances including the national recession, coincidental poor weather, and perceived overbuilding at Mammoth Lakes during the early 1980s (Mader & Blair, 1987). Nonetheless, premature business closure and self-evacuations are likely to affect the image of tourist towns at calderas, and the confidence of tourists in visiting. The effect on tourism may be short-lived if the unrest declines, as shown by the almost record ski season of 1983–84 at Mammoth Lakes, despite the unrest earlier in the year (Mader & Blair, 1987). A marketing campaign by the businesses of Mammoth Lakes in 1984 appeared to have successfully boosted tourist numbers (Mader & Blair, 1987). However, in some cases the increase in business uncertainty may disrupt the local economy for years to decades.

The investment market at Mammoth Lakes was hit harder by the caldera unrest than the tourism industry (Mader & Blair, 1987). This appeared to be due to the perceived risk on short-term visitors being less than the “constant threat” on long-term property investments. The decline in the real estate market was blamed on the potential for volcanic hazards (Mader & Blair, 1987). The insurance industry is also likely to be affected during caldera unrest, largely due to repeated and potentially damaging earthquakes. Changes by insurance agencies can include not reinsuring, cancelling cover, or changing what the insurance includes. After the 1983–85 Rabaul Caldera unrest episode, building insurance was restricted and had a high cost, resulting in a lack of finance from lending institutions (Lowenstein, 1988).

Historical caldera unrest episodes worldwide have resulted in a range of consequences, which prompted various degrees of response. These included developing effective evacuation routes, constructing alternative wharves and airstrips, updating plans, decreasing exposure by moving business supplies away from hazardous areas, and mass evacuations (e.g., Barberi et al., 1984; Mader & Blair, 1987; Davies, 1995a). Further information on mitigation strategies for unrest is included in Appendix 2.

2.2.2.3 Caldera unrest management challenges

In addition to mitigating the hazards and possible societal consequences caused by caldera unrest, the management of a caldera unrest crisis involves dealing with high levels of uncertainty. The uncertainty stems from the short duration of unrest records, and the infrequency of caldera eruptions causing difficulties with determining the intensity and range in duration of unrest episodes prior to an eruption. Additionally, the proportion of unrest episodes that do not lead to an eruption (and associated potential for 'false alarms'), and the range in possible magnitude and style of eruptions contributes towards heightened uncertainty. The outcomes of volcanic unrest were summarised by Moran et al. (2011) as deep intrusion; shallow, stalled intrusion; sluggish, viscous magmatic eruption; and rapid, often explosive, magmatic eruption (Figure 2.5).

The ability to forecast whether intruded magma will stall (i.e. parts 1 and 2 of Figure 2.5), or reach the surface and erupt (i.e. parts 3 and 4 of Figure 2.5) partly depends on the monitoring and interpretation of unrest phenomena. Due to the lack of evidence left by most volcanic unrest phenomena in the geological record, knowledge of unrest episodes is restricted to the duration of literate human occupation.

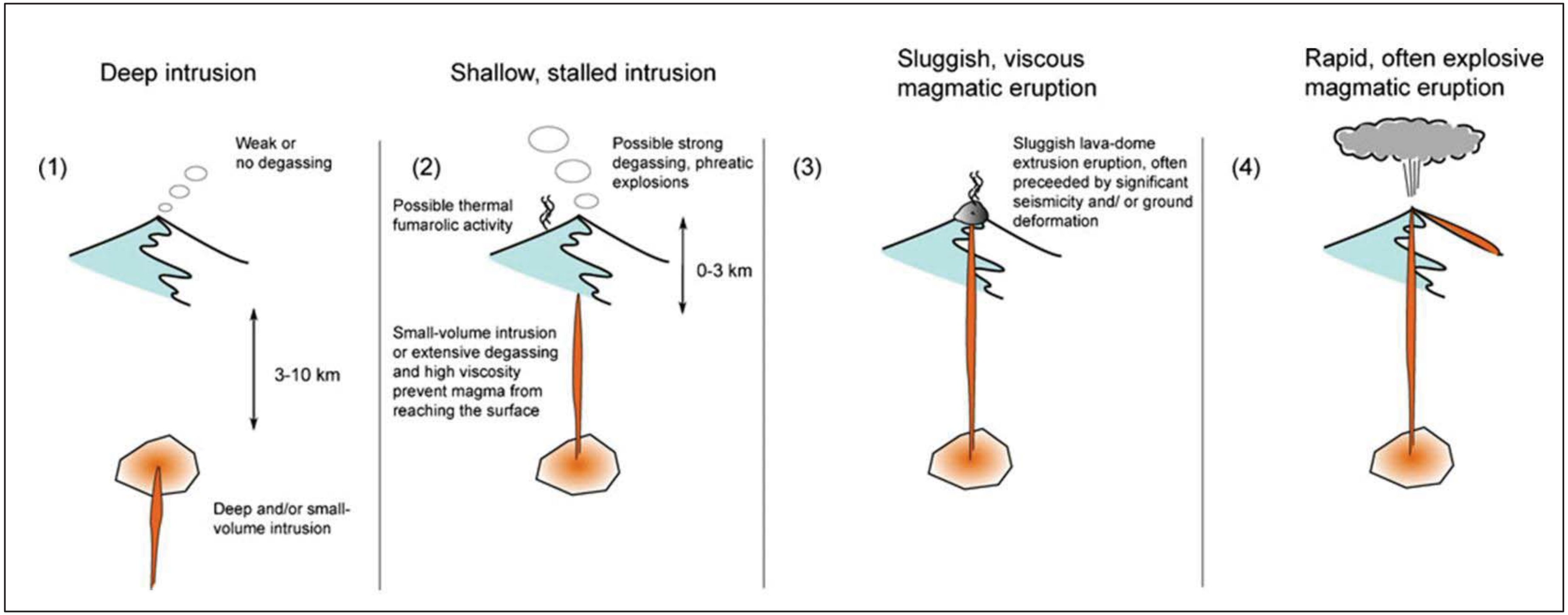


Figure 2.5. Possible outcomes of volcanic unrest resulting from magmatic processes. Source: Moran et al. (2011, p. 117).

Very few historical caldera-forming eruptions have occurred; the record, adapted from Lipman (2000), contains:

- Pinatubo (Philippines, 1991 AD)
- Fernandina (Galapagos Islands, 1968 AD)
- Katmai (Alaska, U.S., 1912 AD)
- Krakatau (Indonesia, 1883 AD)
- Tambora (Indonesia, 1815 AD)
- Kilauea (Hawaii, U.S., 1750–1790? AD)
- Kuwae (Vanuatu, ~1450 AD)
- TVC (New Zealand, 232 ± 5 AD; Hogg et al., 2012, although the nearest population was over 2000 km away, in Australia)
- Santorini (Greece, 3600 years before present).

Few of these eruptions were witnessed at a distance close enough to experience and record preliminary unrest phenomena, and many of them were not at the scale of the larger caldera-forming eruptions in the geological record. This lack of witnessed precursory unrest creates uncertainty over the intensity of unrest that may be observed prior to future caldera-forming eruptions. Therefore, knowing the full range in intensity of potential unrest is difficult. Intense unrest occurred at Rabaul (McKee et al., 1985) and Campi Flegrei (Barberi et al., 1984) calderas in the early 1980s, but did not result in an eruption (until 10 years later at Rabaul). Given this uncertainty in unrest intensity, it is also a challenge to ascertain what intensity constitutes background activity and the point at which it can be considered as unrest (e.g., Jolly et al., 2008).

Also stemming from the infrequency of eruptions at large calderas (i.e. >5 km in diameter), the duration of unrest episodes prior to an eruption is uncertain, and seems to be largely dependent on the definition of unrest used. In 1994, Rabaul Caldera erupted after only 27 hours of intense unrest, following nearly a decade of relatively low levels of unrest (Davies, 1995b), whereas Campi Flegrei has had decades of on-going unrest, without resulting in an eruption (as of the time of writing; e.g., Dvorak & Gasparini, 1991; Del Gaudio et al., 2010). Analysis of reported global unrest between January 2000 and July 2011 by Phillipson et al. (2013) found that the average duration of pre-eruptive unrest at large calderas (a total of 12 volcanoes) was two months, twice the duration of pre-eruptive unrest episodes at stratocones.

However, non-eruptive unrest at calderas was found to be significantly longer in duration than non-eruptive episodes at stratocones (Phillipson et al., 2013). These authors also found that a longer inter-eruptive period at a volcano does not necessarily indicate a tendency for longer pre-eruptive unrest duration.

A key challenge associated with determining the outcome of unrest episodes is ascertaining the likelihood of an eruption to occur, based on the proportion of non-eruptive to pre-eruptive unrest episodes. Phillipson et al. (2013) found that 52% of reported unrest episodes at large calderas resulted in an eruption. This is similar to the finding by Newhall and Dzurisin (1988) that 48% of unrest episodes at calderas result in an eruption. However, only one in six episodes of unrest were found to have resulted in an eruption at large silicic calderas which have not erupted for at least 100 years (Newhall & Dzurisin, 1988). Thus, the outcome of any unrest at large silicic calderas is highly uncertain, with a range of possibilities from no eruption to a very large catastrophic eruption, causing difficulties in managing the response to volcanic unrest at caldera volcanoes. A number of factors promote and resist the ascent of magma from depth, to the surface (Moran et al., 2011). These are summarised in Figure 2.6.

Instances in which "magma reaches but does not pass the 'shallow intrusion' stage, i.e., when magma gets close to, but does not reach, the surface" are defined by Moran et al. (2011, p. 115) as "failed eruptions". 'False alarms' can occur when warnings of an impending eruption are issued, but the eruption does not occur. False alarms may be detrimental because of the potential impact on society and the economy, particularly at caldera volcanoes due to the associated perception of the size and impacts of an eruption. The impact of an apparent false alarm on scientific credibility is also an issue for successful mitigation, as identified by Newhall and Punongbayan (1996b).

However, as stated by Banks et al. (1989, cited in Tilling, 1989, p. 263)

> "It seems prudent to treat every occurrence of unmistakable precursory activity as having the potential for eruption and to advise emergency-response officials accordingly. With this prudent approach, "false alarms" (actually aborted eruptions) will be unavoidable… If society wishes to maximize effective response to warnings of volcanic hazards, it must be prepared to accept the unavoidable false alarms. False alarms themselves can provide, through objective assessment of the scientific and public response to a volcanic crisis that ended without eruption, valuable lessons useful in making

or improving contingency plans for the next crisis, which could culminate in an eruption."

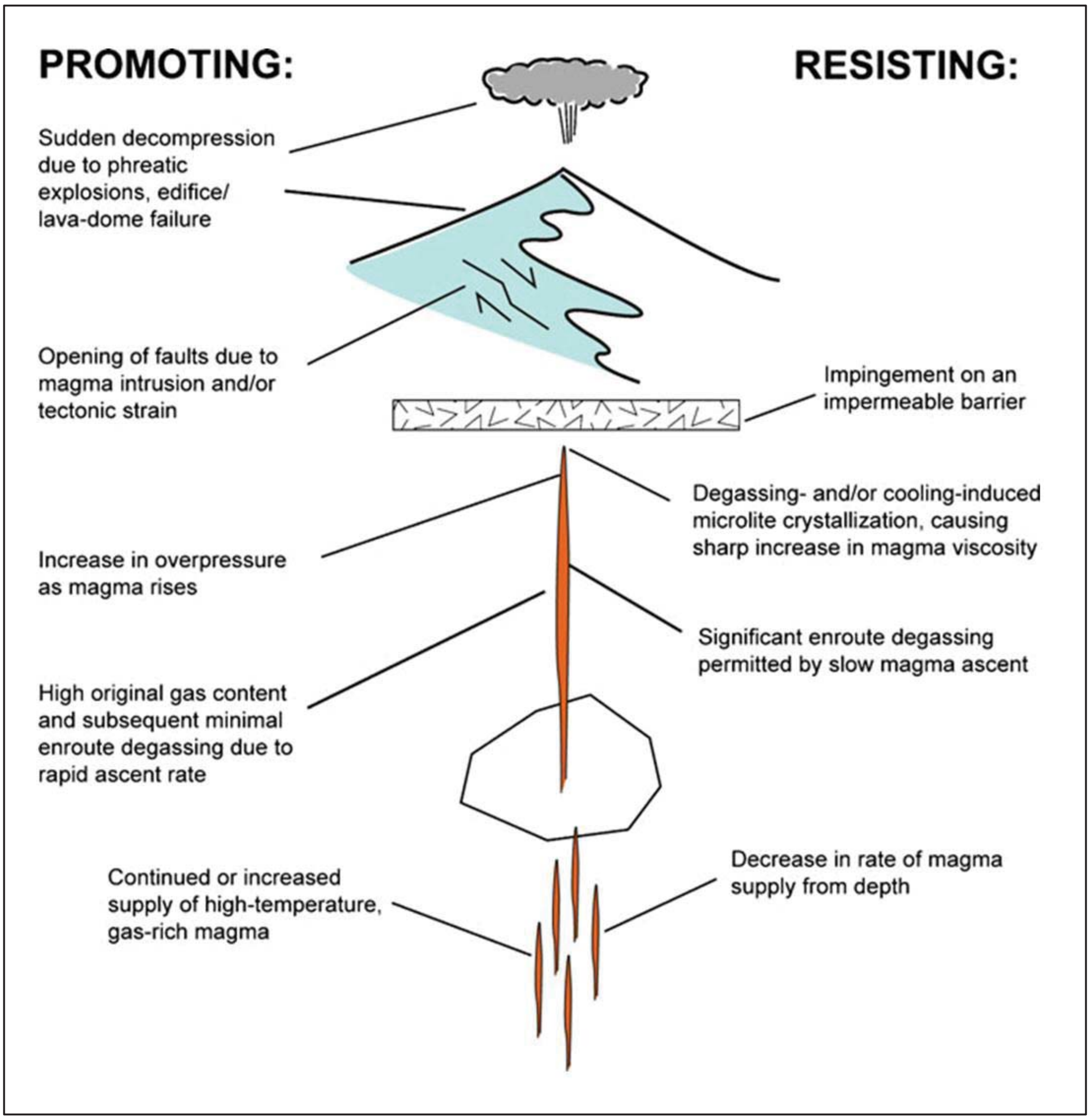


Figure 2.6. Schematic illustrating factors that may promote and resist the ascent of magma. Source: Moran et al. (2011, p. 119).

While it might be difficult to identify "unmistakable precursory activity" due to the uncertainties involved, the point of the paragraph remains valid. The uncertainty involved in potential failed eruption situations can be addressed through risk assessments, consideration of the precautionary principle (e.g., Stirling, 2007), and the effective communication of scientific information (e.g., Banks et al., 1989, cited in Tilling, 1989; Marzocchi et al., 2004;

Moran et al., 2011). This is particularly important for caldera unrest and other instances of failed eruptions, which may result in so-called false alarms.

Dow and Cutter (1997) researched the influence of warning fatigue from previous 'false alarms' on the decision made by the public to act during warnings prior to hurricanes in Eastern United States. They found that there was in fact only a minor influence as a result of warning fatigue, compared to the individuals' assessment of storm characteristics and their confirmation of information from multiple sources (mainly media). Whilst the intention of the public to evacuate during hurricanes in the future are not influenced greatly by 'false alarms', there was a significant reduction in the perceived credibility of government officials (Dow & Cutter, 1997). These researchers identified that the public's decision to evacuate prior to a hurricane was made on an individual basis, taking into account the social context and their understanding of the hazard. This is likely to be due to rigorous education programmes, and implies that for the most effective management for reduction of societal risk in a community faced with a hazard, a wide range of related information should be made available to give the public an appropriate basis for their decision (Dow & Cutter, 1997).

Determining the vent location of a potential eruption may be more difficult at large calderas, particularly those with multiple vents generated without a temporal pattern, compared to at a single-vent volcano. This can cause uncertainty in providing spatial and impact-related hazard and forecasting information. Forecasting the potential eruption magnitudes, styles, and hazards may also be difficult due to the range in past eruption activity. At Rabaul Caldera, there were initial concerns that the small eruptions in 1994 could lead into a large eruption (Davies, 1995a). Eruptions have (so far) continued at a smaller scale. At TVC in the past 27,000 years, the frequency of caldera-forming eruptions is far out-weighed by the frequency of smaller eruptions (Wilson, 1993). However, as the most recent eruption was caldera-forming, determining the magnitude, style, hazards, and vent location of the next eruption will be difficult.

2.2.2.4 Caldera unrest at Taupo Volcanic Centre

Four previously recognised episodes of historical caldera unrest have occurred at TVC in 1895, 1922, 1964–65, and 1983 (e.g., Johnston et al., 2002). These episodes have included deformation, hydrothermal activity, mainshock-aftershock tectonic earthquake sequences, and earthquake swarms. Locations of earthquake epicentres that occurred during these four episodes are depicted in Figure 2.7. The episodes resulted in public alarm, self-evacuations, and an impact on the tourism industry. Additionally, "notable changes in background activity" occurred in 1996–99 and 2008, sparking the question of "what constitutes unrest at Taupo Caldera?" (Jolly et al., 2008). A brief overview of these six (potential) unrest episodes, as recognised prior to the findings of the current research, is provided below.

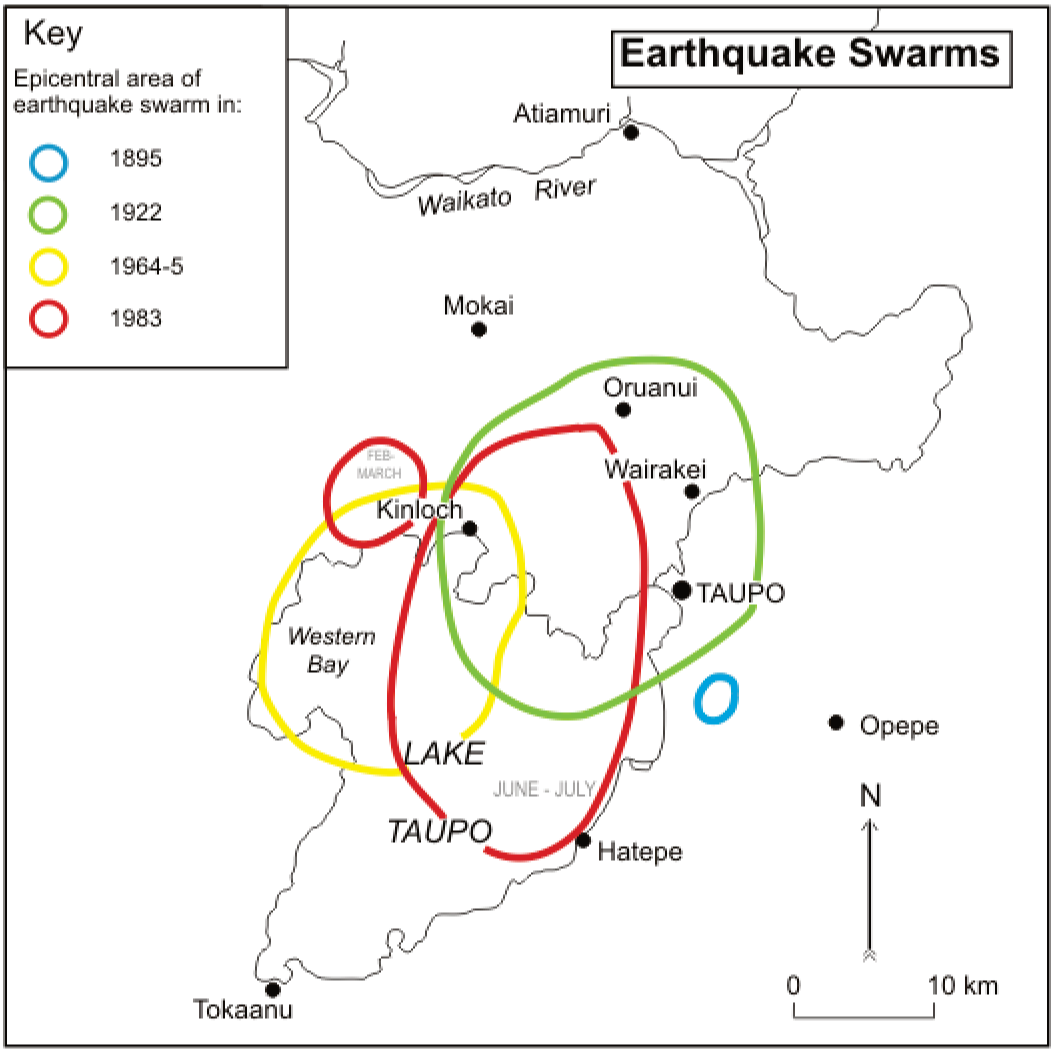


Figure 2.7. Epicentre locations for earthquake swarms in 1895, 1922, 1964–5, and 1983 at TVC, represented by coloured polygons. Selected settlement names are provided. Source: based on maps by Morgan (1923), and Grindley and Hull (1986); reproduced from Johnston et al. (2002).

Unrest in 1895 began on 17 August with an earthquake of shaking intensity MM8 (Eiby, 1968) striking Taupo and causing widespread damage. Most of the town's chimneys collapsed, bottles and crockery were smashed, and "chaos reigned supreme" (Poverty Bay Herald, 19 and 20 August 1895). Landslides blocked roads around the lake, and residents and visitors camped outside overnight. A 0.6 m wave was observed on Lake Taupo, and springs in the Hatepe region emitted quantities of fine pumice (Hawke's Bay Herald, 20 August 1895). Springs changed temperature and tremors continued until at least September 1895 (Poverty Bay Herald, 2 September 1895).

An episode of unrest occurred in 1922, with many damaging earthquakes felt in and around Taupo. Fissuring and faulting, landslides, and minor changes to activity at hot springs and geysers were reported. Subsidence of 3.7 m on the northern side of Lake Taupo caused a sunken shoreline, and hundreds of water fountains were observed (Evening Post, 14 July 1922). Several chimneys collapsed in communities around Taupo; bottles, crockery, books, and other items were thrown on the floor; and the Taupo town clock stopped.

From September 1964, earthquakes increased in number and intensity, peaking in December 1964 with magnitudes of up to 4.8 (Eiby, 1966). 140 events were reported per day and over 1100 earthquakes over magnitude 2.7 were felt in two months (Gibowicz, 1973). Seismicity decreased again until February 1965, and there was a further small swarm in December 1965. The epicentres migrated from the Western Bay of Lake Taupo in early December 1964, to northern Lake Taupo by 21 December and then to slightly north of Hatepe by January 1965 (Gibowicz, 1973). Possible uplift of 90 mm in the latter area was observed (Grindley & Hull, 1986); no further faulting or deformation was reported.

Seismicity clustered in February and June 1983 with up to 30 earthquakes recorded a day. Uplift of 55 mm was followed by equivalent subsidence at a block west of Kaiapo fault, which ruptured on 23 June (Otway et al., 2002). Minor damage from the earthquakes was reported, including cracked chimneys and fallen ornaments (Otway et al., 1984).

Increased seismicity was observed between 1997 and 1998, accompanied by uplift with a maximum rate of 1 cm per year measured on the eastern side of the caldera between 1996 and 1999 (Johnston et al., 2002; Peltier et al., 2009).

In April to October 2008 a seismic swarm was recorded at TVC by the GeoNet monitoring networks, with 13 earthquakes over magnitude 3, and a notable increase in the number of small magnitude earthquakes. Uplift of approximately 30 mm at Horomatangi Reef was recorded during 2008, and was interpreted to be a shallow, inflating source (Jolly et al., 2008). It is this episode of unrest which prompted the research question for this thesis of 'when a caldera volcano starts showing signs of unrest, at what point should the Volcanic Alert Level be raised?'

This summarised record of caldera unrest at TVC relies on episodes previously identified in the literature; it does not include results from any in-depth investigations into the early record, nor does it integrate geothermal phenomena with deformation and seismic unrest parameters. This has left a gap in the knowledge-base, causing difficulties with accurately determining the likelihood of unrest to result in an eruption, with understanding the average and range in duration of unrest, and with ascertaining the potential range in intensity of unrest. This knowledge gap is addressed in Chapter 6.

2.3 GNS Science and volcano monitoring

The establishment of interagency protocols and continuous monitoring of potential hazards acts as a basis for the generation of warnings. In New Zealand, GNS Science is the agency appointed by the Government to provide scientific advice to local, regional, and central government organisations for geological hazards, as stated in Guide to the National CDEM Plan (MCDEM, 2006) and the MCDEM/GNS Science Memorandum of Understanding (GNS Science & The Ministry of Civil Defence and Emergency Management, 2009). GNS Science is similar to Geological Survey institutions in other countries, and is a Crown Research Institute (CRI). New Zealand's volcanoes have been monitored by GNS Science through the GeoNet project since 2001 (Scott & Travers, 2009), funded primarily by the New Zealand Earthquake Commission (EQC). The collection and refinement of volcano-related data by scientists requires large amounts of time and effort, and yet the data need to be interpreted for maximum value for end-users (Ronan et al., 2000; Figure 2.8). Scientists from universities assist with monitoring and interpretation of volcano data, and in the communication of the related information.

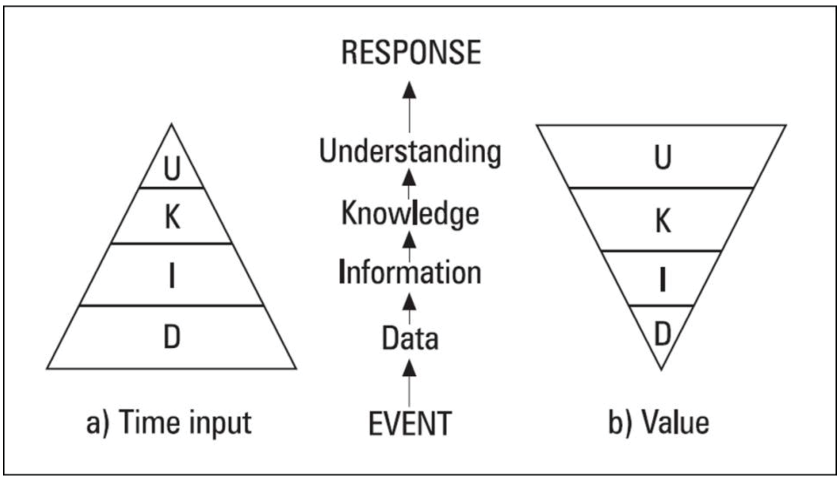


Figure 2.8. The value associated with the time input for each stage in the data-to-understanding transition for volcanology. Source: Ronan et al. (2000, p. 342).

The next section provides an overview of the evolution of government scientific organisations in New Zealand, with a focus on volcanology.

2.3.1 GNS Science and its forerunners

The first detailed geological exploration of New Zealand was undertaken in 1858 by Austrian Ferdinand von Hochstetter (Burton, 1965). Provincial geological surveys were commenced following this, and the New Zealand Geological Survey (NZGS) was established in 1865. NZGS was directed by James Hector and resourced by the Government, which had only been formed 13 years beforehand (Atkinson, 1976). The NZGS experienced a shrinkage in both funds and staff numbers in the mid-1880s due to politics and the economic depression (Burton, 1965), unfortunately coinciding with the 1886 Tarawera eruption, resulting in limited data capture.

Recommendations for further resources and how science in New Zealand should be organised began to emerge from 1916 (Burton, 1965). Demands from various industries for a coordinated scientific research programme came to a head when Sir Frank Heath, director of the British Department of Scientific and Industrial Research (DSIR) visited New Zealand in 1926 (Atkinson, 1976). He produced a proposal for the Government indicating the need for New Zealand to set up its own version of DSIR to help aid the growth of the national economy. The Scientific and Industrial Research Act was passed on 31 August 1926, and the new Department was created, with Dr Ernest Marsden named the Secretary (Atkinson, 1976). Throughout his tenure, Dr Marsden attempted to group research units of DSIR Divisions and Universities due to his "conviction that the day of the individual scientist working alone was nearly ended, and that, in future, teams of workers from complementary disciplines would be needed to solve the complex problems of industry" (Atkinson, 1976, p. 26). From the outset, DSIR was given an advisory role instead of an administrative role. "This has enabled its officers to give scientific opinions on a wide range of topics, from a strictly impartial position. […] DSIR built an enviable reputation for accuracy and impartiality that was respected by both sides in many arguments" (Atkinson, 1976, p. 201).

In the first few decades of the DSIR, various divisions were created and disbanded to incorporate a diverse range of sciences into the Department, reflecting the flexible organisational structure envisioned by Dr Marsden (Atkinson, 1976). A DSIR Regional Office was created in the town of Rotorua in 1945 (Burton, 1965), and included a Volcanologist position, which was filled by James Healy. The Dominion Observatory in Wellington was the hub of earthquake observations, and this was incorporated, along with the Magnetic Survey, Ionosphere, and Geothermal Research branches of DSIR, and the Geophysical Survey section of the Geological Survey, into the newly formed Geophysics Division of DSIR in April 1951 (Atkinson, 1976). The Tangiwai railway disaster in 1953 confirmed the need for more rigorous monitoring of Ruapehu, and prompted the suggestion to include it in the recently developed volcanic research programme (Board of Inquiry, 1954). At this stage there were seven seismographs throughout New Zealand – this number increased to 28 by 1976 (Atkinson, 1976).

The Geophysics Division focused its attention on the Wairakei geothermal power plant (10 km from Taupo township) in the mid-fifties. At a similar time, extensive magnetic surveys were undertaken throughout the country, including the volcanic areas. The first geophysical volcano monitoring site was established in 1956 at the Chateau, on Ruapehu (Atkinson, 1976). The year prior to this, the Division of Nuclear Sciences was created within DSIR, combining the isotope and nuclear physics sections (Atkinson, 1976). This Division began to encompass nuclear research and became the Institute of Nuclear Sciences in 1959.

By the late 1960s, monitoring at White Island by Victoria University of Wellington included deformation surveys, and temperature and gas observations (e.g., Clark, 1970). A nation-wide gravity survey was virtually completed in 1972. The National Civil Defence Planning Committee on Volcanic Hazards was set up in October 1980, with members across a number of organisations (Dibble et al., 1985). Information was gathered on the volcanoes of New Zealand, the associated risks, and eruption probabilities.

In 1990 major restructuring of DSIR took place, amalgamating 23 divisions into 10 (Clark, 1992). As part of this restructuring, NZGS amalgamated with the DSIR Geophysics Division, forming a new DSIR Geology and Geophysics Division (Wilson, 1990). DSIR was then disestablished as a result of the Government restructuring New Zealand's science sector on 1 July 1992, forming ten CRIs (Christie, 1993). One of these CRIs was the Institute of Geological and Nuclear Sciences Limited (IGNS), a combination of several disestablished DSIR Divisions, including Geology and Geophysics, Nuclear Sciences, Engineering Seismology, and most of the Geochemistry Divisions (Christie, 1993). The personnel based in the Rotorua office moved to Wairakei at this time; the other offices were in Gracefield, Lower Hutt, and Kelburn (all within the Wellington Region); and Dunedin (Christie, 1993). IGNS operates under the Companies Act 1993 and Crown Research Institutes Act 1992 (Callan, 2008). In 2006 IGNS rebranded to become GNS Science, however the registered company name remains the Institute of Geological and Nuclear Sciences Limited.

The UN Guiding Principles for Effective Early Warning (IDNDR Early Warning Programme Convenors, 1997) recommends the "sole responsibility for the issuance of early warnings for natural and similar disasters should rest with an agency, or agencies, designated by the Government". In New Zealand, this responsibility has been assigned to GNS Science, utilising the GeoNet monitoring project, which is described in the next section.

2.3.2 Volcano monitoring in New Zealand

Monitoring volcanoes and the interpretation of resultant data assists with the detection of precursory unrest and the communication of warnings. This contributes towards the protection of life and property from hazardous eruptions (e.g., Scott & Travers, 2009). Developing a monitoring programme during periods of quiescence is important in order to record levels of background activity. This assists with the recognition of activity which is beyond normal levels, i.e., volcanic unrest. Integration of parameters is important for optimum volcano monitoring (Tilling, 1989). The interpretation of monitoring data provides a basis for determining the VAL.

Volcano monitoring in New Zealand began during the 1945 Ruapehu eruption (Hurst, in Gregory & Watters, 1986; Scott & Travers, 2009). Over time, potential consequences and therefore the risk associated with volcanic hazards have amplified through an increase in population, which is reflected in the development of monitoring technology and network density, and through increased scientific understanding. Since 2001, monitoring of New Zealand's volcanoes has been undertaken by the GeoNet project, operated by GNS Science (Scott & Travers, 2009). Monitoring techniques used include visual observations, including webcams; seismographs; deformation monitoring (e.g., Global Positioning System (GPS) networks, tilt, and levelling); and gas and chemical measurements (Scott & Travers, 2009). Geological investigations also assist with determining the magnitude and style of past eruptions, as well as analysing eruption deposits to give an indication of what might be expected in the future. Most of the monitoring stations transmit data in near real-time, enabling two duty officers to respond to pager alerts. The monitoring network aims to "strike a balance between cost and the need for accurate and reliable data" (Scott & Travers, 2009, p. 266). Further to the information below, a description of the monitoring of each of

New Zealand's volcanoes and an explanation of techniques used is provided on the GeoNet website (www.geonet.org.nz).

The first seismometer for volcano monitoring was installed in 1952 at Tongariro Volcanic Centre (Hurst, in Gregory & Watters, 1986). The network was slowly expanded to monitor the active volcanoes in New Zealand with either a single seismograph for isolated island volcanoes, or a multi-site network for mainland volcanoes (Scott & Travers, 2009). Seismic monitoring at TVC was installed in 1985 (Sherburn, 1992). There are currently seven seismic monitoring stations surrounding Lake Taupo.

Ground deformation monitoring techniques at New Zealand's volcanoes have included Electronic Distance Measurement equipment (EDM), precise levelling, and more recently, GPS, tilt monitoring, and InSAR. Lake Taupo (and other large water bodies within volcanoes) has been used as a giant spirit level to record vertical ground deformation since 1979 (Otway et al., 2002). There are nine telemetered GPS monitoring sites around TVC, including one within the lake on Horomatangi Reef, near the location of the most recently active vent. Additionally, there are a number of campaign levelling sites which are visited to ascertain 'background' levels, or as needed during an unrest crisis.

GeoNet monitors volcanic gas chemistry (including at fumaroles), the rate of gas emissions (e.g., CO_2 and SO_2 flux), and the chemistry of crater lakes and thermal springs. LiCor and Interscan gas detectors are used in conjunction with correlation spectrometer (COSPEC) and FLYSPEC airborne measurements. A mini-DOAS system at White Island, also used temporarily at Te Maari craters on Tongariro, provides near real-time geochemical measurements. Temperatures of emissions are also obtained. Soil gas surveys are undertaken periodically at a number of the volcanoes. Crater Lake levels and temperatures, and the rate of water discharge of the lakes are also recorded where possible. At TVC, deep bores are sampled annually.

Monitoring calderas can be difficult when they are filled by large water bodies, such as Lake Taupo and Lake Rotorua. For example, Ellis et al. (2007) demonstrated that a hypothetical inflation event involving up to 10 km^3 of magma could almost entirely be hidden beneath Lake Taupo. Selecting monitoring sites at large calderas may also be difficult due to the uncertainty of the location of the next eruption vent. There can also be uncertainty in determining where to undertake gas flux monitoring at calderas many kilometres in diameter (such as Yellowstone, OVC, and TVC), due to an unknown future vent location.

New Zealand has a number of rapid detection monitoring and warning systems. Due to the risk of lahars on Ruapehu's ski fields, the Ruapehu Lahar Warning System was commissioned in 1984, and upgraded following the 1995 eruptions, becoming known as the Eruption Detection System (EDS) (Sherburn & Bryan, 1999; Scott & Travers, 2009). This system is designed to detect eruptions which may cause lahars on the Whakapapa ski field. Once triggered, an automated lahar warning message is broadcast across Whakapapa ski field. Another system is the Eastern Ruapehu Lahar Alarm and Warning System (ERLAWS), which was initiated to warn responders about the collapse of the Crater Lake natural dam, so mitigation measures could rapidly be put in place along the Whangaehu River. Both EDS and ERLAWS are operated, monitored, and maintained by the primary land manager of Mt. Ruapehu (DoC), with support from GeoNet and GNS Science (Leonard et al., 2008).

Technology used to monitor volcanoes is developing over time, becoming more sensitive and accurate. This enables micro-earthquakes, deformation in the order of millimetres, and real-time changes in gas concentrations to be observed, which were not observable in the past. Additionally, data transmission is improving, enabling real-time coverage, and processing software can provide more complete and accurate pictures of subsurface processes. These advances in the amount, timing, and accuracy of data should improve the capabilities of scientists to warn of impending hazards. However, more data does not necessarily equate to more information, as people are required to sift through the incoming data to find the information required for their decisions (Endsley, 2000). Decisions need to be made on whether these small magnitude changes equate to volcano unrest, and whether events of that size should be communicated as a warning.

2.4 Dissemination and communication of warnings

Communication between agencies and the dissemination of scientific information is critical to the effective management of a volcanic crisis, including during caldera unrest (e.g., Fiske, 1984; Peterson & Tilling, 1993; Newhall & Punongbayan, 1996b; McGuire et al., 2009). Warnings should be "generated and disseminated in an efficient and timely manner and in a format suited to user needs" (UN/ISDR PPEW, 2006, p. 6). The organisation that is the source of the warnings needs to be recognised in legislation or government policy in an appropriate way, and strategies developed to build credibility and trust in the warning system with the minimisation of false alarms (UN/ISDR PPEW, 2006). In New Zealand, GNS Science issues scientific advice on geohazards, as stated in a Memorandum of Understanding with MCDEM

(GNS Science & The Ministry of Civil Defence and Emergency Management, 2009). Discussions are held in collaboration with university scientists (both during crises and quiescence), and information disseminated in a variety of formats. Aspects of achieving effective communication of scientific information are described in the next section, followed by an outline of communication tools used for disseminating volcanic information (including for aviation, and VALs) and New Zealand's National Warning System (NWS). The decisions involved with forecasting and warning about volcanic activity are then investigated, including influences and other aspects on decision-making under uncertainty.

2.4.1 Effective communication of scientific information

Warnings of volcanic activity need to be adequately disseminated in order to be useful (Newhall, 2000). Scientific information must be communicated in an appropriate form, and be understandable to end-users, the media, and the public, who have a wide range in their level of existing knowledge (Tilling, 1989). Scientific information is used in various ways, including contributing towards general knowledge, and informing important and consequential decisions impacting people's lives, livelihoods, and the economy.

Scientists can find it difficult to explain technical information to non-scientists, especially when met with a hostile audience and journalists who write inaccurate articles. Specific communication advice for scientists, Emergency Management Committees, and the media during a volcanic crisis is provided by the "communication during volcanic emergencies" guidelines for stakeholders at Caribbean volcanoes (Benfield Greig Hazard Research Centre, 2003), and is summarised in Appendix 4. A balance needs to be achieved between limiting errors in measurements and estimates of risk and eruption forecasts, and maintaining credibility and specificity, in order to retain trust and promote actions by end-users (Voight, 1990). In order for local authorities, media, and response personnel to understand and believe the issues facing the community, effectively prepare for it, and heed warnings, scientific information needs to be in an appropriate style, and contain appropriate content (Mileti & Sorensen, 1990). The style of the warning message needs to be clear, specific, accurate, certain, and consistent, while the content considered as important includes the hazard or risk, location, time, source of the warning, and guidance (Mileti & Sorensen, 1990). These style and content factors can be cross-tabulated (Table 2.1) to ensure an effective message is generated.

Table 2.1. Template to cross-tabulate the content and style of a message to assist with communicating an effective warning. Source: Reproduced from Mileti and Sorensen (1990, p. 3.10).

Message style	**Message content**				
	Hazard	Location	Guidance	Time	Sources
Specificity					
Consistency					
Accuracy					
Certainty					
Clarity					

Unfortunately, due to the inherent complexity of volcanic systems, often any one of the factors described by Mileti and Sorensen is missing (Peterson & Tilling, 1993). This is because despite slowly reducing epistemic uncertainties through increasing knowledge and scientific developments, the level of aleatoric uncertainty is irreducible (Woo, 1999; Marzocchi et al., 2012). The misunderstanding of uncertainty in volcanic information, and precautionary actions taken in response to this information by emergency management agencies are often confused by the public for incompetence, as found in research conducted at Montserrat by Haynes et al. (2008). In the communication of warnings, uncertainty is increasingly being acknowledged by scientists in the form of probabilistic statements. Doyle et al. (2011) discuss the inclusion of information relating to uncertainty in risk assessments. They review the psychological literature on communication of uncertainty, stating that there is conflicting advice on whether the inclusion of uncertainty increases or decreases levels of trust and credibility of the information provider. The phrasing of context provided with a probability has been found to influence the comprehension of the information (Doyle et al., 2011). Strong relationships between the information provider and its end-users is critical to the effective use of science advice (Doyle et al., 2011).

Conflicting scientific advice in the public arena during a volcanic crisis can cause difficulties in reducing the impact on end-users. This occurred at La Soufrière volcano on the eastern Caribbean Island of Guadeloupe in 1976, as described by Fiske (1984). In this crisis, initial eruptions triggered the evacuation of 72,000 people from the slopes of the volcano, resulting in hardship for the evacuees, and economic and political repercussions, particularly due to the impact on the tourism industry. A very large eruption seemed imminent, and the evacuation was supported by one team of scientists. However, a separate team of scientists maintained from the outset that no such eruption was going to take place, that there would be adequate warning if a large eruption was about to occur, and that the evacuation was unnecessary. The disagreement between the two teams of French scientists became public, with debates aired on television, in magazines and newspapers, and in a book. Civil authorities did not know who to believe, and an international panel of experts was consulted. The recommendation was made that the volcano posed a lesser degree of hazard, and the evacuation was immediately called to an end. The activity at the volcano continued to decrease without resulting in a large and hazardous eruption. The disagreements between the scientists in the public domain had been the focus of the media more than the volcanic activity (Fiske, 1984). Potential actions during future crises to reduce the chance of disagreements of scientists in the public arena were identified as:

1) restrict the access of journalists to the scientific headquarters, where robust scientific debates occur;
2) limit interviews to a few scientists or an information officer who recognises their responsibility to present cross-disciplinary scientific information (and not focus on their speciality);
3) determine consistent messages for presentation to the media (Fiske, 1984).

Open disagreement can exacerbate public and civil defence personnel's distrust of the scientists, decreasing the perceived credibility and authority of the latter (IAVCEI, 1999). It is thought that there should be one official source of information, which should be the government (Gross, 2003), including the affiliated scientists. In New Zealand, the potential problem of conflicting science advice is being addressed through the development of science advisory groups. Currently, there is a Tsunami Expert Panel, and four volcanic advisory groups: Taranaki Seismic and Volcanic Advisory Group (TSVAG), Auckland Volcanic Science Advisory Group (AVSAG), the Central Plateau Volcanic Advisory Group (CPVAG) for Tongariro Volcanic Centre volcanoes, and the Caldera Advisory Group (CAG). Some of these volcanic advisory groups focus on the coordination of scientific advice between science agencies, by providing an avenue for scientific input and debate. Others are more focussed on end-user planning and raising awareness among stakeholders. All are driven by regional councils, and have mixed membership including scientific agencies and end-users. Through meeting every three to six months, these groups provide the opportunity to forge interagency relationships before a crisis occurs. Additionally, during volcanic crises, university scientists (and occasionally end-users) often contribute to monitoring data and interpretation discussions led by GNS Science, and provide advice, such as laboratory results from tephra analysis, and flow hazard modelling for hazard maps.

Peterson and Tilling (1993) noted that due to the long periods of quiescence at caldera volcanoes, communities tend to not understand the related hazards, and of those that do, some may ignore the danger in order to promote commercial growth. Scientists who issue warnings may be met with antagonism and scepticism if the community is not prepared for the hazard, if they cannot see, feel, or hear any signs, or if the level of uncertainty is high (Newhall & Punongbayan, 1996b). Members of the public, civil defence and response personnel, and managers of land surrounding volcanoes have an existing understanding and perception of volcanoes and their hazards and risks. This is likely to be based on what they have heard from friends and family (i.e. predominantly other non-experts), what they have experienced, and what they have witnessed through media (e.g., on TV, movies, radio, and the internet). The communication of scientific information thus 'competes' against possibly incorrect prior knowledge built over a lifetime of experience and rumours. The scenario in which there is a relatively high chance of conflict between scientists and the public is during unrest at a large and potentially explosive volcano which has not erupted for more than 100 years, and where there have been previous "false alarms" (Peterson & Tilling, 1993). This scenario of interagency conflict occurred at Mammoth Lakes, Long Valley Caldera in 1982 (as discussed in section 2.2.2.2; Mader & Blair, 1987), and may occur at TVC, New Zealand. Trust in providers of scientific advice is clearly an important element of achieving an optimal response in a volcanic crisis (e.g., Peterson & Tilling, 1993). Haynes et al. (2008) found that the high level of trust in scientists at Montserrat was based on high perceived levels of reliability, openness, integrity, and competence.

Response agencies, including local, regional, and national government organisations in the New Zealand CDEM system, often pass scientific information on to other end-users and the public. In order to do this effectively, they need to consider the information and decision needs from several perspectives, including where the information was obtained, collaborative agencies, and the receivers of the information (Paton et al., 1998b). The wide range of end-users' roles and experience results in differences in their information needs. For example, ash thickness and composition information can be interpreted differently by each of the civil aviation, agriculture, conservation, utility, and transport sectors, as they use it for diverse purposes and decisions (Angrosino, 2008). This information is further modified according to variations in spatial distribution, meteorological and temporal factors, and chemical interactions (e.g., interactions between ash and water or soil), contributing to the complexity of the end-users’ decision-making (Ronan et al., 2000).

It should be recognised that volcanologists usually understand volcanoes and their hazards better than anyone else, including planning and response personnel. It is thought that assisting end-users with the responsibility of protecting communities by providing volcano-related response advice should be a high priority for volcanologists (Tilling, 1989; Tilling & Lipman, 1993). However, it is also noted in the literature that the provision of scientific advice is seen to be better separated from political emergency management advice (e.g., Newhall, 2000). This is in order for science advice to be issued free from political pressure. Therefore, there is a ‘grey area’ between the provision of scientific and response advice, which volcanologists are sometimes pressured to cross during discussions with decision-makers (e.g., Marzocchi et al., 2012). The relationship between scientists and decision-makers was tested during the recent L’Aquila earthquake in 2009, in an example of this grey area of roles and responsibilities (Cartlidge, 2011). Emergency management and law enforcement officials require certain advice from scientists in order to protect affected communities, e.g., to determine areas to evacuate and to restrict access, and for decisions relating to search and rescue operations (Peterson & Tilling, 1993). However, these decisions require knowledge of economic impacts, population distribution and vulnerability, infrastructure capabilities, politics, and many other factors which are outside the expertise of most scientists (Marzocchi et al., 2012). There is the risk that scientists could be held accountable in an eruption which causes casualties where response advice is given outside their realm of expertise (see Cartlidge, 2011 for an overview of the L'Aquila situation; Marzocchi et al., 2012).

2.4.2 New Zealand’s communication tools for volcanic activity

It has been identified that locally appropriate communication methods should be established for the distribution of warnings (IDNDR Early Warning Programme Convenors, 1997). Volcanic information in New Zealand is communicated using a number of methods and tools. A one-way communication of information (with prior multi-directional input) is provided before, during, and after volcanic crises through presentations by scientists during meetings (including multi-agency crisis response meetings), conferences, workshops (including an annual ‘volcanic short course’ for stakeholders, led by GNS Science), and public lectures; on websites (including text, photos, schematics and YouTube videos); in scientific and non-scientific publications; and via the media. Likewise, emails, faxes, pager alerts, and SMS text messages provide one-way scientific information to registered end-users during crises or changes in volcanic activity.

Volcanic ash impact posters[2] (a product of the Volcanic Impact Study Group, commissioned by the Auckland Engineering Lifeline Group) provide accessible information for critical infrastructure stakeholders.

Recently, social media, and 'ask an expert' interactive online sessions allow question and answer sessions from the public in real-time. Informal conversations during meetings, workshops, or on the telephone provide end-users with more specific information from volcanologists, with the opportunity for two-way communication. Long-term hazard maps have been created for some of the more active volcanoes, based on geological evidence of past eruptions. Event-specific hazard maps are created before or during unrest, depending on the situation, likely vent location, and the style and magnitude of the potential eruption, etc. Event-specific hazard maps were created prior to and after the Tongariro eruption in 2012.

2.4.2.1 Communication of volcanic ash information for aviation

The 1995–96 eruptions at Ruapehu had a significant impact on New Zealand's aviation industry, resulting in the cancellation and diversion of many flights (Lechner, 2012). The reported economic cost to the aviation industry at the time as a result of these eruptions was approximately NZ$2.4 million (Johnston et al., 2000). Based on experiences from this eruption episode, the Civil Aviation Authority (CAA) of New Zealand reviewed its procedures and those used internationally to refine the Volcanic Ash Advisory System (VAAS; Lechner, 2012). Internationally, many other instances of impacts on the aviation industry have occurred, including the costly near shut-down of airspace in Europe following an eruption at Eyjafjallajökull in Iceland in 2010, and the impact on aviation in the Southern Hemisphere in 2011 from the Puyehue-Cordón Caulle eruption in Chile, which caused an ash cloud to circulate the globe.

Organisations and tools used to communicate volcanic ash information to the civil aviation industry are rife with acronyms. The CAA assists the civil aviation industry in managing the use of air space in proximity to volcanic ash (Lechner, 2012). The New Zealand VAAS is the local implementation of the International Civil Aviation Organization (ICAO) International Airways Volcano Watch system (IAVW). GNS Science, the Meteorological Service of New Zealand (MetService), Airways Corporation of New Zealand, and aircraft operators provide input into the VAAS (Scott & Travers, 2009; Lechner, 2012). New Zealand's Volcanic Ash Advisory Centre

[2] http://www.gns.cri.nz/Home/Learning/Science-Topics/Volcanoes/Eruption-What-to-do/Ash-Impact-Posters, accessed on 10 January 2014

(VAAC), based at the MetService office in Wellington, is designated by the IAVW to communicate ash information for a large section of the southwest Pacific, including New Zealand's active volcanoes (Lechner, 2012). MetService issues Volcanic Ash Advisories in text and graphic form, and disseminates NOTAMs (Notice to Airmen), which describe hazards along a flight route. These are issued when the VAL changes, prompting Volcanic Hazard Zones (referred to as NZVs) to be created. Restrictions on the use of airspace during a volcanic eruption using the VAAS and the NZVs are outlined in Lechner (2012). After consultation with GNS Science, Volcanic Ash Advisories are also communicated to MCDEM, in addition to being provided to international aviation agencies, and meteorological communities (MCDEM, 2006). Volcanic Ash Advisories from MetService forecast the distribution of tephra in the atmosphere for the purpose of aviation safety, whereas GNS Science issues ashfall prediction maps relating to the distribution and thickness of tephra deposits at ground level.

GNS Science issues Volcano Observatory Notices for Aviation (VONA) to the VAAC at MetService to report on ground-based volcanic activity whenever there is a change in the Aviation Colour Code (ACC; Table 2.2). VONAs are "succinct, plain-English messages" aimed at pilots, dispatchers, and air-traffic controllers (as described on the USGS website[3]). The ACC is defined by the ICAO and allocated by GNS Science, and is used by the CAA in New Zealand to alert the aviation industry to changes in the status of volcanoes within the designated coverage area (Lechner, 2012). While VAACs provide the aviation community with information regarding where ash currently is in the air, the role of the ACC is more about warning (Gardner & Guffanti, 2006). This encompasses the recognition of the level of volcano activity for the purpose of attention by the aviation industry, and to inform their decisions, such as regarding re-routing or extra fuel (Gardner & Guffanti, 2006). The ACC relates to activity at or near a volcano and is not intended to apply to volcanic hazards occurring at a distance, such as ash drifting downwind (Lechner, 2012). The international nature of the ACC reflects the need for aviation personnel to ascertain the status of volcanic activity across a number of countries and VAL systems (e.g., Guffanti & Miller, 2013; and as described by the World Organization of Volcano Observatories website[4]). Meanings placed on the levels in the ACC by the USGS are described further in Gardner and Guffanti (2006).

[3] http://volcanoes.usgs.gov/activity/vonainfo.php, accessed 20 October 2013
[4] http://www.wovo.org/aviation-colour-codes.html, accessed on 20 October 2013

Table 2.2. The International Civil Aviation Organization (ICAO) Aviation Colour Code (ACC) for volcanic activity. Source: Lechner (2012).

ICAO Colour Code		Status of activity of volcano
GREEN		Volcano is in normal, non-eruptive state. *Or, after a change from a higher alert level:* Volcanic activity considered to have ceased, and volcano reverted to its normal, non-eruptive state.
YELLOW		Volcano is experiencing signs of elevated unrest above known background levels. *Or, after a change from a higher alert level:* Volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
ORANGE		Volcano is exhibiting heightened unrest with increased likelihood of eruption. *Or,* volcanic eruption is underway with no or minor ash emission *[specify ash-plume height if possible].*
RED		Eruption is forecasted to be imminent with significant emission of ash into the atmosphere likely. *Or*, eruption is underway with significant emission of ash into the atmosphere *[specify ash-plume height if possible].*

2.4.2.2 Communication of other volcano-related information: Volcanic Alert Levels

Volcanic Alert Levels (VALs) are outlined in Chapter 1 of this thesis. They are seen as an "essential part of volcanic risk preparedness", used to "transfer the consensus of the scientific advisors to the responsible authorities, so they have the essential means for decision making" (De la Cruz-Reyna et al., 2000, p. 1205). Scales are often used to compress verbose descriptions into shorthand, represented by a single number or short label (Grünthal, 1998). They are often descriptive rather than interpretive or analytical (Grünthal, 1998; Blong, 2003). An overview of New Zealand's VAL system is provided here, in addition to some of the methods used to determine VALs worldwide.

The following information describes the events preceding the development of New Zealand's first VAL system. The Civil Defence Act was passed in December 1962 (Civil Defence public health seminar notes, Whakatane, 24–25 May 1974, GNS Science archives), stating that the DSIR had the obligation of advising the Ministry of Civil Defence (as it was then known) of observations relating to potential natural disasters (Ministry of Civil Defence., 1973, p. 21). Following the passing of the Civil Defence Act 1983 (and the occurrence of the 1983–84 unrest episode at TVC), a meeting was held between the Ministry of Civil Defence and DSIR in January 1984 to discuss the need for improvements to New Zealand's volcano monitoring network and warning systems. It was decided that in order to fulfil their obligations to warn the public of hazards, the "Ministry of Civil Defence will have to take the initiative in the establishment of an adequate volcanic warning system, for the rhyolitic volcanic fields in particular" (meeting notes from 16 January 1984, GNS Science archives).

It was proposed in 1989 that the Minister of Civil Defence should set up a National Civil Defence Scientific Advisory Committee, from which a sub-committee on Volcanic Hazards was formed. Members included a number of scientific institutions, and the group advised the Ministry of Civil Defence on volcanic matters. In January and February 1992, members of the Volcanic Hazards Advisory Group helped create the Nga Puia caldera eruption national exercise centred at OVC. This Group used a colour-coded VAL system based on the USGS system at the time to work through the exercise (*pers. comm*. V. Neall, 2012). In a post-exercise review of Nga Puia, Martin (1992) identified a couple of issues with the system. One issue identified was that there was no mention of public advice in the 'Action' column of the VAL system prior to a state of emergency being formally declared. The post-exercise review also stated that the duplicate use of colours in the VAL system as well as in the 'control zones' used in the exercise created confusion (Martin, 1992).

Following the Nga Puia exercise, it was recommended by the Volcanic Hazards Advisory Group that a National Volcanic Contingency Plan should be formed (as stated in correspondence between B. D. Sinclair (Ministry of Civil Defence) and Dr Ian Nairn (IGNS) on 8 September 1992, GNS Science archives). During a convenors meeting for the development of this plan on 30 September 1992, it was suggested that the VAL system should be a four or five stage alert system only, and it should be devised by the scientists (according to meeting notes taken, stored in GNS Science archives folder #5235). It was also suggested that time should be stated in numbers, evacuation areas should be depicted in colours, and the VAL system should "outline the actions to be taken by civil defence and also the other various organisations that would be required to respond". Lessons from the Rabaul Caldera unrest and eruption response in the 1980s and 1990s were used to develop the new VAL system (Nairn & Scott, 1995).

In November 1994, Annexe C was added to the National CDEM Plan, and outlined warnings, responsibilities, and introduced the 'Scientific Alert Level Table' (SAL) for New Zealand's active volcanoes (*pers. comm*. B. Scott, 2013; Table 2.3). In December 1994 activity at Ruapehu started to increase and the SAL had its first official use. Problems which arose from this system, according to B. Scott (GNS Science, *pers. comm*. 2013) included:

- no level zero recognising 'no unrest'
- no clear differentiation between frequently active and reawakening volcanoes
- multiple different and conflicting definitions within one level
- there were difficulties applying this system to Ruapehu's eruption activity.

Table 2.3. Scientific Alert Level Table introduced in 1994 (Annexe C from the CDEM Plan; sourced from B. Scott, 2013).

Scientific Level	Phenomena Observed	Scientific Interpretation
1	Abnormal seismic, hydrothermal or other signatures	Initial sign of volcano reawakening. No eruption imminent. Possible minor activity.
2	Increase in seismic, hydrothermal and other unrest indicators. Increase from usual background weak eruptions.	Indicators of intrusion process or significant change in on-going eruptive activity.
3	Relatively high and increasing unrest shown by all indicators. Commencement of minor eruptive activity at reawakening vent(s) or increased vigour of on-going activity.	If increasing trends continue there is a real possibility of hazardous eruptive activity.
4	Rapid acceleration of unrest indicators. Established magmatic activity at reawakening vents or significant change to on-going activity.	Hazardous volcanic eruption is now imminent.
5	Hazardous volcanic eruption in progress.	Destruction within the Permanent Danger Zone (red zone) and significant risk over wider areas.

The SAL system was therefore reviewed, and a significantly revised and amended version was adopted in September 1995, just one week before the 1995–96 Ruapehu eruption episode started. The resulting system is the system currently in use (Table 2.4), and was renamed from SALs to VALs in 2008 as part of a review of the Guide to the National CDEM Plan. This system included a level zero for 'no unrest', and was split into two separate sections, one for frequently active volcanoes, and the other for reawakening volcanoes. The volcanoes allocated to each are listed in VAL table (Table 2.4).

Table 2.4. New Zealand's current Volcanic Alert Level system. Source: reproduced from the Guide to the National CDEM Plan (MCDEM, 2006).

Frequently active cone volcanoes White Island, Tongariro/Ngauruhoe, Ruapheu, Kermadecs		**VOLCANIC ALERT LEVEL**	**Reawakening volcanoes** Northland, Auckland, Mayor Island, Rotorua, Okataina, Taupo, Egmont/Taranaki	
Volcano status	**Indicative phenomena**		**Indicative phenomena**	**Volcano status**
Usual dormant, or quiescent state	Typical background surface activity, seismicity, deformation and heat flow at low levels.	**0**	Typical background surface activity; deformation, seismicity, and heat flow at low levels.	Usual dormant, or quiescent state.
Signs of volcano unrest	Departure from typical background surface activity.	**1**	Apparent seismic, geodetic, thermal or other unrest indicators.	Initial signs of possible volcano unrest. No eruption threat.
Minor eruptive activity	Onset of eruptive activity, accompanied by changes to monitored indicators.	**2**	Increase in number or intensity of unrest indicators (seismicity, deformation, heat flow and so on).	Confirmation of volcano unrest. Eruption threat.
Significant local eruption in progress.	Increased vigour of ongoing activity and monitored indicators. Significant effects on volcano, possible effects beyond.	**3**	Minor steam eruptions. High increasing trends of unrest indicators, significant effects on volcano, possible beyond.	Minor eruptions commenced. Real possibility of hazardous eruptions
Hazardous local eruption in progress.	Significant change to ongoing activity and monitoring indicators. Effects beyond volcano.	**4**	Eruption of new magma. Sustained high levels of unrest indicators, significant effects beyond volcano.	Hazardous local eruption in progress. Large-scale eruption now possible.
Large hazardous eruption in progress.	Destruction with major damage beyond volcano. Significant risk over wider areas.	**5**	Destruction with major damage beyond active volcano. Significant risk over wider areas.	Large hazardous volcanic eruption in progress.

The frequently active volcanoes system includes one level for unrest (VAL 1) and four levels of increasing magnitudes of eruption (VAL 2–5), whereas the reawakening volcanoes system includes two levels for unrest (VAL 1 and 2) and three eruption levels (VAL 3–5). The VAL is based on a volcano's current status, and is not necessarily predictive (Scott & Travers, 2009).

Determining the VAL and ACC in New Zealand is currently the statutory responsibility of GNS Science, according to a Memorandum of Understanding with MCDEM (GNS Science & The Ministry of Civil Defence and Emergency Management, 2009). The decision is usually made by scientists once the monitoring data has been assessed and compared to background levels, subjectively ascertained from past activity. Further details on this process are described in Chapter 4. In the case of the need for an immediate response (e.g., an eruption has taken place), the GeoNet Volcano Duty Officer can make the VAL decision alone.

As identified by Newhall (2000), scientists must be willing to raise and lower the alert level as necessary to maintain their credibility. However, the decision to change the VAL can be challenging in the context of uncertainty (e.g., Metzger et al., 1999; Fearnley, 2011). Decision-making under uncertainty, including the determination of VALs and the ACC, is discussed further in section 2.4.4.

In New Zealand, the status of volcanic activity, including changes to the VAL and ACC, is communicated by the dissemination of VABs. These are issued by GNS Science and sent to anyone who registers to the list managed by GNS Science, including MCDEM, CDEM Groups, local government, lifelines utilities, emergency responders, tourist operators, major land managers, media, and members of the public. VABs usually include the time and date of dissemination; a summary sentence (or short paragraph) in bold font at the head of the one to two page document; photographs of points of interest (particularly during an episode of heightened unrest or eruption event); a description of the scientific data on which the information is based; a definition of the VAL, ACC, and the GeoNet monitoring project; and a short description of activities leading up to the issuance of the VAB. Occasionally, possible future scenarios are included in the VAB, and/or information relating to the threat. For example, in a 2013 White Island VAB describing an overnight eruption which deposited tephra on the crater floor visited by tourists during daylight hours, it was stated "This eruption is larger than recent events and would have been life threatening to people on the island" (VAB WI-2013/23). VABs may be issued without a change in VAL to provide information on recent monitoring trips, to issue ashfall forecasts, or to simply state that no change of activity has occurred. Up-to-date information on the current status and alert levels for New Zealand's volcanoes, as well as the VAB just mentioned, and GeoNet 'Volcano News' articles (containing more general information, or items not deemed appropriate for a VAB) are available on the GeoNet website (http://www.geonet.org.nz/volcano/). The 'Volcano News' articles are a passive supply of information, requiring end-users to actively check the GeoNet website, or the GeoNet Facebook web page to be aware of the information.

2.4.3 New Zealand's National Warning System

New Zealand's National Warning System (NWS; Figure 2.9) is maintained by MCDEM, and has the aim of disseminating civil defence warnings based on information received from responsible agencies (e.g., GNS Science in the case of volcanic activity) (MCDEM, 2006). Warnings are communicated to certain government departments, CDEM Groups, local authorities, police, lifeline utilities, and specific broadcasters (MCDEM, 2006). CDEM Groups (at the regional level) must maintain local warning systems, and, on receipt of the national warning, must communicate it to local communities (MCDEM, 2006). Other recipients of the message respond according to their own arrangements, including further dissemination of the message. In the event of volcanic unrest or an eruption, GNS Science is supported by MCDEM and MetService (MCDEM, 2006).

National warning messages are disseminated on instruction by the Director of CDEM or the National Controller, whenever it is deemed that there is enough public interest to state that there is not a threat, or when an event poses a threat to life safety and/or property, and may result in an emergency (MCDEM, 2006). The message is issued as either a Warning or an Advisory, depending on the type of event and potential impact; all are accompanied by media releases (MCDEM, 2006). Advisory messages communicate information relating to 'no threat' posed by a hazard, or a 'potential threat', while a Warning message describes a 'threat'. Both types of messages are either followed up with frequent updates, or a cancellation message. The NWS message service is tested four times per year.

Warnings are disseminated through the NWS to those agencies registered, using email, SMS text message, and fax (MCDEM, 2006). MCDEM Regional Emergency Management Advisors (REMAs) are contacted, who liaise with regional CDEM Groups to ensure the message has been received. A request is sent to media for the message to be broadcast, and the delivery of the message is monitored (MCDEM, 2006).

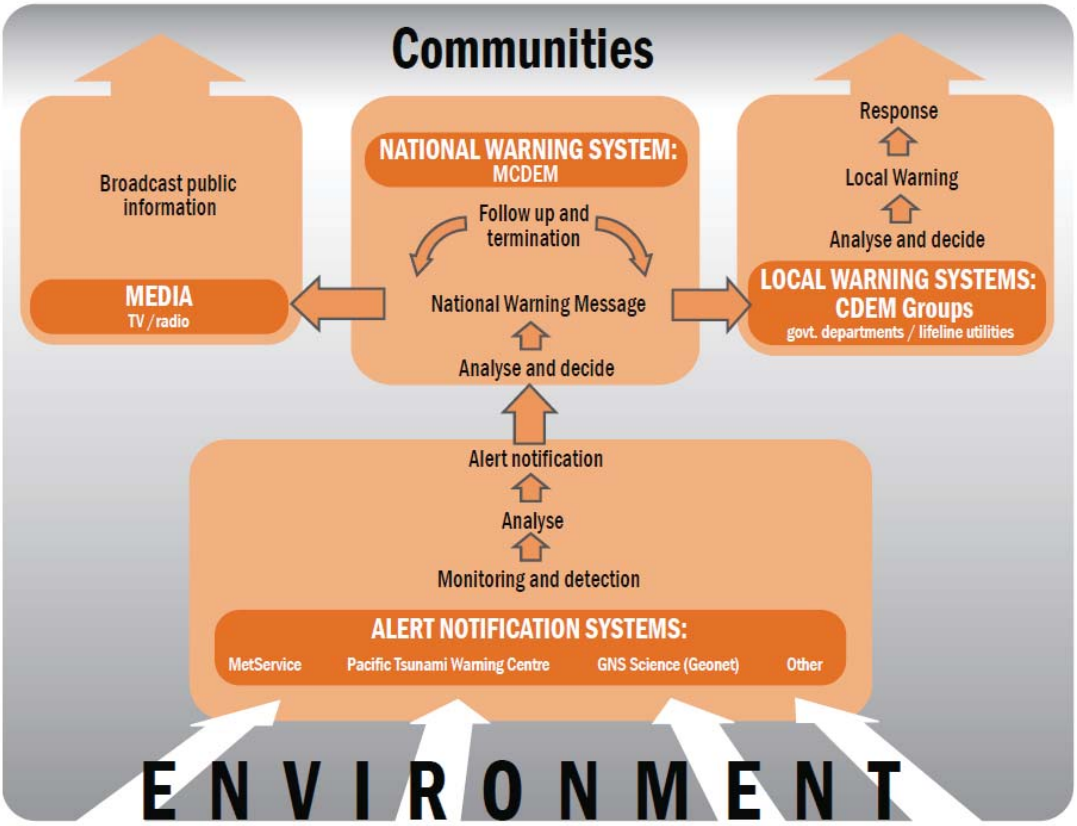


Figure 2.9. New Zealand's National Warning System. From the Guide to the National Civil Defence Emergency Management Plan (MCDEM, 2006, section 19.3).

The Guide to the National CDEM Plan (MCDEM, 2006; section 19.1) describes volcanic eruptions as "predictable events", in which warnings are to be disseminated as soon as practicable, "so that local authorities, agencies, and people can take action to reduce loss of life, injury, and damage". Messages relating to volcanic activity are issued by GNS Science and the GeoNet monitoring project using VABs, which include VAL messages. Depending on the volcano that is showing signs of activity, messages issued by MCDEM relating to volcanic unrest may be disseminated nationally, and thereafter "scaled down to potentially affected CDEM Groups as necessary" (MCDEM, 2006, section 19.4.2). Messages relating to imminent eruptions, or eruptions which have occurred, are disseminated to all agencies registered to the NWS. MCDEM generally reissues VABs received from GNS Science without making changes as an Advisory or Warning message. GNS Science disseminates VABs and VALs for all levels of activity to a separate list of registered agencies, members of the public, and media.

2.4.4 Decision-making under uncertainty

Part of the process of warning about volcanic hazards and responding effectively is making decisions under uncertainty. As described in the introduction and Figure 1.3, there are a number of decision-making points within a warning system, and for virtually every one of them, there is the influence of both aleatoric and epistemic uncertainties (Sorensen & Mileti, 1987; Woo, 1999). Decision-making is essentially a link between monitoring data and communication of information. Of particular interest in this research are the decisions made by scientists relating to the determination of the VAL. This is an example of naturalistic decision-making, where decisions are made "in real-world contexts that are meaningful and familiar to them" (Lipshitz et al., 2001, p. 332). Both individual and group decision-making processes can influence the outcome of this VAL decision, as with any group making a joint decision.

The traditional method for decision-making involves heuristics, a simple and fast method of judgement and decision-making relying on inherent capacities (Gigerenzer, 2004). The decision is made using the knowledge and experience of experts, without applying probabilities and statistics to every factor involved. This is the basis of the current method for decision-making at GNS Science for changing the VAL, for integrating monitoring data into conceptual models, and for determining at what intensity background activity becomes unrest. It is also the basis for response decision-making in New Zealand at Emergency Operation Centres (EOCs). The downfalls with this method are the potential for biases, which impact group interactions and may include obedience to authority (Milgram, 1974), compliance to a group (Asch, 1952), the influence of the minority (Crano & Chen, 1998), group polarisation (i.e. Stoner, 1961), the groupthink phenomenon (Janis, 1982), and the presence of an audience affecting performance (Dashiell, 1930). The way humans test theories or assess probabilities, such as the confirmation bias (McKenzie, 2004), the bias towards available information (Tversky & Kahneman, 1974), and the way people tend to notice data which supports their hypothesis more than data which may disprove it (Klayman & Ha, 1987), can also cause issues in heuristic decision-making. This method is not easily traceable in the event of the decision turning out to be 'wrong', and can be difficult to justify to officials, public, and media. Despite these potential issues, the heuristic method is the oldest and most proven way to make decisions involving high uncertainty and risk. It is a comfortable and familiar process for scientists during a period of high stress and limited time, and may sometimes take a short period of time (and therefore money), especially if the decision is reasonably straightforward.

Structured decision-making models use probabilities of a series of events to provide an optimal outcome to a difficult decision involving uncertainty and risk. They are new and mostly untested methods for dealing with volcanic crisis decision-making, but are gaining in popularity world-wide. These methods include Bayesian Event Trees (BET), Hidden-Markov models, and Bayesian Belief Networks (e.g., Aspinall & Cooke, 1998; Newhall & Hoblitt, 2002; Aspinall et al., 2003; Marzocchi et al., 2004; Aspinall et al., 2006; Lindsay et al., 2010), cost-benefit scenarios (Marzocchi & Woo, 2007; Woo, 2008; Sandri et al., 2012), and expert elicitation (e.g., Cooke, 1991; Aspinall, 2006). These methods are most effective when set up before an unrest or eruption crisis, and each have advantages and disadvantages. Probabilities for all factors involved in the decision are required to be entered into a decision tool, for each individual volcano, relating them to previous activity. These data do not yet exist in New Zealand, however progress is being made in this direction.

A probabilistic Bayesian approach is an example of 'evidence-based volcanology', in which weights of relative importance are estimated for a range of possible volcanic unrest phenomena, enabling all situations to be considered at once (Aspinall et al., 2003). It is a defensible method, allowing the collective consideration of multiple data. Lindsay et al. (2010) tested the probabilistic eruption forecasting model BET_EF (BET for Eruption Forecasting; Marzocchi et al., 2004; Marzocchi et al., 2008), modified to be applied to a volcanic field, during Exercise Ruaumoko for the Auckland Volcanic Field (AVF). The BET_EF model was set up prior to the exercise to incorporate current knowledge of the AVF, and volcanic processes. The probabilities of the eruption style, vent location, and timing were calculated with input by two experts. The weights given to monitoring phenomena were essentially thresholds used to determine the level of activity considered to be 'unrest'. BET_EF was run parallel to the heuristic decisions made by the remaining science experts, with the outcomes of each method compared afterwards. The model used one month time windows, resulting in the model indicating a change of VAL at a later stage than when the scientists changed the VAL using a heuristic decision method. Lindsay et al. (2010) described this traceable method as useful to facilitate scientific group discussions and speed up the group consensus; however they state the outcome is still reliant on the inputs and beliefs of the scientists. Provided the model is set up prior to an event occurring, it is thought that structured probabilistic models are a useful tool for volcanic decision-making (Lindsay et al., 2010).

Other decision-making support methods to determine the VAL (and ACC) include check-box systems, and using individual intensity thresholds for each (or a combination of) unrest phenomena, as has been used by the USGS.

The USGS does not have any formal structural decision-making methods for changing the VAL during volcanic unrest (Yellowstone Volcano Observatory, 2010). The decision is made by the Branch Chief, with the support of the other coordinating scientists and the event coordination committee. A panel of experts may also be formed, including scientists across a range of geological disciplines (i.e. seismology, volcanology, and geodesy) from a variety of institutes, including the USGS, universities and government scientific agencies. This panel is consulted during periods of quiescence as well as periods of unrest, and provides support in dealing with the media (Yellowstone Volcano Observatory, 2010).

The USGS response protocols for unrest at Yellowstone and Long Valley Calderas use thresholds of intensity of activity for individual unrest phenomena as a guideline (Hill et al., 2002; Yellowstone Volcano Observatory, 2010). For example, the VAL may be increased from Normal to Advisory at Yellowstone if previously observed parameters at Yellowstone are surpassed, including if there is a significant release of SO_2, or if there is an intense earthquake swarm (with quantified limits indicated), accompanied by rapid ground deformation (i.e. >5 cm over 30 days) or a significant hydrothermal explosion (Yellowstone Volcano Observatory, 2010). The response protocols at Long Valley Caldera describe how most VALs have multiple sub-levels with thresholds of activity (Hill et al., 2002). For example, the ‘green’ stage (no immediate risk) is split into four levels, ranging from ‘background or quiescence’ through unrest levels up to ‘moderate to strong unrest’. This latter level could include five minutes of harmonic tremor recorded on at least two seismic stations, as well as >500 (over magnitude 1) earthquakes, all without entering the ‘yellow/watch’ alert level stage (Hill et al., 2002). Some VAL systems, including in Vanuatu, have used other types of checklist approaches to determine the VAL (*pers. comm*., S. Cronin, 2012).

The complication with using specific thresholds and checklists is the inflexibility of the system. The USGS thresholds are intended to be used as only a guideline (Hill et al., 2002). If an unrest episode occurs in which the observed phenomena do not match those described in the system, and the scientists decide to change the VAL anyway, it is likely that they will have to justify their decision to the public and other interested parties. As each volcano displays different unrest phenomena, any thresholds used may need to be considered on an individual basis (hence the different thresholds at Yellowstone and Long Valley Calderas).

Situation awareness (SA), or "knowing what is going on around you", is described by Endsley (2000, pp. 3–4) as the "main precursor to decision making", in addition to the involvement of many other factors. As SA increases, the probability of making a good decision and performing well also increases (Endsley, 2000). It involves the perception of cues, comprehension of information, and the ability to project into the future by forecasting future situations and dynamics. SA is limited by attention and working memory. Assessing information according to prior expectations also influences the level of SA of a decision-maker, as people tend to "see what they expect to see" (Endsley, 2000, p. 14). SA is enhanced by matching the situation with preconceived patterns and autonomously selecting an action, and assessing data according to goals (i.e. being goal-driven, not data-driven). The effective use of long-term memory in the form of mental models assists with enhancing SA (Endsley, 2000). Mental models (i.e. underlying knowledge) "serve to help direct limited attention in efficient ways, provide a means of integrating information without loading working memory, and provide a mechanism for generating projection of future system states" (Endsley, 2000, p. 11). SA is essentially the current state of the mental model. A shared mental model assists group decision-making and effectiveness of interactions between groups by allowing members to have a common understanding of roles and responsibilities, information needs, and the task (Lipshitz et al., 2001). Incorporating a good mental model that incorporates both scientists and end-user decision-makers promotes the ability to effectively communicate science advice. This is achieved by the implicit supply of information (i.e. good, unprompted advice) based on the needs of the end-users (Doyle & Johnston, 2011).

The assessment of the status of a volcano and decision to change the VAL incorporates an element of subjectivity (Donovan et al., 2012b; Fearnley, 2013). As such, there are numerous influences on the making of this decision. However, as stated in Barclay et al. (2008), very few volcanologists have had formal training in methodologies and epistemologies outside of the traditional physical sciences. This may result in a lack of awareness of the potential influences and biases. As well as heuristic biases, as detailed above, discussions and decisions made as a group have been found to influence the opinions and confidence of individual experts, including in the field of geological decision-making (e.g., Sniezek, 1992; Polson & Curtis, 2010). Influences on VAL decisions made by scientists at the USGS were described by Fearnley (2013), and could be summarised as:

- scientific monitoring data
- institutional dynamics (protocols, procedures)
- scientists' experience
- local environmental, social and political contexts
- familiarity with the volcano, and "gut feeling"
- the "type of volcanic activity occurring" and associated strategies for VAL movement
- credibility
- perceived risks and vulnerabilities
- local contingencies through assessing various end-user and societal factors
- economic drivers (internal to the USGS and external agencies/industries).

The VAL system was seen to be embedded within these social, political, economic, cultural, and institutional contexts in the USGS environment (Fearnley, 2013). Fearnley's research is the only published research on the dynamics of VAL decision-making. Prior to this study, the New Zealand context had not been investigated.

2.5 Response capability

An effective EWS requires the public and officials to have the capabilities to respond to warning information. This involves education of risks arising from natural hazards, participation of the community in exercises, and disaster preparedness (UN/ISDR PPEW, 2006). Warnings need to be trusted, which is influenced by the credibility of the source, and by actively developing strategies to enhance trust and credibility. False alarms need to be minimised, and potential public reactions understood to increase effectiveness of warnings (UN/ISDR PPEW, 2006). Response plans and preparedness strategies need to be developed and disseminated, and hazard and risk information communicated, particularly to vulnerable communities. It was recognised as important by UN/ISDR PPEW (2006) to involve local community officials in a 'bottom-up' approach to enhance EWS effectiveness. This is reflected in New Zealand's Guide to the National CDEM Plan (MCDEM, 2006, section 19.1), which maintains that "relevant government agencies, CDEM Groups, local authorities, and lifeline utilities must maintain arrangements to respond to warnings".

The next section includes an outline of response capabilities in New Zealand, and the history of CDEM, to set the context for this thesis. Further information on response capabilities in New Zealand is outlined by the CDEM Act 2002 (MCDEM, 2002), the National CDEM Plan Order

2005 (MCDEM, 2005), the Guide to the National CDEM Plan (MCDEM, 2006), and the National CDEM Strategy (MCDEM, 2007), as well as region-specific government response and volcanic contingency plans, and local government response plans; most are available on the Councils' websites[5].

2.5.1 Civil Defence and Emergency Management in New Zealand

The obligation for New Zealand's central government and local authorities (which includes city/district and regional councils) to continue to operate to the fullest possible extent during an emergency, and be capable of responding to the situation as required, is stipulated in the CDEM Act 2002 (as described by the Guide to the National CDEM Plan; MCDEM, 2006). MCDEM is the lead agency for civil defence emergencies, provides structures and support to enhance local capabilities to respond, and manages national-scale responses if needed (MCDEM, 2006). Under the CDEM Act 2002, local authorities are required to form and maintain CDEM Groups (which are predominantly at a regional level). There are 16 Groups in New Zealand. Most CDEM Groups have several district or city councils and CDEM offices within their jurisdiction. As an example, TVC is situated within Taupo District Council's CDEM area, which is located within the area managed by Waikato Region CDEM Group. Local authorities are expected to work in partnership with lifeline utilities and emergency services to provide CDEM at a local level (MCDEM, 2007).

The history of government emergency response organisations has been summarised in a publication by the Ministry of Civil Defence (1990). The information contained in this paragraph is sourced from this document. A national level of civil defence dates back to the 1930s, after a M7.8 earthquake struck the city of Napier in 1931, resulting in the deaths of 256 people. This event highlighted the expectation by the central government that response should be undertaken at a local level, for which the responsible organisations were completely unprepared. The Public Safety Conservation Act was passed in 1932 allowing emergencies to be declared. An Emergency Precautions Scheme was established in the mid-1930s relying on voluntary participation at a local level. A boom in volunteer numbers occurred during World

[5] For example (all accessed on 23 October 2013):
Auckland Council: http://www.aucklandcivildefence.org.nz/About-Us/ACDEMG-Plan-2011-2016/
Waikato Regional Council: http://www.waikatoregioncdemg.govt.nz/Policy-and-Plans/Page-1/
Bay of Plenty Regional Council: http://www.boprc.govt.nz/knowledge-centre/plans/cdem-group-plan/
Taranaki Regional Council: http://www.trc.govt.nz/taranaki-cdem-publications/
Rotorua District Council: http://www.rdc.govt.nz/our-services/civil-defence-and-emergency/Pages/default.aspx
Taupo District Council: http://www.taupodc.govt.nz/our-services/Civil-defence-and-emergency/about-civil-defence/Pages/civil-defence-in-the-taupo-district.aspx

War II, and several of the committees responded to earthquakes during this time. The Local Authorities Emergency Powers Act was passed in 1953 largely in preparation for a nuclear attack, and the Government Action in a Major Emergency Plan was created in 1954 focussing on roles of government departments. The Ministry of Civil Defence was officially established in April 1959, and the Civil Defence Act passed in 1962. The development and role of the Ministry was based on the British and United States Civil Defence organisations. These systems were tested in 1968 during the widespread storm which sank the Wahine ferry near Wellington, killing 51 people, as well as in the severe Inangahua earthquake on the West Coast of the South Island. The Civil Defence Act of 1962 was amended six times by 1979, and in 1983 the new Civil Defence Act was passed. The Ministry of Civil Defence was renamed the Ministry of Civil Defence and Emergency Management (MCDEM) in 1995, and the CDEM Act was passed in 2002. A national state of emergency was declared following the 22 February 2011 Christchurch earthquake in Canterbury (a M6.3 aftershock following the M7.1 mainshock on 4 September 2010), which resulted in the deaths of 185 people in and around Christchurch city. Since the CDEM Act 2002 has been in place, no state of emergency has been called at a regional or national level for a volcanic eruption to test the system with this type of hazard.

2.5.2 Interagency communication and coordination

Multi-agency coordination is important to ensure timely, meaningful, and accurate warnings can be disseminated, and that they result in appropriate actions (IDNDR Early Warning Programme Convenors, 1997). In New Zealand Emergency Operation Centres (EOCs), there are four main components which make up the Coordinated Incident Management System (CIMS; as described in the 2009 amendment of MCDEM, 2006): Control, Planning and Intelligence, Operations, and Logistics. When an EOC has been activated during a volcanic emergency, science advice is generally provided to the Planning and Intelligence role (Doyle et al., 2011).

As reported by Paton et al. (1998a), multi-agency coordination was a key problem for agencies affected by the 1995–96 Ruapehu eruptions in New Zealand. A range of agencies were involved in the response to this event across a number of jurisdictions. In Paton et al.'s (1998a) research, a lack of communication was identified by 37% of those organisations surveyed afterwards. During normal circumstances there was very little contact between organisations. Therefore, it was identified that this inter-organisational communication must be nurtured before a crisis event by establishing networks, anticipating information needs and methods of communication, and establishing consistent terminology and compatible systems. Further issues while responding to an event that were identified by Paton et al. (1998a), included a lack of clear responsibility within and between organisations, problems with management, lack of appropriately trained personnel, and managing media. Similar issues were identified during the response to the Mount St. Helens eruptions in 2004–06, especially in managing the media and public interest during the earlier stages of unrest (Frenzen & Matarrese, 2008).

Multi-organisational readiness and response for the 2007 Ruapehu Crater Lake lahar proved successful, with mitigation and warning systems emplaced, emergency preparedness plans practised, and personnel trained ahead of the event (Keys & Green, 2008; Massey et al., 2009). This was largely helped by the small geographical area involved and the relatively high level of predictability for the initiation of the dam-break lahar. During Exercise Ruaumoko in 2008, the lack of communication between CDEM Groups and the National Crisis Management Centre (which is the national level EOC, based in Wellington) was reported as a problem (MCDEM, 2008). The placement of scientific advisors in EOCs was considered a success.

The establishment of Volcanic Advisory Groups (discussed in section 2.4.1) and conduct of exercises are likely to have greatly improved inter-organisational relationships, channels of communication, and coordinated response plans for a volcanic event in New Zealand. Lessons learnt from various events and exercises need to be transferred to establish practices and plans for an effective response to a caldera unrest crisis. The size, complexity, and unpredictability of a caldera unrest crisis would require a greater number of organisations and jurisdictions to work together, which may amplify the difficulties which occurred during previous events and exercises.

2.6 Summary

This chapter has built on the knowledge gaps and research aims identified in Chapter 1. It has provided an overview of four components of New Zealand's VEWS – risk knowledge, monitoring, dissemination and communication of warnings, and response capability. It has also described findings of relevant literature to provide a theoretical context to this thesis. Additional background information is provided in Chapters 5 and 6, which are 'self-contained' papers submitted for publication. The next chapter describes the methodology used to meet the aims of this research.

CHAPTER THREE

METHODOLOGY FOR VOLCANIC ALERT LEVEL EXPLORATION

3 METHODOLOGY FOR VOLCANIC ALERT LEVEL EXPLORATION

3.1 Introduction

Chapters 1 and 2 reviewed VEWSs and the New Zealand context, and identified gaps in the current state of knowledge. This chapter describes the framework and methodology used to explore these gaps relating to the research aims and questions. It examines the methods used in similar hazard research, and outlines the rationale behind the selection of methods employed in this research. Details relating to analysis methods and potential limitations are then described. The methodology described in this chapter predominantly relates to the exploration of the VAL system, the findings of which are presented in Chapter 4. Additional methodological details are presented in Chapters 5 and 6.

3.2 Research framework

3.2.1 Methodological context

This section describes the context that frames the methodology chosen to achieve the aims of this thesis. It provides background information on the broader methodological framework (qualitative research), and then becomes more specific in the description of detailed methodology (ethnography in a transdisciplinary, naturalistic environment), and theoretical perspective (symbolic interactionism).

The aims of this research require an exploration into New Zealand's VEWS and the ways in which volcanic crises are managed. In particular, the use of the VAL system, meanings placed on it by scientists and end-users, and the associated decisions made by scientists are explored. Developing an understanding of these aspects can be ascertained through an interaction with the scientists who created and regularly use the VEWS and VAL system, and with end-users. **Qualitative research methods** meet these needs as they enable underlying meanings and reasons behind processes and choices to be recognised more effectively than the use of more traditional quantitative research methods, through building an understanding based on listening to participants' ideas (Creswell, 2003).

Qualitative research is described by Denzin and Lincoln (1994, p. 2) as "multimethod in focus, involving an interpretive, naturalistic approach to its subject matter. This means that qualitative researchers study things in their natural settings, attempting to make sense of, or interpret, phenomena in terms of the meanings people bring to them". The underlying theme of qualitative research, as described by Miles and Huberman (1994, p. 10), is the **naturalistic** collection of data (researching in the participants' natural environment) relating to ordinary, 'real-life' events as they happen, and not retrospectively with the local context removed, as in telephone surveys or in a laboratory. The local context is instead taken into account, permitting the strong possibility of understanding "latent, underlying, or nonobvious issues". The complexity of the data, including their "richness and holism" can then be recognised. In particular, the question of 'why?' a phenomena or process occurs can be researched, with inherent flexibility in the methods contributing, instead of focussing on a snapshot of 'what?' or 'how many?' as seen in quantitative studies. Qualitative research also allows the meanings placed on events, systems, and processes to be recognised, as well as how they connect with the social context (Miles & Huberman, 1994).

The use of qualitative research in sociology was established in the 1920s and 1930s by the 'Chicago school', and developed during the same period in anthropology by the predominantly immersed study of native cultures (Denzin & Lincoln, 1994). It was used with increasing popularity, particularly throughout the 1970s and 1980s, and applied to a wide variety of disciplines. Qualitative research within the field of disasters originated in a study on the Halifax explosion by Prince (1920, cited in Phillips, 2002). Qualitative research is increasing in its frequency of use by disaster researchers (Phillips, 2002). While the use of multiple qualitative research methods (e.g., interviews, observations and document analysis) is still relatively rare in disaster research, it is increasing in popularity as the potential to improve the credibility and trustworthiness of research findings is recognised (Phillips, 2002).

The fundamental interpretive nature of qualitative research involves subjectivity imposed by the researcher who draws conclusions about data through a lens (Creswell, 2003). For this reason, doubts have been raised by quantitative positivist scientists regarding the validity and potential for biases in qualitative research (Carey, 1989, cited in Denzin & Lincoln, 1994). Nonetheless, the strengths qualitative research bring to understanding processes, meanings and reasons why events and actions take place have promoted its widespread application.

The discipline of volcanology, based on multiple primary fields such as physics, mathematics, chemistry, and geography, traditionally uses quantitative research methods. However, the development of **transdisciplinary** research and inclusion of qualitative methodologies in the field of volcanology is promoted by the social context in which volcanoes become hazardous. It is thought by some social scientists that focussing on a single discipline is 'reductionist', as it only captures part of the situation, whereas practical problems in reality require a transdisciplinary approach (Horlick-Jones & Sime, 2004). Horlick-Jones and Sime (2004, p. 444) state that in transdisciplinary research, "elements of methodologies drawn from different disciplines are combined within a single approach". The integration of volcanology and social science in this research follows a transdisciplinary approach to investigate the practical issue of the communication of volcano-related information. Specifically, volcano-related knowledge, such as the significance of individual unrest phenomena for forecasting eruptions within the Volcanic Unrest Index (VUI; discussed in Chapter 5), is integrated with aspects of social science, including communication-related knowledge; and the construct of labelling 'unrest', and the implications of this within warning tools. Additionally, knowledge of complex volcanic hazard phenomena and how it is scientifically interpreted and classified by volcanologists is integrated with biases and heuristics in decision-making methods during the exploration of the VAL system (in Chapter 4), to develop recommendations for future use, including a new VAL system. The disciplines are particularly linked in the Discussion chapter (Chapter 7).

Interest in researching the social context of volcanology through the use of qualitative methodologies has increased in recent years. Mader and Blair (1987) used interviews, observations over three years, and document analysis to report the impacts of caldera unrest at Long Valley Caldera in the early 1980s. Other examples include research by Cronin et al. (2004), who used Participatory Rural Appraisal methods, while Fearnley utilised interviews, observations, and document analysis in her multi-sited ethnographic research (Fearnley, 2011, 2013; Fearnley et al., 2012). Paton et al. (1998a) used **mixed methods** (a mixture of qualitative and quantitative methods) in their survey of organisational response to the 1995 Ruapehu eruptions. Mixed methods were also used by Haynes et al. (2007, 2008) and Donovan et al. (2012a, 2012b, 2012c), involving qualitative interviews, participant observations and quantitative surveys with statistical analysis. Reasons behind the mixed-methods approach by these authors included the need to understand the reasons behind attitudes and behaviour through qualitative methods, while quantitative methods were used to triangulate (i.e., cross-check) the data, explore relationships within the data using statistical analysis, and to enable the testing of qualitative results over a wider sample (Haynes et al., 2008). Metzger et al. (1999) also used mixed methods including interviews, document analysis, and quantitative surveys to investigate the context and impacts of a VAL change in Quito, Ecuador, in October 1998.

Ethnographic methodology involves the study of a group of people and their culture (Patton, 2002). It is the primary research method of anthropologists, who historically studied “the non-European ‘others’ who had traditionally excited the anthropological imagination” within academia (Stocking, 1983, p. 4). The early studies in the 19th Century focussed on the relationship between people and their environment (e.g., Boas from 1894 to 1897, cited in Cole, 1983), and understanding native cultures for political and scientific purposes (e.g., research lead by Cushing on Native Americans in the 1880s, cited in Hinsley, 1983). Early geographical and cultural investigations in the U.S. were established in 1879 within the U.S. Geological Survey, which included the Bureau of Ethnology. According to Stocking (1983), ethnographic fieldwork (and in particular participant observation) gained momentum in the 1940s following on from Bronislaw Malinowski’s observations on Trobriand Islands. With the decline of unstudied cultures, the withdrawal of colonial power, and increasing ethical constraints, anthropology suffered a degree of identity crisis. Feminist theory and other reflexive studies began to gain momentum in European and American societies, along with the ethnographic method of **participant observation** (described further in section 3.3.2.2), rooted in relatively modern anthropology and focussing on issues other than understanding native cultures (LeCompte & Schensul, 1999). The researching of sociocultural problems and the use of the research findings to bring about positive change in the community is referred to as **applied ethnographic research** (LeCompte & Schensul, 1999).

A common theoretical perspective amongst ethnographers is **symbolic interactionism**. This perspective stems largely from George Herbert Mead and his student Herbert Blumer, initially discussed by Blumer in 1969. It is concerned with the behaviour of people and meanings they place on objects based on their interaction with their social environment. The three basic assumptions involved in symbolic interactionism (Blumer, 1969, p. 2) are:

- ‘that human beings act toward things on the basis of the meanings that these things have for them’
- ‘that the meaning of such things is derived from, and arises out of the social interaction that one has with one’s fellows’
- ‘that these meanings are handled in, and modified through, an interpretive process used by the person in dealing with the things he [or she] encounters’.

The implication of these assumptions in choosing a methodology is the need for the researcher to take on the role of the participants and establish a dialogue to understand the social context and meanings placed on objects from their perspective (Blumer, 1969; Crotty, 1998). It requires naturalistic methods in order to directly examine the "empirical social world" (Blumer, 1969, p. 47).

The context described above informed the selection of the methodological framework used in this research to address the questions presented in Chapter 1.

3.2.2 Methodological framework

The guiding research question of 'w*hen a caldera volcano starts showing signs of unrest, at what point should the Volcanic Alert Level be raised?'* prompted the development of research aims (listed in section 1.3.1). In order to address the aims relating to an exploratory investigation of New Zealand's VAL system, a pragmatic approach to the selection of a research methodology was initially followed. This is described by Patton (2002, p. 72) as enabling "*methodological appropriateness* as the primary criterion for judging methodological quality".

Very little research has been done on VAL systems internationally, and none in New Zealand, therefore an **exploratory** strategy was employed, supported by a **qualitative framework**. Very few quantitative methodologies were included in this VAL research, as the issue warranted exploration, rather than ascertaining ratings of pre-determined questions. Exploratory research is described by Blumer (1969, p. 40) as "a flexible procedure in which the scholar shifts from one to another line of inquiry, adopts new points of observation as his [or her] study progresses, moves in new directions previously unthought of, and changes his [or her] recognition of what are relevant data as he [or she] acquires more information and better understanding". This approach enables flexibility throughout the process rather than being confined to a pre-determined idea of the final outcome. This research is guided by an open-ended research question established during the research process, rather than establishing a hypothesis at the beginning, as is commonly done in quantitative research (Patton, 2002).

In order to gain a 'genuine understanding' of the processes internal to GNS Science, including staff interactions, decision-making processes, and the use of the VAL system, I needed to identify and experience the issues in question from the participants' perspectives and develop a level of tacit knowledge. Tacit knowledge is described by Collins and Evans (2007, p. 6) as "the deep understanding one can only gain through social immersion in groups who possess it". This understanding is an important aspect of the research as many of the processes influencing VAL system decisions in New Zealand are only accessible from within GNS Science, and stem from this tacit knowledge. To explore the culture and processes in place within the volcanology section of GNS Science, an **ethnographic methodology** is utilised in this research.

Meanings placed on the VAL system by its users could be understood by undertaking **naturalistic research** using **symbolic interactionism**. This perspective suggests that the social environment, including the interaction of scientists within GNS Science, contributes towards the meanings placed on the VAL system. Ethnography supports the naturalistic collection of data to achieve this understanding.

Grounded theory, described as the discovery of theory from “data systematically obtained from social research” (Glaser & Strauss, 1967, p. 2; Strauss & Corbin, 1990), was also considered as a methodology. The overall aim of grounded theory research is to inductively generate theory based directly on data. This is opposed to the often deductive methods used in quantitative methodologies where aspects of broader theories are tested in detail. Grounded theory has set rules on the selection of participants through theoretical sampling, the constant analysis between data collection in the field (generally interviews, less often observations and document analysis), and directing interview questions throughout the process to target areas of interest in constraining the theory (Glaser & Strauss, 1967; Creswell, 1998). A drawback of using grounded theory is its tendency to not emphasise the local context of participants, and how and why they make meanings, and to stifle the exploratory open-ended methods such as those emphasised in ethnography. Therefore, grounded theory was not utilised. However elements of its inductive nature and resulting theory based on the data were drawn upon in this study, as is common in ethnographic studies (LeCompte & Schensul, 1999).

The methodological framework described above shapes how research methods are selected (Crotty, 1998), as is the case in this thesis. The specific methods used are detailed further in section 3.3. The selection of a methodological framework and methods are both influenced by the perspectives of the researcher, which is discussed next.

3.2.3 My role as researcher

As the researcher in an ethnographic study of qualitative inquiry, I am the primary research tool (LeCompte & Schensul, 1999; Patton, 2002). The role of the researcher in qualitative methodologies influences the findings by inevitably viewing and interpreting the data through a lens (e.g., Creswell, 2003). Additionally, the "baggage" of the researcher is sometimes seen to influence the researcher, and their interpretation of the data and conceptualisation of developed theories (Scheurich, 1995). Therefore, an examination of my demographic information, and some of the values and assumptions I bring to this research is required.

An emphasis in qualitative methodologies on the awareness of the culture, gender, age, and class of the researcher on their relationship with the research participants prompts the need to explore these demographic attributes. I am a 29 (as of early 2014) year old female, born and raised in New Zealand, of European descent. While social class is not emphasised in the New Zealand culture, many participants are from overseas (including the UK, U.S., South Africa, and France), and may place a higher emphasis on this; I would be comfortable to be labelled as middle class. I first worked at GNS Science as a high school student for three summers from 2002/3, and lived in Taupo permanently between the ages of 10 and 18 (in addition to the three year duration of this research), and therefore was familiar with some of the research participants prior to this research. This familiarity and status as a local resident is likely to have increased my acceptability as a researcher in the midst of the GNS Science and end-user communities. The participants have a reasonably wide age range, of which, apart from one other PhD student, I am the youngest. Of 17 staff members and students associated with the volcanology section (not including myself), six are female.

The researcher's assumptions about reality (theoretical perspective) and understanding of human knowledge ('how we know what we know', referred to as epistemology) contribute to the lens applied to the qualitative data (Crotty, 1998). Thus, a brief review of my past experiences follows, which form a basis for my epistemology and theoretical perspective.

A 2.5 year stint (from 2007 to 2010) in a local government environment at Waikato Regional Council (New Zealand) provided me with experience as an emergency management duty officer. I was a potential end-user of the VAL system, however no volcanic eruptions took place requiring a response while I was in this role. Throughout this PhD research I was a CDEM volunteer at the local Taupo District Council, receiving training through the CDEM structure, but witnessing no events. I was also a subcontracted consultant for district and regional councils, contributing towards projects relating to CDEM Plans during this research. This involvement in the CDEM community has allowed an insight that has proved to be very useful in this research, and is a likely influence on the way I view this sector, their information needs, systems, and processes.

I have a background in geology with a Bachelor of Science, and I also completed papers in psychology as an undergraduate at Victoria University of Wellington, New Zealand. This experience promoted an objectivist, positivist perspective in the way I see science to be ‘correctly’ implemented. This means I believe reality is real and knowable and able to be separated from the social actors within it. Crotty (1998, pp. 5–6) describes objectivism as the “view that things exist as *meaningful* entities independently of consciousness and experience, that they have truth and meaning residing in them as objects (‘objective’ truth and meaning, therefore), and that careful (scientific?) research can attain that objective truth and meaning”. However during this research either through increased awareness or a paradigm shift of sorts, I have gained a more interpretive perspective, with the belief that “what people know and believe to be true about the world is constructed… as people interact with one another over time in specific social settings” (LeCompte & Schensul, 1999, p. 48). Changes in theoretical perspectives over time have also been recognised by previous researchers (e.g., Corbin, as noted in Corbin & Strauss, 2008).

These attributes contribute to a framework which influences the way I understand and interpret the research data. They are also reflected in the methodology and choice of research methods (Crotty, 1998; Patton, 2002).

3.3 Research methods

Multiple methods were applied in this research, and are described in this section. Interviews were conducted with scientists and end-users of the VAL system. Participant observations occurred within GNS Science for three years, and countless scientific meetings were attended, as well as those involving end-users and the public. Document analysis provided background information, participants’ thoughts communicated via email, and data relating to historical events. The use of these multiple methods (interviews, observations, and document analysis) enabled triangulation, one of the strategies used to increase the validity of the research through the strengths of one method compensating for the weaknesses of another (Patton, 2002; Creswell, 2003). This approach is ‘embraced’ by ethnographic research (Wolcott, 1999), and it achieves the goals associated with symbolic interactionism of understanding the social context and meanings from the participants’ perspectives.

The fortuitous occurrence of a volcanic crisis event in mid- to late-2012 consisted of coinciding unrest and eruptive activity from three volcanoes in New Zealand after years of quiescence. This provided an ideal structure to this research, of pre-crisis interviews, participant observations and ethnographic informal conversations during the crisis, and feedback by participants on my findings after the events.

3.3.1 Interviews

Interviews are a method used to obtain participants' opinions, thoughts, and experiences (Patton, 2002). They enable the researcher to understand the internal thought processes of participants, which observations alone cannot do. Interviews are particularly helpful to obtain contextual data, memories of events, and information not recorded in other mediums. They are a method useful for actively *enquiring* about aspects of interest, which passive observations often do not allow (Wolcott, 1999). Interviews were used instead of focus groups in order to provide an equal opportunity for both introvert and extrovert participants to share their opinions, and to remove the potential for social psychology influences which may prevail in the group environment.

Interviews in this research were undertaken from mid-2011 to early 2012 with the purpose of extracting information relating to the VAL system. They were **semi-structured,** which involves the predetermination of questions to be used as a guideline during an interview, whilst also permitting participants to discuss what they feel is relevant and important. The semi-structured interviews allowed flexibility, and ranged in length from 30 to 90 minutes. Predominantly open-ended questions were asked during conversations, meetings, and interviews to explore aspects of the VAL system and related processes. Interviews took place face-to-face within the participants' usual place of work (including two scientist participants who I interviewed via videoconference to their place of work, and except for one end-user participant who I met at his home). This enabled their local context to be retained, and enabled me to observe body language, which would not have been possible had the interviews taken place over the phone.

A potential limitation of interviewing as a research method is the reliance placed on the participants' perceptions, their memories, and their selection of what is told to the interviewer. Bias can be introduced if a participant has an ulterior motive, or are otherwise skewed in their version of events. Participants in this research may have been subjected to the desire to guard their professional reputation, particularly as the volcanic context involves factors relating to life safety and politics (and for scientists, competition for funding). Including participants from numerous different organisations, and the building of trust prior to interviews likely helped to reduce these effects. Additionally, inclusion of observations and document analysis methods helped to reduce these effects.

3.3.1.1 Sampling method

Initial sampling boundaries were established based on the reasonably broad and exploratory research questions relating to the VAL system. A **purposeful sampling** method was utilised. This is the intentional selection of research participants – a sampling method commonly used in qualitative research (Miles & Huberman, 1994). People who have used the VAL in the past and/or who are most likely to use the VAL in the future were invited to participate in this research. Further participants were identified as the research progressed to target roles in various organisations to contribute towards addressing the overall research questions (“conceptually-driven sequential sampling", Miles & Huberman, 1994, p. 27). A small number of participants were identified based on **reputational case selection** (i.e. people recommended by other participants and experts in the field, Miles & Huberman, 1994). These participants (from both scientist and end-user groups) were generally in specific roles representative of an industry, or had experience which was thought might contribute valuable input to the research. **Typical case sampling** was also used to identify what is “normal or average” (Miles & Huberman, 1994), among end-user participants who were in roles more removed from the field of volcanic management but who may be called upon during future events. This strategy was used to gain an understanding of the general level of knowledge, practices, awareness, and opinions of particularly the end-user community and decision-making personnel within volcanic regions, but also volcanology scientists at universities.

Many end-user participants were identified through Volcano Advisory Group meetings (including TSVAG, CPVAG, and CAG). These participants were targeted based on their roles and locations, related to their likely involvement in future volcanic events. End-user participants also represented MCDEM, CAA, major land managers (i.e. DoC), and the insurance industry. Participants were nested within multiple layers of context. For example, a participant may have a specific role involving volcanic crisis management, located within a local council organisation, within a regional CDEM Group, and within the nationwide CDEM framework, who is allocated to the end-user participant group for this research. This means that the position of a participant on this ladder correspondingly influenced their familiarity with organisational roles during a response, ranging from national strategic management processes down to the details of a localised practical response to an event.

Scientist participants who were affiliated with GNS Science were selected based on a range of roles, including a technician, volcano seismologists, geodesists, other volcanology roles, and management. Most of these GNS Science participants are involved in VAL decision-making during a crisis, and most regularly attend routine monitoring meetings to discuss the status of activity at New Zealand's volcanoes. The people in these roles were identified during this research while I was based at GNS Science and by attending various meetings. Volcanologists from multiple universities nation-wide were also interviewed. These participants collaborate with GNS Science for research, as well as during volcanic crises (as was observed during this research).

Random sampling, which is often used in quantitative research with large sample sizes and a wider population than more focused qualitative research, was not used in this research as specific concepts were to be explored among a defined user group. Additionally, the number of people in scientific and end-user communities in New Zealand who are potentially involved in a volcanic event is relatively small. Therefore it was logistically possible for many people in these communities to be involved in this research. The recruitment of participants ceased at the point of saturation, where no further new information was collected.

All participants were initially contacted and informed about this research by email. A brief introduction to the research was provided, along with information relating to ethics (which is discussed further in section 3.4). Almost all participants accepted the invitation. One scientist and one end-user did not accept the invitation, and one further end-user participant agreed to a phone interview meeting but was subsequently unavailable. In keeping with the more common sampling practices from qualitative research (Miles & Huberman, 1994), a reasonably small number of people were interviewed in this research. 19 scientists and 13 end-users of the VAL system were interviewed over a period of 10 months from mid-2011 to early 2012. As with all research which samples only a proportion of the population, the findings do not represent the opinions of the entire population.

3.3.1.2 Interview structure and questions

As Patton (2002, p. 294) described, "documents prove valuable not only because of what can be learned directly from them but also as stimulus for paths of inquiry that can be pursued only through direct observation and interviewing". An initial document analysis (described further in section 3.3.3) of GNS Science and end-user manuals, plans and reports, and informal conversations with scientists and end-users contributed towards the formation of interview questions.

In order to target paths of inquiry identified prior to the interviews and maintain flexibility for an exploratory approach, a semi-structured interview strategy was adopted. Preconceived neutrally worded, open-ended questions were used as a guideline in the interviews (example interview questions are included in Appendix 5). The scope of the questions in the guideline resembled an ‘hour glass’ structure with general, broad questions at the start to ease each participant into the interview, followed by more specific (narrow) questions relating directly to aspects of the VAL system. The interview ended with more general, open-ended questions to incorporate any further issues the participant felt were related. Within this structure, questions were re-ordered as necessary to maintain the feel of a natural conversation. Additional questions were added in response to issues discussed by participants, and some questions which became redundant based on an individual’s responses were eliminated. A small number of questions were added to interviews throughout the data collection stage to investigate issues raised by earlier participants.

Interviews were recorded with the permission of every participant using a small Sony Digital Voice Recorder. Minimal notes were taken during the interviews in order to engage fully with participants and maintain a conversational feel. When specific gestures were made by participants (particularly towards a VAL on the paper copy in front of them), I would enter into a dialogue with them, clarifying what they were pointing to for the benefit of later analysis using the transcript from the voice recording.

Once the interview questions had been asked, if the conversation continued it inevitably had a more informal feel. Sometimes participants waited until the recorder had been turned off before expressing what may be their ‘true’ opinions on more sensitive topics. Therefore it is possible, even likely, that the presence of the voice recorder altered or censored the participants’ responses during interviews.

Immediately after each interview, notes were taken as extensively as possible to aid recollection, particularly regarding aspects such as:

- the interview setting
- any interruptions
- body language impressions

- an overview of the participant's opinions and comments as a backup to the voice recording
- my reflexive thoughts on concepts.

The voice recording was backed up as soon as possible and metadata recorded, with both copies kept in secure electronic folders. The signed (hard copy) ethics form and notes taken were stored in a locked filing system in my office at GNS Science, Wairakei, for the duration of the research. I promptly transcribed the voice recordings for the first two interviews to check my interview technique and to begin the analysis process. The rest of the voice recordings were transcribed professionally (i.e. by someone else) for later checking and analysis.

3.3.1.3 My role as interviewer

It is recognised that how a researcher presents themselves can influence the outcome of the study (Fontana & Frey, 2008). Participants were recognised as the experts during the interviews, as I sought to understand their opinions and meanings placed on the VAL system and other aspects of volcanic crisis management. I wanted to understand the participants' role and viewpoint from their perspective rather than "superimpose [my] world of academia and preconceptions on them" (Fontana & Frey, 2008).

Whilst the topic of discussion with participants was generally not as sensitive as many other disciplines of qualitative research, I wanted to build a degree of rapport and trust before and during the interviews. This was not only to obtain as much information as possible, but also to build a pathway for future encounters with these participants. As identified as a common approach by Fontana and Frey (2008), a friendly tone and informal conversational technique was used in this research, while following pre-established guidelines throughout the interview.

3.3.2 Naturalistic observation

The method of observation in ethnography is fundamental (e.g., Adler & Adler, 1994). It allows a first-hand collection of data relating to behaviour and social processes. **Naturalistic observation** involves observations in a setting which is generally natural to the community being researched.

Observation traditionally had a goal of being as unobtrusive as possible to maintain objectivity, seen by many as central to social and behavioural science, and a throwback to quantitative research methods (Angrosino, 2008). The earlier practise of attempting to be a complete and unobtrusive observer, with no knowledge by the participants of the research, is no longer ethically tolerated (Angrosino & Rosenberg, 2011). Following the participant observation methods of Bronislaw Malinowski, there was a “shift in the conception of the ethnographer’s role, from that of inquirer to that of participant ‘in a way’ in village life” (Stocking, 1983, p. 93). This is thought to aid in the understanding of a culture and allow it to be described in terms specific to its members.

The **postmodernist** theoretical perspective (which, in its most basic form, rejects the notion that objectivity is possible in qualitative research, Scheurich, 1995) questions whether ethnographers can and perhaps should be aiming for objectivity in observational research (Clifford, 1983, cited in Stocking, 1983)[6]. The process of observation is inescapably selective as the researcher constantly chooses what to register and record (Miles & Huberman, 1994). Nonetheless, the benefits of including observation as a research method to validate interview findings are substantial, and so this approach was taken. The method of observational research provides context in which ethnographers become members of the community to be studied (Angrosino & Rosenberg, 2011). It requires an awareness and acknowledgement of the influences created by the presence of the researcher on participants, and the resulting relationships with members of the community, not just the minimisation of those influences (Angrosino, 2008).

Limitations of exclusively using observations as a research method are the inability to understand internal thought processes of participants, the potential to influence the behaviour of the community if they are aware they are being observed, and the distortion of data by the observer’s interpretation, introducing biases to the research (Patton, 2002). The use of interviews and document analysis in additional to observational methods lessens these limitations, as does a lengthy duration of observation.

3.3.2.1 Research setting – GNS Science

As discussed in Chapters 1 and 2, GNS Science is the government-appointed agency to monitor New Zealand’s volcanoes (through the GeoNet project) and communicate this information to end-users. Most GNS Science staff in the volcanology section are based at the volcano

[6] This also applies to the method of interviewing, as postmodernists reportedly believe that the “conventional, positivist view of interviewing vastly underestimates the complexity, uniqueness, and indeterminateness of each one-to-one human interaction” (Scheurich, 1995, p. 241).

observatory at Wairakei Research Centre, 10 km northeast of Taupo township. A small number of GNS Science volcanology staff are based at an office in Avalon (Wellington), 370 km south of Taupo; they occasionally visit the Wairakei office, and regularly join meetings via videoconference. In order to undertake naturalistic observations, this research was undertaken at the Wairakei office. The duration of my immersion in the GNS Science community was three years, from August 2010 to August 2013. After the initial research planning stage and completion of the ethics approval process (described further below) between August 2010 and May 2011, participant observations contributing towards the findings of this research took place between May 2011 and August 2013. The focus of observations was on the culture of GNS Science volcanology staff relating to their use of the VAL system, and the identification of improvements which could be made to the VAL table itself.

At the time of the interviews (mid-2011 to early 2012) no eruptions had occurred at New Zealand's volcanoes since a short-lived phreatic eruption at Ruapehu in September 2007 (GeoNet, 2007). Since that eruption, one exercise took place (Exercise Ruaumoko in 2008), and there was an unrest episode at Ngauruhoe from June 2006 (GeoNet, 2006) until December 2008 (GeoNet, 2008), as well as on-going low levels of unrest at White Island and Ruapehu volcanoes. The coinciding unrest and eruptive episodes at Tongariro, Ruapehu, and White Island volcanoes during this research was out of the ordinary for scientists at GNS Science, and a test of team dynamics and functions during a full response. This provided an ideal situation in which to observe the culture of the group, their management of concurrent unrest periods, and their use of the VAL system, including multiple level changes for volcanoes with different characteristics.

In mid-2012 (after the completion of the interviews for this research), the volcanology department at GNS Science underwent a re-structure. The GeoNet monitoring programme reached the end of its initial development stage, and the focus shifted to maintenance. Role changes for some staff resulted in months of uncertainty and anxiety. This occurred immediately prior to the onset of the July 2012 White Island eruptive sequence, and the August 2012 Tongariro eruption, and in the middle of this ethnographic research. Therefore it is acknowledged that the restructuring may have caused the GNS Science response to the eruptions to be unusual in some way with respect to past and future events, potentially affecting the representativeness of the findings of this research.

This research was funded by GNS Science and the New Zealand Earthquake Commission (EQC) through a stipend and covering research costs. In June 2011 I started part-time contract employment with GNS Science, which continued for the duration of this research. From July 2013 onwards I was employed full-time by GNS Science as a Social Science Researcher, and work on this thesis continued only in evenings and weekends. I also undertook paid work as a subcontractor for two of the councils which had staff members involved as participants in this research. These funding relationships need to be acknowledged due to the potential for biases they may cause.

3.3.2.2 My role as observer – participant observation

Participant observation is described by Angrosino (2008, p. 165) as being “grounded in the establishment of considerable rapport between the researcher and the host community and requiring the long-term immersion of the researcher in the everyday life of that community”. In essence, it is the *experiencing* of naturally occurring events by the researcher (Wolcott, 1999).

An active (or borderline complete) membership role of observation, involving participating in the groups’ activities and taking on responsibilities (Adler & Adler, 1994), was assumed in this research. Participant observation was undertaken at GNS Science (the “community” in the definition above) from May 2011 to August 2013. I attended virtually all internal meetings, many interagency meetings with end-users (Table 3.1), as well as social events during this period, and became very much immersed in this ‘community’.

The volcanology staff members at GNS Science were well aware that I was observing the use of the VAL system and reviewing its content (see the ethics section, below). Many of the staff would occasionally have ‘casual conversations’ (an important aspect of ethnographic fieldwork, and in a sense, a form of interviewing, Wolcott, 1999) with me about the reasoning behind comments and behaviour, and the way the system is used by themselves and their colleagues. Emails were also sent to me from GNS Science staff documenting their thoughts and assumptions in using the system.

Table 3.1. Examples of meetings (excluding conferences) attended during this ethnographic research, between August 2010 and August 2013.

Meeting	Description	Frequency and number attended
Internal (GNS Science)		
Volcano surveillance monitoring meetings	Routine meetings attended by GNS Science scientists to discuss monitoring data and vote for the VAL and ACC.	Held regularly (fortnightly up until mid-2012, and then weekly), and more frequently during unrest and eruption events. I attended almost all of them.
Volcanology section meetings	Meetings to discuss administration, technical and strategic aspects of routine issues.	Quarterly, attended almost all.
Internal post-crisis debriefs	Discussion on GNS Science response to an event for identification of strengths and weaknesses.	Held after the White Island and Tongariro eruptions, attended all.
Multi-agency		
New Zealand Natural Hazards Platform	A multi-agency platform aiming to increase resilience to natural hazards through collaborative research.	Occasionally attended monthly meetings.
Caldera Advisory Group	A multi-agency strategic planning group for caldera unrest in the Taupo Volcanic Zone.	Held every 3–6 months, attended almost all.
Taranaki Seismic and Volcanic Advisory Group	Meeting of various scientific and stakeholder agencies to discuss scientific information and plans for an eruption at Taranaki Volcano.	Attended 2 meetings (August 2010 and October 2011).
Auckland Volcanic Science Advisory Group	Multi-agency planning meeting for an unrest and eruption event at Auckland Volcanic Field.	Attended 1 meeting in November 2012.
Central Plateau Volcanic Advisory Group	Meeting of various scientific and stakeholder agencies to discuss scientific information and plans for eruptions at Ruapehu, Tongariro, and Ngauruhoe.	Held every 3–6 months, attended most.
Volcanic Short Course	Hosted by GNS Science, Massey University, University of Canterbury and University of Auckland, aimed at communicating scientific information to end-users on volcanoes and hazards.	Held annually, attended all, and I coordinated it in 2012 and 2013.
Coordinating Executive Group (regional council) meetings (Bay of Plenty and Waikato regions)	Local government meetings to discuss plans relating to all hazards. Invited along to present on caldera unrest.	Attended in July 2011 and July 2012.
Lifeline utility meetings (Bay of Plenty and Waikato regions)	Local government meetings to discuss plans relating to all hazards and lifeline infrastructure. Invited along to present on caldera unrest.	Attended in September 2011 and February 2012.

Emergency Management Committee (district and regional CDEM) meeting	Local government meeting to discuss plans relating to all hazards. Invited along to present on caldera unrest.	August 2011.
Waikato Catchment Services meeting	Local government meeting. Invited along to present on caldera unrest.	November 2012.
Tongariro and White Island eruption science response meetings	Hosted by GNS Science and (usually) attended by multiple universities and other stakeholders to discuss monitoring data and scientific interpretation.	Multiple frequent meetings from July to August, and November to December 2012.
Tongariro eruption community preparation and response meetings	Hosted by a local community at their marae (meeting house), close to Tongariro, and attended by a few stakeholders and GNS Science. GNS Science provided a science overview of the unrest and likely scenarios (prior to the eruption), and eruption information (after the eruption).	2 attended – before and after Tongariro August 2012 eruption.
Tongariro eruption response meeting with concessionaires	Post-eruption information sharing between GNS Science and DoC with Tongariro Crossing (and other related businesses) concessionaires.	1 attended after August 2012 Tongariro eruption.
Lake Taupo Caldera workshop	Hosted by GNS Science and funded by EQC, attended by stakeholders and scientists from universities to discuss research relating to Taupo Volcanic Centre.	May 2013

As a member of the volcanology section, I had the opportunity to take part in the monitoring meeting discussions and vote for the VAL and ACC. I often abstained from this vote in an attempt to minimise biases. In particular, I wanted to avoid any noticeable consistencies on my preferences in voting. For example, had I voted for a consistently higher VAL than the majority, this may have resulted in participants' comments being more strongly in defence of an opposite viewpoint than an otherwise more neutral account. Nonetheless, whenever I felt a moral obligation to vote, I would do so. As my experience and knowledge grew throughout the duration of this research, I was occasionally called upon for my opinion in group meetings, especially relating to VALs. I tended to oblige, whilst trying not to influence the research findings. I believe the impact of any biases my participation in the volcanology section at GNS Science had during this research are vastly outweighed by the opportunity to discuss the VAL system as a colleague with the scientists, rather than as an 'outside' researcher attempting to understand the system and internal processes.

My presence as an observer may have influenced the behaviour of GNS Science staff. It appeared that on the rare occasions that a voice recorder and/or video cameras were used, there was an effect on some of the participants' behaviour, influencing their choice of seating (so they were not visible by the camera), and, it seemed, causing them to censor some of their comments. However, due to the long time period of the observations, and small proportion of discussions being recorded, the effect of my presence on the findings seemed to be insignificant.

An observational protocol (Creswell, 2003) was followed when taking field notes during observations throughout the time spent at GNS Science. Field notes taken included situational context and demographic information (e.g., setting, who was present, date and time), whether the discussion was electronically recorded, notes on the topic discussed, and identification of specific points of interest. Notes were generally objective, although some included an element of interpretation (as described by Mack et al., 2005). Reflective notes were also documented, tracking my opinions, understandings, assumptions, and ideas over three years.

The method of observation causes findings to be limited to the activities which occurred only during the time period of the research. Often in research involving observations, the time period spent immersed in the community is short. Due to the extensive amount of time spent at GNS Science in this research, I believe my observations of 'everyday activities' have provided a robust basis for my findings. The opportunity to observe the response to the volcanic crises in 2012 has greatly benefitted this research. The frequency of volcanic eruption activity (albeit small events) and the associated VAL fluctuations was higher during 2011–13 than in the past decade – a matter of fortunate timing for this research. The use of interviews and document analysis methods in addition to observations further increases the robustness of this research.

3.3.3 Document analysis

Much of life in modern society is in the form of written texts (Peräkylä, 2008). The method of document analysis enables an insight into historical events, as they are written closer to the time of the event than recollections during retrospective interviews. It involves an *examination* of documents produced by others (Wolcott, 1999). A relatively informal approach to document analysis was utilised in this research due to the subsidiary and complementary role of this method (Peräkylä, 2008).

The main purposes of using document analysis in this research were to contribute towards:

1) The creation of research and interview questions
2) Analysis of how the VAL system is used by end-users (through end-user response planning manuals)
3) Analysis of how scientists determine the VAL (including emails sent to me relating to participants' thoughts on the VALs)
4) The development of foundations for future VAL systems (including detailed thoughts recorded in documents by participants, and notes taken during pre-research meetings).

Additionally, extensive document analysis contributed towards the creation of the Volcanic Unrest Index (with methods discussed further in section 5.5), and the creation of the TVC unrest catalogue (the methods of which are discussed further in section 6.4).

3.3.4 Thematic analysis

Once the interview transcriptions were carefully checked against the recording, thematic analysis was utilised. Thematic analysis is described by Braun and Clarke (2006, p. 79) as "a method for identifying, analysing and reporting patterns (themes) within data". This analysis method is widely used in qualitative research, and seen as a foundational method for analysis. It is used as a contributory tool within other qualitative analysis methods, including grounded theory (Glaser & Strauss, 1967; Strauss & Corbin, 1990), and is proposed by Braun and Clarke (2006) to be an analysis method in its own right. It is flexible, and is not constrained in its application to certain epistemological and theoretical perspectives. It can provide a "rich and detailed, yet complex, account of data" (Braun & Clarke, 2006, p. 78). In this type of analysis, **themes** are identified, which are recognised as a pattern of meaning identified from the data set. An **inductive approach** to analysis was followed, allowing themes to be identified that were different to the initial research and interview questions and analytic preconceptions – a 'bottom-up', data driven approach. This has similarities with grounded theory analysis, but without the theoretically-driven constraints.

Themes were developed through **coding** of the data. Coding is the process of grouping together 'chunks' of text which are thought to have a similar meaning (Miles & Huberman, 1994). The 'chunks' are labelled, and referred to as **codes**. A list of codes was initially created (Appendix 6), with a mix of data-driven and theory-driven codes (Braun & Clarke, 2006). These codes were based on the initial reading of the transcripts and using my notes, and were structured according to initial thoughts on their relationships (adding clarity to the meanings of the codes). The transcripts were then systematically coded, with a small number of additional codes developed during this procedure (for example 'scientists hiding information from the end-users'). Context was retained as much as possible during the coding process through consideration of text surrounding each coded extract. NVivo (v9) software was used to aid the qualitative analysis of the transcriptions. This software allows the written transcript, audio files, and notes to be viewed together to retain context. Additional notes were added to the transcript file from those taken during and after the interview.

Codes were collated into common concepts, and structured into themes (Appendix 7). In order to contain the topic and focus on the VAL system, information provided by the participants on wider subjects (such as general volcanic crisis management information) was not investigated further. These codes were not included in any thematic maps or analysed further from this point. At this stage, the concepts (and related sub-concepts), themes, and relationships relating directly to the VAL system were investigated in more detail by reading and interpreting coded extracts, and creating memos (a record of the researchers thoughts and hypotheses). Differences in participants' opinions were noted and possible reasons for these differences hypothesised. Field notes from observations contributed to this processes. As patterns and relationships were identified, some concepts were re-coded. Concepts and themes were defined based on coded text. Some definitions were developed throughout the interview process. For example, the concept 'what is the purpose of the VAL system?' was identified early on in the interview process based on comments made by initial interview participants. After the realisation that participants had different meanings of what the purpose is, this question was included in subsequent interviews. The concept was developed and defined based on a number of related codes (some resulting from responses to other questions).

The final list of 82 codes used is presented in Appendix 8. Throughout this process, thematic maps (e.g., Appendix 9) were drawn and re-drawn based on these concepts and themes (Miles & Huberman, 1994; Braun & Clarke, 2006), and all relationships were described (or hypothesised) based on the data. Main themes grew and shrank, merged together, and were renamed, and concepts within them were reorganised. For example, the theme which started out being named as 'current phenomena-based VAL system' in Appendix 7 changed to 'content and structure of VAL systems' in Appendix 9 and was finalised as 'a review of the current VAL system' with the main concepts of 'structure' and 'content' (discussed further in section 4.4, with the final version of the thematic map in Figure 4.3). By the end of the analysis process, five major themes had been identified from the data. These were:

1) Establishing the context of the VAL system
2) The relationship between end-users and the current VAL system
3) A review of the current VAL system
4) Influences on scientists' determination of the VAL
5) Future VAL systems

These themes (which are described in more detail in Chapter 4) were investigated in further detail by the analysis of related coded text. The concepts and sub-concepts in each theme were described, and their relationships to the theme defined. The themes are descriptive (semantic), and identified by their 'containment' of related concepts. Themes 4 and 5 in particular also contain interpretive (latent) concepts. The variation in the number of coded extracts for each theme (i.e. the sum of the codes for all concepts within each theme) is between approximately 280 (end-user's relationship to the VALs theme) and 990 (VAL table review theme). The proportion of codes per theme reflects the focus of the questions asked during the interviews. Relationships between the themes and research questions are also described (as suggested by Braun & Clarke, 2006) in Chapter 7 of this thesis.

3.3.5 Maximising validity

To ensure that the findings are as valid as possible, the meanings interpreted from the data need to be tested (Miles & Huberman, 1994). Strategies used to ensure the highest possible level of validity, accuracy, and credibility of these qualitative research findings include triangulation, member-checking, and seeking alternative explanations (each described below). The prolonged period of time spent within GNS Science greatly enhanced my understanding of the processes, assumptions, and culture, which helps to maximise the validity of this research (Creswell, 2003). Additionally, potential biases are clarified throughout this thesis (as suggested by Fontana & Frey, 2008).

Triangulation is the verification of findings through multiple approaches. The use of three types of research methods (interviews, observations, and document analysis) enabled **methods triangulation**, which strengthens a study by increasing its credibility and validity (Patton, 2002; Creswell, 2003). This strategy allows the strengths of one method to compensate for the weaknesses of others. In addition, a variety of data sources were considered, termed **triangulation of sources** (Patton, 2002).

An example of how the use of triangulation improved the findings of this research involved the case of Raoul Island (in the Kermadec Islands, discussed in section 4.4.1.2). This volcano suddenly and briefly erupted in 2006. It was identified through initial interviews with GNS Science participants that at some stage during this event, the volcano switched from the reawakening volcanoes VAL system to the frequently active VAL system. One interview participant discussed the Raoul Island situation, but struggled to remember exactly when it switched sides relative to the eruption. This was checked with two further participants ('triangulation of sources'), who suggested the switch may have occurred at the time of the eruption, but they were not sure. Through document analysis of VABs ('methods triangulation') it was discovered that the change occurred three weeks *after* the 2006 eruption. It was only then that I realised the 'wrong' side of the VAL system was used for three weeks (i.e. despite the Kermadecs being attributed to the reawakening volcanoes VAL system, the frequently active volcanoes VAL system was mistakenly used). This finding was subsequently checked in person with a scientist involved (a type of 'member-checking'), and confirmed.

Member-checking is the testing of the accuracy of research findings by presenting them to participants for feedback (Stake, 1995), and can be considered as a type of **analytical triangulation** (Patton, 2002). After an initial 'peer debrief' of the research findings with supervisors (as suggested by Creswell, 2003), member-checking was undertaken through the presentation of the full VAL results (the draft version of Chapter 4), and a short summary document (Appendix 10), to the participants of this research. These documents were sent out via email to all interview participants and to additional individuals who are likely to be effected by the research findings (including the entire volcanology department at GNS Science), and other potentially interested end-user individuals who were not part of the interview process (also referred to as an 'external audit', Creswell, 2003). 43 per cent (20 out of 47) of those who received the findings provided feedback. General comments were received, as well as a ranking of their preference of the five example systems described in section 4.6, as they had been requested to do. This feedback was incorporated into the final results.

The third method contributing towards the maximisation of validity in this research was **seeking alternative explanations** based on the data throughout the analysis process. This reduces the risk of the identification of one explanation, or definition of a theme, without considering other possible alternatives. An example in this research is the consideration of multiple different interpretations from participants in establishing the perceived purpose of the current VAL system. The different perceptions were included in the results, and the final definition of the purpose was a compilation of the more commonly expressed ideas. It is recognised that this does not accurately reflect the perception of every individual participant, and that each of their opinions is just as valid. However, on the whole, the final definition is thought to be a valid description of the community's perception, which was reinforced by the participants during the feedback process.

3.4 Ethical considerations

Ethnography is the "business of inquiring into other people's business" (Wolcott, 1999, p. 284). It is this process that can potentially harm participants, including their professional reputations and self-esteem. Interviews can affect participants (and researchers) in ways that are not foreseen (Patton, 2002). As such, and as with all research involving human participants, potential consequences need to be considered. Institutional ethics committees provide safeguards to ensure research is undertaken without harming participants' health and wellbeing (Corbin & Strauss, 2008).

Based on the research plan and initial interview guideline used, the risk to participants (including aspects such as social and cultural sensitivity, minimisation of harm, avoidance of deception, respect for persons, and avoidance of conflict of interest) were carefully considered. It was established through discussions with university staff and research colleagues, and in consultation with the Massey University Code of Ethical Conduct, that the interviews and observation methods proposed were low risk, and no more than is normally encountered in the participants' usual roles. A low risk notification (Appendix 11) was accepted by Massey University in April 2011, prior to the collection of data.

All participants were informed of the purpose and aims of the research and what their participation would involve. They were informed of the voluntary nature of participating, and that if they chose to participate

- their identity would remain anonymous and individual responses confidential
- they may decline to answer any questions
- they may withdraw from the study at any time

- they may ask any questions about the study at any time
- they would have access to a summary of the project findings.

In addition to my contact details, participants were given contact information for the supervisors of this research, as well as the director of the Massey University Research Ethics Committee. This information was provided on the consent forms (which are in Appendices 12 and 13) that were signed by interview and observation participants. Data were collected, utilised and stored with methods that comply with the Massey University Code of Ethical Conduct. Caution was taken in the presentation of findings to not cause harm to participants and their professional reputations, and especially to retain anonymity.

3.5 Presentation of results

The findings of this qualitative research relate to the aims described in Chapter 1, and are presented in Chapter 4, structured by themes and concepts. The methodological framework described in the present chapter has influenced the writing style, with the occasional inclusion of personal experiences to demonstrate internal thought processes of the primary research tool (the author).

As previously mentioned, the methods and findings relating to the creation of the Volcanic Unrest Index (VUI) and the catalogue of volcanic unrest at TVC are described in Chapters 5 and 6, respectively. The self-contained nature of these chapters reflects their status as manuscripts that have been submitted for publication to international scientific journals.

CHAPTER FOUR

AN EXPLORATORY INVESTIGATION OF NEW ZEALAND'S VOLCANIC ALERT LEVEL SYSTEM

4 AN EXPLORATORY INVESTIGATION OF NEW ZEALAND'S VOLCANIC ALERT LEVEL SYSTEM

4.1 Introduction

Chapters 1 and 2 provided the background to VEWS, and describe VALs as a communication tool, including for use during caldera unrest. Chapter 3 gave an overview of the qualitative document analysis, interview, and observation methods used in this exploratory ethnographic research to gauge the opinions of scientists and end-users about New Zealand's current VAL system. The results of this research are expressed as five high-level themes. This chapter begins by establishing the context of the VAL system (Theme 1). The relationship between end-users and the current VAL system is then investigated (Theme 2), including their awareness and emphasis placed on the system, and how their actions are influenced by VAL changes. The content and structure of the current VAL system are reviewed according to the participant's opinions (Theme 3), followed by a section on the influences on the scientists as they decide which VAL to allocate (Theme 4). Possibilities for future VAL systems (Theme 5) are then explored, with five options presented as potential foundations, and example systems provided. The inclusion of predictive language and response advice for end-users is considered, followed by a summary of the findings of this research, and an assessment of the impacts of changing the VAL system. A new VAL system for New Zealand is recommended.

Quotes in this chapter are taken directly from participants' responses in this research. To minimise the possibility of identification of individual participants, particularly due to the relatively small number of people involved with volcanological issues in New Zealand, participants' organisations and roles are generally not included with quotes. Each participant is instead identified by a unique number, and is classified as either an end-user (EU) or scientist (Sc).

4.2 Theme 1: Establishing the context of the VAL system

This section explores the context of the VAL system, relating it to other scientific information available for end-users during a volcanic crisis, including the International Aviation Colour Code (ACC). By establishing the context of the VAL system within other scientific information, and ascertaining participants' overall satisfaction and the perceived underlying purpose of the system, a framework can be built for a review of the system. This includes reviewing the table itself, assessing the use of the system by end-users and scientists, and exploring potential future systems. The framework allows a deeper understanding of the positioning of the VAL system both within the related information, and at an interpretive level (establishing the meaning of the system according to the participants). Understanding the context of the VAL system is Theme 1, relating to the first and second research aims (to 'understand the context of New Zealand's VEWS', and to 'explore New Zealand's VAL system and how it is used', respectively) and contributes towards the overall picture of effectively managing and communicating information during a volcanic crisis in New Zealand.

4.2.1 Scientific information in a volcanic crisis

Volcanic information varies widely in purpose, content, source, and reliability. A VAL system is a tool used to simply communicate volcanic information to end-users, but it is not the only source of information that is available during a volcanic crisis. Supplementary sources provide further details, particularly regarding the context around the situation, as well as volcanic hazard mitigation information and CDEM response plans. Sources of supplementary information identified by the participants include:

- Volcanic Alert Bulletins (VABs) (a report issued by GNS Science with volcanic status updates including changes in the VAL)
- Person-to-person contact with GNS Science (particularly by phone during a crisis, or through regular meetings and presentations) and volcanology staff from universities
- Websites (including those run by GNS Science, GeoNet, councils, international organisations and general Google searches)
- Organisation plans (particularly existing council plans and multi-agency plans)
- Workshop course notes (particularly the GNS Science Volcanic Short Course hand-outs)
- Scientific reports (usually volcano-specific and commissioned)
- Media interviews of scientists
- Print media (particularly the MCDEM Tephra magazine volcano issue from September 2004, volume 21)
- MCDEM Datasquirt information bulletins (the vehicle for VAB dissemination to the CDEM sector)
- Regional and Local Councils (who may interpret scientific information and present it with a local context and response advice)
- Organisations including Department of Conservation, Police, and Health organisations

- Local residents, businesses, and tourism operators who can directly observe the volcanic activity
- Volcanic ash reports from aircraft via MetService to GNS Science
- Volcanic ash advisories from Wellington VAAC.

Hardcopy supplementary information, particularly planning manuals, reports, and course notes, tend to be static and are likely to become outdated over time. Sources such as VABs, websites if regularly updated, and person-to-person communication with scientists are generally the most reliable methods of receiving up-to-date information. The information requirements (or wishes) identified by the end-user participants during a volcanic crisis include:

- What is the current situation? Include as much information as possible, such as why the decision to change the VAL was made.
- What are the potential impacts and hazards relating to the current situation, particularly at a local scale? Clear and specific language wanted on who is potentially affected.
- What are the societal impacts likely to be, including on human behaviour and the economy?
- What is likely to happen in the future – is the situation trending upwards or downwards? Will the volcano erupt?
- What has happened in the past and elsewhere? What are the potential scenarios?
- How long can the current situation be expected to last? When will the volcano erupt?
- What is known? What is unknown? Clear statements needed.
- What should the public and other end-users be doing in this situation?

Some end-users would like emergency response action advice (for example, should the town be evacuated?) from the scientists, while others were clear that they expected only scientific information to base their emergency response decisions on.

As there are many sources of supplementary information, and the VALs are issued with VABs, the VAL may not need to contain all elements of desired scientific information as would otherwise be necessary. Furthermore, end-users believe talking directly to the GNS Science scientists is very important to verify information and understand it in a local context, so detailed scientific information should continue to be communicated in this way.

It is generally understood by end-users that there are many uncertainties involved in understanding volcanic systems. While some expressed the wish (as was expected by the scientist participants) for yes/no answers to their questions, they were all aware that it is very unlikely that they will be given these answers due to the uncertainties. Perhaps surprisingly, some participants were comfortable with this. What was stated as more important was receiving the information regularly and in a timely fashion from the scientists, and having the estimates of uncertainty included in the communication.

> "You'd be wanting…[to know] very early on that things are moving through [VAL]3 and we're getting close to a 4, so it would be that wish for that constant flow of information about how things were changing, and even if it was to say – 'we don't know', or 'uncertain', or 'all of these issues that we can't resolve', but it would be [better] to have that communicated rather than to be nothing coming through until a bulletin is issued... We'd be looking to have that conversation and dialogue ahead of the communication of that bulletin" (EU9).

End-users are supportive of receiving information in the form of probabilities. Some of the information for other hazards used by the Regional Councils is already given as probabilities and it is seen as useful to be able to compare the quantitative values for planning purposes.

4.2.2 ICAO Aviation Colour Code

The decision to allocate an ACC has a basis on currently observable phenomena in the same way as the present VAL system. Therefore, as they stand, these two systems are inextricably linked. Some end-users are unsure of what actions need to be taken when the ACC changes. When the ACC changed from Green to Yellow for Ruapehu in April 2011(VAB RUA-2011/02[7]), many end-users phoned the airports to check they had been notified, some phoned other CDEM staff to query the significance, and others communicated the information throughout the CDEM Group structure. Pilots were reportedly confused over the meanings of the levels, and after hearing about the ACC change through other sources, were wondering why they had not been told anything. Additionally, some end-users confused the ACC with the VAL during interviews.

The purpose of the ACC, as described by an end-user participant, is

[7] http://info.geonet.org.nz/pages/viewpage.action?pageId=1474969, accessed on 18 January 2014

> "to give airlines and other air traffic […] organisations a 'heads up' idea about what's going on. It's [… a] trigger for them to look more closely at the more detailed information contained in the volcanic ash advisory message or even the VONA [Volcano Observatory Notices for Aviation] message that we have now" (EU11).

A participant identified the potential confusion caused by having both a number-based and colour-based system as part of the VEWS. The use of colours may also cause confusion with colour-based hazard maps in the future.

At times, the ACC in New Zealand is set at Green ('normal, non-eruptive state') at the same time that the VAL is at 1 ('signs of volcano unrest') at a particular volcano. Because the descriptions for 0 and Green, and 1 and Yellow are similar, this indicates that there are differences in how the ACC and VAL systems are being used (by a majority of voters), and that the words are not being taken at 'face value'. It has been identified through discussions with one GNS Science participant that a potential reason for this is the inclusion of eruption forecasting in the interpretation of the meanings of the descriptions.

An element of eruption forecasting is implicitly being included in the decision-making process in determining the ACC due to its perceived purpose of anticipating where ash will be in the atmosphere in the near future (hours to days). For example, if a volcano is in unrest but the scientist is confident there will not be an ash-producing eruption in the next couple of days based on the monitoring data and time period since the last eruption, they will most likely vote for Green – the lowest level (despite Yellow meaning essentially 'unrest'). This is imposing a linear equal-interval scale onto the ACC with new interpretations applied, rather than using the words in the table at face value. As end-users tend to interpret the two systems based on the face value of the words, this may cause the perception of inconsistency between the two systems, which would result in credibility and trust issues.

The VAL system, not the ACC, is used to determine the size of the Volcanic Hazard Zones (referred to as NZVs) for aviation flight restrictions (Lechner, 2012). The NZVs are effectively cylinders of varying radii and heights centred at a point on the likely vent, the sizes of which depend on the VAL. The NZVs are areas prohibited for flying when meteorological conditions (e.g., clouds) and/or darkness cause an inability to see ash in that area. The reasons behind the use of VALs for these restrictions were attributed to the ACC being introduced recently compared to the NZV system, and the perception that the VAL was more useful in triggering the VAAS. GNS Science scientists put considerable thought and discussions into the decision to allocate an ACC at every monitoring meeting and yet it apparently leads to no procedural actions for any end-user at all. Based on these findings, it is recommended that the use of the ACC to determine NZVs, instead of the VALs, be investigated by the appropriate organisations. As the current NZVs are based on a six level system and the ACC has just four levels, reconfiguration of these zones would be required.

During a routine monitoring meeting, a participant suggested that the ACC may be more effective if it is taken away from the public arena (i.e. not included in VABs or put on the website) and given solely to the aviation industry, for which it is designed. If this suggestion were implemented, it is likely that the potential for confusion would be minimised, particularly when also using coloured hazard maps, and may it reduce the threat to scientists' credibility through decreasing the need for justification if the ACC is changed without a coinciding change in the VAL. While a recommendation of removing the ACC from the public would be supported by the CAA participant, it is possible that it will be seen by some end-users as the scientists trying to hide information (however, the Wellington VAAC does issue this information publically for those end-users who are particularly interested in it).

It is recommended that the 'face value' of the words be used when determining the ACC, as the system was designed and intended for the aviation industry, so no further interpretation needs to be applied. This will achieve consistency across the internationally used system, and is supported by the CAA participant. While the ACC and VAL do not necessarily have to be changed in tandem (this would be difficult as the ACC has four levels and the VAL has six), the meanings of the words in both systems are very similar. If the 'face value' of both the ACC and VAL systems are used the two systems can essentially be associated as shown in Table 4.1. The ACC is not a linear, equal-interval system ranging from no unrest to eruption.

The USGS ACC is the same as the New Zealand ACC (Guffanti & Miller, 2013). During a restructure of the four-level VAL system by USGS in 2006, the VAL and ACC were initially going to be combined into one system (Fearnley, 2011). In this case, the four levels of Normal, Advisory, Watch, and Warning from the VAL system would change in tandem with the Green, Yellow, Orange, and Red levels from the ACC. However, it was decided that the systems should be separate in order to "provide more flexibility to accommodate not only different volcanic hazards, but eruptive styles, and ground and aviation based user communities", particularly in the top two levels (Watch/Orange and Warning/Red) (Fearnley, 2011, p. 165). These two systems can be changed simultaneously in the U.S., but it allows for flexibility in cases where the ground and air hazards are at different levels. A similar approach is taken in New Zealand, which enables flexibility, however the meanings of the levels need to be considered carefully during the decision-making process.

Table 4.1. Potential associations between the New Zealand ACC and VAL based on the 'face value' wording in both systems.

<table>
<tr><th colspan="2">Frequently Active Volcanoes</th><th colspan="2">Reawakening Volcanoes</th></tr>
<tr><th>ACC</th><th>VAL</th><th>ACC</th><th>VAL</th></tr>
<tr><td>Green</td><td>0</td><td>Green</td><td>0</td></tr>
<tr><td>Yellow</td><td rowspan="2">1</td><td rowspan="2">Yellow</td><td rowspan="2">1</td></tr>
<tr><td>Orange</td></tr>
<tr><td>Orange</td><td>2</td><td>Orange</td><td>2</td></tr>
<tr><td>Red</td><td>3</td><td>Orange</td><td>3</td></tr>
<tr><td>Red</td><td>4</td><td>Red</td><td>4</td></tr>
<tr><td>Red</td><td>5</td><td>Red</td><td>5</td></tr>
</table>

Information supplementary to the VALs, including the ACC, is vital to the effective management of a volcanic crisis and would benefit from further research. Due to time and funding constraints, however, this research focuses exclusively on reviewing the VAL system.

4.2.3 Overall satisfaction of current system

The participants were predominantly satisfied with the current VAL system (Figure 4.1), however the need for minor changes was identified. The end-users were more satisfied with the system than the scientists, potentially because they were influenced by their level of awareness and emphasis on the system, the perceived ownership of the system by the scientists (and therefore a trust in the scientists that the system is the best it can be), and inexperience with using it due to the infrequency of eruptions. This indicates the end-users believe the current system generally meets their needs, although many issues were also raised. The outcome of this VAL review is hoped to further increase their satisfaction with the system. The current system has been used in multiple past eruptive episodes, and a scientist participant involved in these eruptions recalls no negative feedback at all on the system. However, as identified by participants, it is important to review the VAL system regularly, even if it's not perceived as "broken". A scientist from GNS Science summarised the need to update the VAL system:

> "This has been developed with a lot of thinking over many years and I guess I just worry that it's out of date in terms of end use, knowledge and expectations, and also what the science can deliver, especially through GeoNet monitoring ... It served a very useful purpose but I think it can be improved" (Sc19).

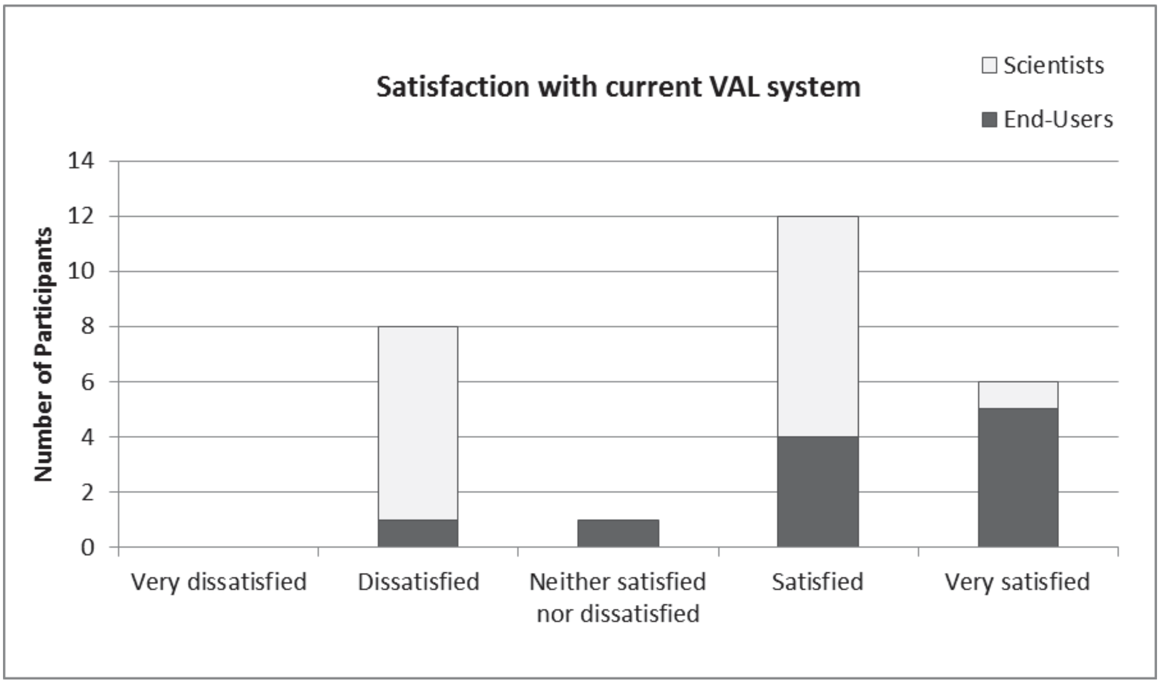


Figure 4.1. Satisfaction of end-user and scientist participants with the current VAL system in New Zealand (N=27).

Major questions associated with the current VAL system that were identified by the participants include:

- What is the purpose of a VAL system?
- Is a phenomena-based system the best foundation for New Zealand's VAL system?
- Should the split between reawakening and frequently active volcanoes remain?
- Is only one level of unrest for frequently active volcanoes adequate?
- Can the system be simplified?

- Should the VAL be determined by the scientists using the system as a guideline or prescriptively?
- Should it include eruption forecasting (i.e. predictive language)?
- Is it appropriate for de-escalation?
- Is it appropriate for all volcano types and risk settings?

These questions are addressed throughout this chapter.

4.2.4 What is the purpose of the VAL system?

The purpose of the VAL system was difficult to define for many of the participants. Opinions were mixed on whether scientists or end-users "own" the system, and who it is designed for.

> "[Is it set up to] make it easy for the scientists, or is it set up so the result is easy for everyone else? If you make the system so easy for everyone else but it's so difficult for the scientists the scientists will never get round to making a decision" (Sc09).

Based on the participants' responses and my observations at GNS Science, it is suggested that the purpose of the current VAL system is *a communication tool used by the scientists at GNS Science to enable end-users to quickly understand the current state of activity at the volcanoes, from which they can decide their response*. Other purposes of the current VAL system that were mentioned include:

- a tool to interpret scientific data for non-scientists
- a guideline for scientists to use to indicate the seriousness of the event to end-users
- the provision of a "reliable baseline" or "level playing field" to help contain rumours
- a tool to communicate the level of hazard or risk
- a "backside covering" exercise to protect GNS Science in case of escalating activity.

The perception of the purpose of the VAL system is mainly influenced by its content, and for end-users, is reinforced through experience and contact with the scientists.

Some of the participants, however, question whether the purpose of the current system stated above is still adequate, given the increase in scientific knowledge of volcanic processes since the current system was formed nearly 20 years ago. Potentially, the purpose of the VAL system (as indicated by the participants) could be:

- a tool to communicate whether the scientists think the activity is going to increase or decrease (in effect forecasting)
- a tool to state the impacts of the volcanic phenomena (essentially a hazard or risk-based system)
- a tool to provide advice on what actions end-users should take
- a tool to indicate the scientific understanding of the underlying magmatic processes
- a combination of the above.

Establishing the intended purpose(s) of the future VAL system will determine what the basis of the future system should be.

The context of the VAL system has now been established. The VAL has been positioned within related scientific information, and the need to recognise the role of VABs and person-to-person communication in the future has been identified. Based on participant's responses, recommendations of changes to the use of the ACC have been made. Participants are satisfied overall with the current VAL system, however they have identified factors that would benefit from a change. In this section the overall purpose of the current system is established, but questions over what the purpose of the future system should be remain. Next is an exploration of the use of the VAL system by end-users.

4.3 Theme 2: Relationship between end-users and the current VAL system

This research involved 13 end-user participants whose roles involve the use of the VAL system, or managing and responding to impacts from a volcanic crisis. They are from a range of organisations including the Ministry of Civil Defence and Emergency Management (MCDEM), regional and district CDEM, civil aviation, insurance, and the Department of Conservation (DoC). The roles, organisations, and industries that use the VAL system impact the factors involved in the relationship, including their perceived purpose and satisfaction with the current system (discussed above), their awareness of it and emphasis placed on it, how they use the system, and their opinions of the content and structure (discussed in section 4.4). The relationship between end-users and the current VAL system, including these factors, is Theme 2, and is depicted in Figure 4.2. Thematic maps such as Figure 4.2 are an important aspect of indicating relationships in qualitative research. An example of a relationship in Figure 4.2 is that an end-user's satisfaction with the current VAL system (the node on the far left) is influenced by end-user factors (such as their role), the perception that scientists 'own' the VAL system, the end-user's awareness of the system, the infrequency of volcanic crises in New Zealand, and the VAL system itself (e.g., the information it contains).

Establishing how the VAL system is used and the users' needs for scientific information within the VAL system enables a clearer picture of what end-users perceptions are based on. This is an important element of constructing effective scientific information for communication to end-users. Understanding the relationship between end-users and the current VAL system is a key theme contributing towards an improvement in the way future VAL systems can benefit end-users.

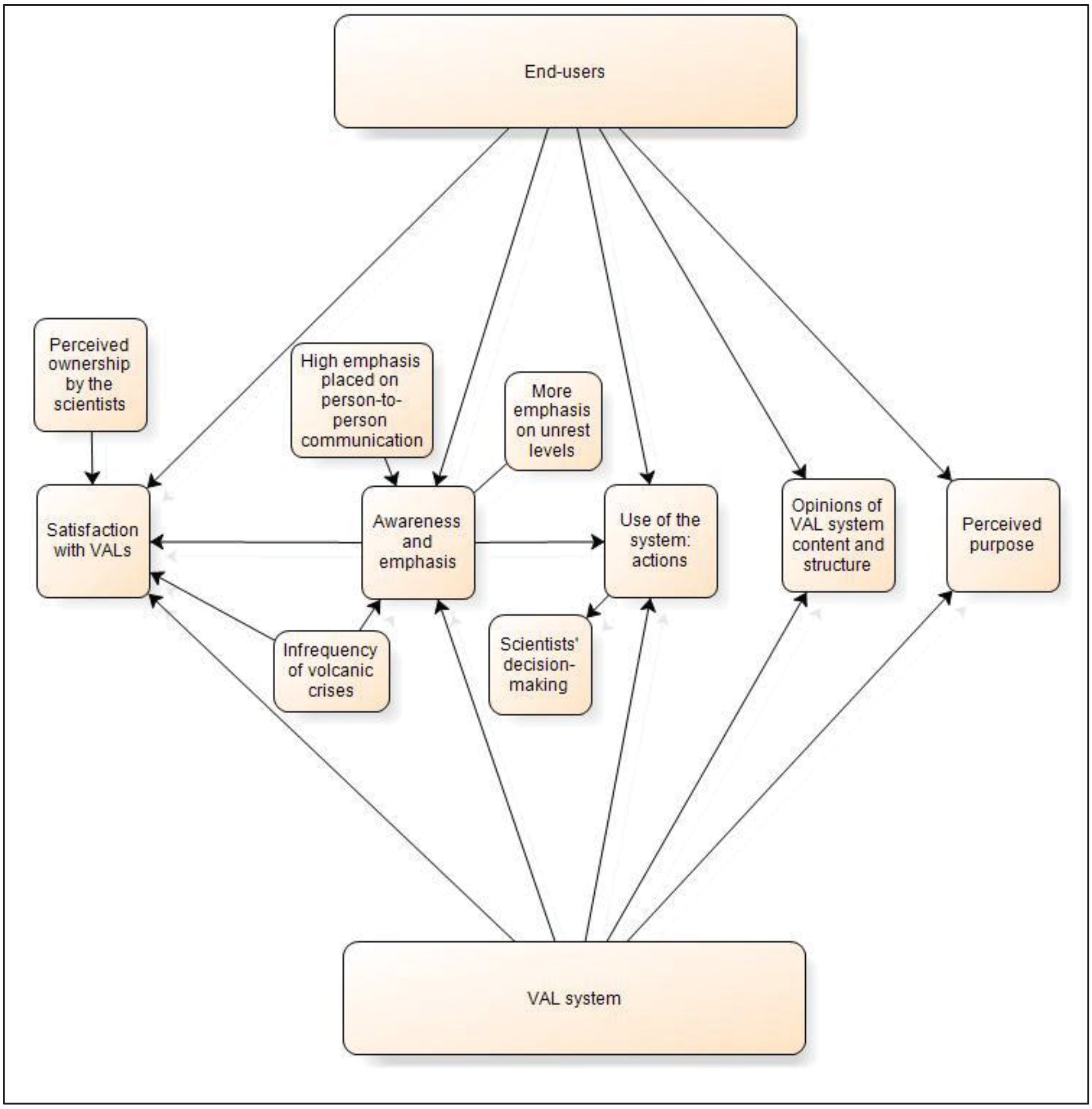


Figure 4.2. A model depicting the relationship between end-users and New Zealand's current VAL system.

4.3.1 Awareness and emphasis on VALs

Almost all participants, regardless of their role, were not familiar with the details of the current VAL system. Some end-users did not realise there was a separate system for reawakening volcanoes, and many were unsure of the overall number and meanings of levels (and therefore at what level to put action plans in place). There was a misperception (amongst a minority) that the VAL system was aligned with the 1–5 tiers of CDEM response, and confusion apparent with other volcanic warning systems, such as for lahars, and the ACC. The lack of awareness of the VAL system was attributed by participants to the infrequency of volcanic crises, especially compared to more frequent hazards in New Zealand such as flooding, and topical hazards over recent years such as tsunami and earthquakes. Additionally, the low emphasis on the system by many end-users is likely to be influenced by the high importance placed on person-to-person communication with scientists. It is thought that should volcanic activity increase in the end-user's region/district or relating to a specific industry, direct communication will provide far more useful information. This indicates that irrespective of the content of future VAL systems and supplementary information, the act of person-to-person communication should be retained and scientists remain readily available, both during a crisis and quiescence. End-user attributes are also a likely influence on their awareness of the VAL tool, including their role, frequency of contact directly with the scientists, experience with volcanic crises, and qualifications and training.

Within the VAL system, more emphasis is placed on levels relating to unrest than eruption by end-users.

> "A system that's basically saying this is how to interpret the [unrest] signs has… far more interest and meaning for people. Once stuff is actually coming out the top or out the side or wherever it's going to come, you're not using the Alert Level in any sort of meaningful way to communicate to the public... They've seen what's happening and they're dealing with it" (EU7).

While this emphasis should be kept in mind for future VAL systems, this reasoning is potentially fuelled by a lack of experience of the use of VALs during long-term eruption situations in which the eruption levels of the VAL system may be useful.

The method of communication of the VAL within VABs may also influence the end-users' awareness and emphasis on the system. One end-user pointed out the lack of emphasis placed on VABs containing VAL information. The participant stated that they would look at the VAL, and if it had not changed (therefore "reconfirming" the current level), they often would not read the rest of the VAB. While scientists place emphasis on supplementary information providing details on an increase in activity (within a single VAL), end-users may not be reading this information and are placing heightened emphasis on the VAL. This encourages the addition of another level indicating heightened unrest to differentiate from the lower levels of unrest commonly observed at some of New Zealand's volcanoes.

This general lack of awareness and emphasis on the VAL system may have influenced the end-users' responses to their overall satisfaction with the current VAL system. It is recognised that issues with the VAL system may have arisen only during a crisis. The low level of awareness of the content of the VAL system is also a likely influence on the end-users' use of the system, potentially causing it to be used inappropriately.

4.3.2 End-user actions influenced by the VAL system

The VAL system is used by end-users to understand the current state (and threat) of activity, on which to base their decisions and actions. The majority of end-users of New Zealand's VAL system do not have detailed contingency plans for volcanic events. Some organisations have planned response actions influenced by the level of volcanic activity, irrespective of the alert level. However a small proportion of actions have been arranged to coincide with specific changes in the VAL. Most of these are fairly generic actions, such as "seek scientific advice", "review plans" or "assemble community leaders" and are flexible arrangements. Other actions associated with VALs are more clear-cut, for example those used by the civil aviation industry.

As described in section 4.2.2, NZVs are used by the civil aviation industry in New Zealand to describe areas of restricted flying due to volcanic hazards, and are determined using the VAL as an "important trigger" (Lechner, 2009). When notified of a change in VAL by GNS Science, or on the detection of volcanic ash by satellite or pilot reports and confirmed by GNS Science, the Meteorological Service of New Zealand Ltd (MetService) request Airways Corporation of New Zealand Ltd (Airways) to issue the appropriate Notice to Airmen (NOTAM), containing NZV information, which is received by the civil aviation industry.

While it is recognised by the aviation industry that a reawakening volcano moving from VAL 0 to 1 does not necessarily signal "imminent volcanic activity", the protocols used by the aviation industry are based on the frequently active side of the current VAL system in New Zealand

(Lechner, 2012). NZVs are prepared for five of New Zealand's more active volcanoes, and the template for future volcanic unrest and eruption episodes for all other volcanoes (including reawakening volcanoes) is also based on the frequently active VAL system. This template was used during Exercise Ruaumoko in 2008 at Auckland Volcanic Field (classified as a reawakening volcano). The CAA created a NZV based on their estimate of where the vent was likely to emerge – a difficult task on a multi-vent volcanic field. The CAA participant in this research reported that the NZV fairly accurately matched the final vent location in the exercise, and that the overall process worked "really, really well".

Concern has been expressed by scientist participants over whether the tying of response actions to VALs is appropriate. The danger of this is seen to be that end-user actions may not be appropriate at the same intensity of activity prompting a VAL change. Instead, it is thought that end-users should carefully consider the actions they need to take, including lead-in times, and only then look for appropriate levels of volcanic activity which might signal this point, whilst keeping the plans flexible. As the current VAL system is predominantly not used in a predictive sense (at least by the scientists), the level is not raised until the phenomena described in that level have actually occurred. Maintaining flexibility to allow pre-event actions to take place is likely to be beneficial for end-users. The inclusion of response advice from scientists in future VAL systems was suggested by a number of participants (discussed further in section 4.6.4), which would impact end-users' actions. This may cause the association between the end-users' actions and the VAL system to be too inflexible and result in inappropriate responses in some situations.

The use of the VAL system by end-users does have an influence on scientific decision-making. This is discussed further in section 4.5.7.1.

The relationship between end-users and the VAL system is an important element of the review of the current VAL system, as well as establishing effective scientific information communication overall. By obtaining input from a range of end-users from many industries and organisations in this research, their opinions on how the content and structure can be improved are incorporated into the review below. Many aspects of the VAL review highlight factors that further influence the end-users' use of the VAL system. In particular, influencing factors associated with the structure include the number of levels overall, the number of levels which relate to unrest vs. eruption, and its use as a linear, equal-interval scale, as these influence the points during a crisis that response actions take place. Factors relating to the content that influence end-user actions include whether the system is predictive or not, and whether it contains response advice. Section 4.6.3 describes the potential for incorporation of forecasting information into the future VAL system, and section 4.6.4 describes response advice inclusion.

Having established the relationship between end-users and the VAL system in this section, the next section involves an investigation of the content and structure of the VAL table itself.

4.4 Theme 3: A review of the current VAL system

The VAL system has been active for just under 20 years in New Zealand. In this time there have been multiple small and short-lived eruptions from numerous volcanoes, a longer duration eruptive episode with small- to moderate-sized eruptions at White Island, one major multi-agency exercise, and one moderate-sized but significant eruption sequence from Ruapehu in 1995–96. This latter eruption sequence prompted the need for a change from the previous VAL system to the current system. As stated by one of the science participants, "in New Zealand we don't have the volcanoes erupting too often, which is a good thing, I guess, but in term of testing the scale it's – it's a bit of a problem" (Sc4). To realise all of the pitfalls of the VAL system, it would need to be fully tested.

The interview participants recognised the need for New Zealand's VAL system to accommodate a wide range of volcano types and potential eruption magnitudes, dormancy periods, eruption and hazard characteristics, and risk environments. In particular, it was identified that the system needs to incorporate the possibility of 'blue sky eruptions' (small eruptions preceded by very little or no heightened unrest precursors) at Ruapehu (and subsequent to the interviews, Tongariro), long and intense episodes of unrest at the calderas, and the unique risk environment of Auckland Volcanic Field.

A review of the current VAL system comprises Theme 3 of this research, and directly relates to research aim #2 ('Explore New Zealand's VAL system, and how it is used'). The opinions of interview participants on the structure and content of the current phenomena-based VAL table are described below, complemented by insights based on numerous meeting observations and conversations, in alignment with the ethnographic methodology used in this research. The structure of this review is outlined in Figure 4.3. An element of discussion is also incorporated with these results to explore ideas suggested by participants. This review considers the context established in sections 4.2 and 4.3 as a basis for interpreting meanings behind participants' responses and perceptions. Possibilities for changes to future VAL systems, including altering the foundation of the system to a hazard, risk, or underlying process focus are detailed in section 4.6.

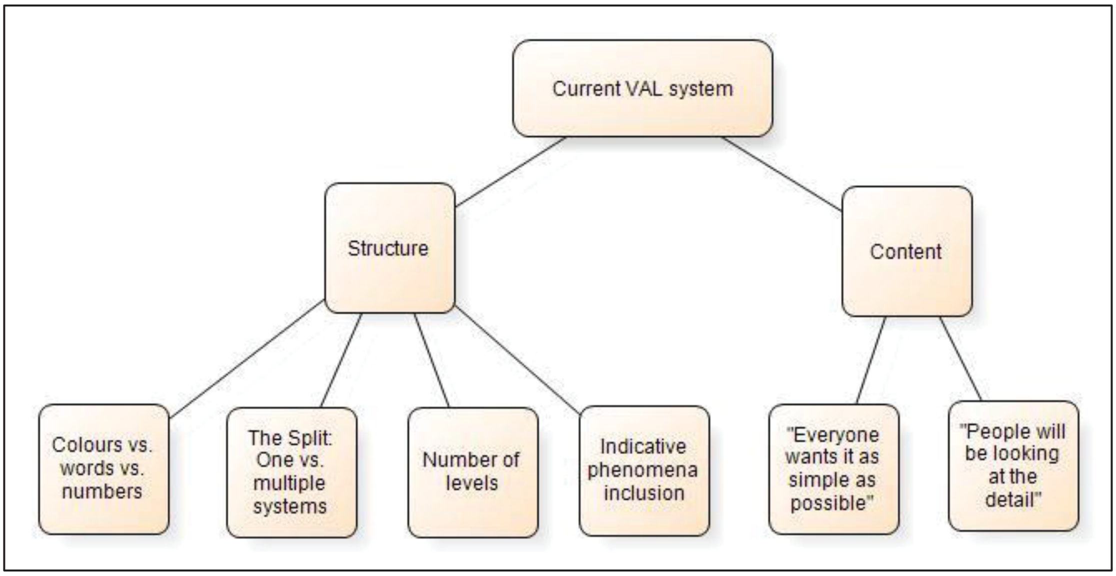


Figure 4.3. Structure of the review of New Zealand's current VAL system.

4.4.1 Structure of the current VAL system

The current VAL system is perceived by some participants as too complicated and unclear with too many words, columns, and multiple duplications. The simplification of the overall structure is seen as being beneficial. The 'official' VAL system in the Guide to the National CDEM Plan (MCDEM, 2006) is displayed as a single table with five columns (Table 2.4), but on the GeoNet website[8], it is displayed differently and split into two separate systems. This discrepancy is seen as confusing and inconsistent.

A suggestion relating to the layout of the current VAL system was to alter the order of the volcano status and indicative phenomena columns so they are the same on both sides to avoid confusion, instead of the current mirrored order either side of the VAL column. Another suggestion was to reorder the numbers so the highest level (5) is at the top and it then decreases to the lowest number (0) at the bottom. This way, as the volcano increases in activity the levels within the VAL system also increase from the bottom to the top.

[8] http://info.geonet.org.nz/display/volc/Volcanic+Alert+Levels, accessed on 11 April 2013

Further considerations relating to the structure of the VAL system are the labels associated with each level (colours, words, or numbers), the split between frequently active and reawakening volcanoes, the number of levels, and inclusion of the indicative phenomena column (Figure 4.3).

4.4.1.1 Colours vs. words vs. numbers

The VAL system currently uses a 0 to 5 scale, where 0 is the lowest level of activity, and 5 the highest (Table 2.4). The use of consecutive numbers implies a linear, equal-interval scale. Furthermore, the classes indicated by the equal intervals are unspecified and may include intensity or magnitude of unrest and eruptive activity, size of the area involved, hazard or danger, time to be spent at each level and/or time before an eruption. Despite this potential for confusion, the majority of interview participants were satisfied with this numeric system.

The use of colour was suggested by a small number of end-user interview participants to aid the identification of the relative level of importance of levels. However the vast majority of participants mentioned that colours may cause confusion with colour-coded hazard maps, and "red-zones" of evacuated urban areas following an event (as was used after a major aftershock of the Canterbury earthquakes in 2011). Additionally, one participant suggested that internationally, colours (and symbols) represent different things to different people and cultures, and may not give the right message. A mixture of colours and numbers are used in the “Volcano Traffic Light Alert System” for Popocatépetl Volcano in Mexico to provide three major levels (Green, Yellow, and Red) of activity, and two to three phases within each colour (De la Cruz-Reyna & Tilling, 2008). A challenge of this system emerged in 2000 when towns excluded from but near to the evacuation zone evacuated, and no ‘negative alert’ could be given for a specific area to indicate that the level of hazard in those areas was relatively low (De la Cruz-Reyna & Tilling, 2008). In this case, communication of the spatial extent of potential hazards, and communication of the level of volcanic activity were merged, and closely tied to response decisions.

The use of words was also considered for New Zealand's VAL system, such as those used by the USGS system (normal, advisory, watch, and warning). New Zealand's MetService regularly issue weather-related warnings also using the terms advisory, watch, and warning. However, these terms are seen by end-users as confusing and not intuitive as to what the relative order is in terms of threat. One end-user participant recognised that the use of watch and warning for thunderstorms in particular by MetService is related to time before the arrival of the forecasted event, and not on levels of predicted severity or probability of occurrence. The weather warning system's association with time may cause difficulties for GNS Science to use similar wording in VALs, due to the current emphasis on describing current volcanic activity only, with no predictive language. No suggestions were made by participants on the possibility of using alternative wording.

In summary, the current numeric system appears to be well received and understood despite the implications of using a linear, equal-interval scale. Colours should not be used, and while the terms advisory, watch, and warning are likely to cause confusion, other words may be able to be applied to future systems.

4.4.1.2 The Split: One vs. multiple systems

New Zealand's current VAL system is divided into two parts; one for frequently active cone volcanoes and the other for reawakening volcanoes (Table 2.4). The 1994 VAL system combined all volcanoes into one system, but included different levels of activity for the volcanoes within each box (Table 2.3). According to scientist participants, scrutiny by media during the early stages of the eruption of Ruapehu in 1995 prompted the need for GNS Science to split the two types of volcanoes into different systems to avoid the confusion and misuse of these descriptions. So why was there a perceived need to have two different meanings for each alert level? Many of the participants, both scientists and end-users were unclear on the purpose of the division between the volcanoes.

The reason given by participants involved in the creation of the current system as to why the split was deemed beneficial is that the outcome of unrest is perceived to be more uncertain for reawakening volcanoes than frequently active volcanoes due to no eruptions being witnessed (except for the 1886 Tarawera fissure plinian eruption, and based on the predominantly rhyolitic geological record, this basaltic eruption was an anomaly (Walker et al., 1984)). Additionally, calderas (which are predominantly in the reawakening volcanoes group) are seen as more likely to exhibit unrest without resulting in an eruption than stratovolcanoes. Scientists have a perception that end-users, who are more familiar with stratovolcano eruptions, think unrest will predominantly result in an eruption. Thus by separating reawakening volcanoes from frequently active volcanoes, it is implied that the volcanoes behave differently, and that unrest at reawakening volcanoes may not result in an eruption. An additional level of heightened unrest was inserted into the reawakening system to help reinforce this meaning. VAL 1 was designed to acknowledge unrest but reassure end-users that there was no threat of an eruption, and VAL 2 allowed the recognition of the eruption threat. These measures were intended to lessen the potential socio-economic implications of the VAL increase to 1. When describing New Zealand's VAL system, Scott and Travers (2009, p. 269) stated that having two systems "reflects the differing responses that are required for these two styles of volcano. The frequently active one has the emphasis on the size of the eruptions, while reawakening focusses more on the preparation for the eruption". This generally ties in with the results of the interview analysis.

Many of the interview participants identified this division as a concern. The majority of participants who expressed their opinions one way or another regarding 'the split' would prefer to have one simplified VAL system for all volcanoes (Figure 4.4).

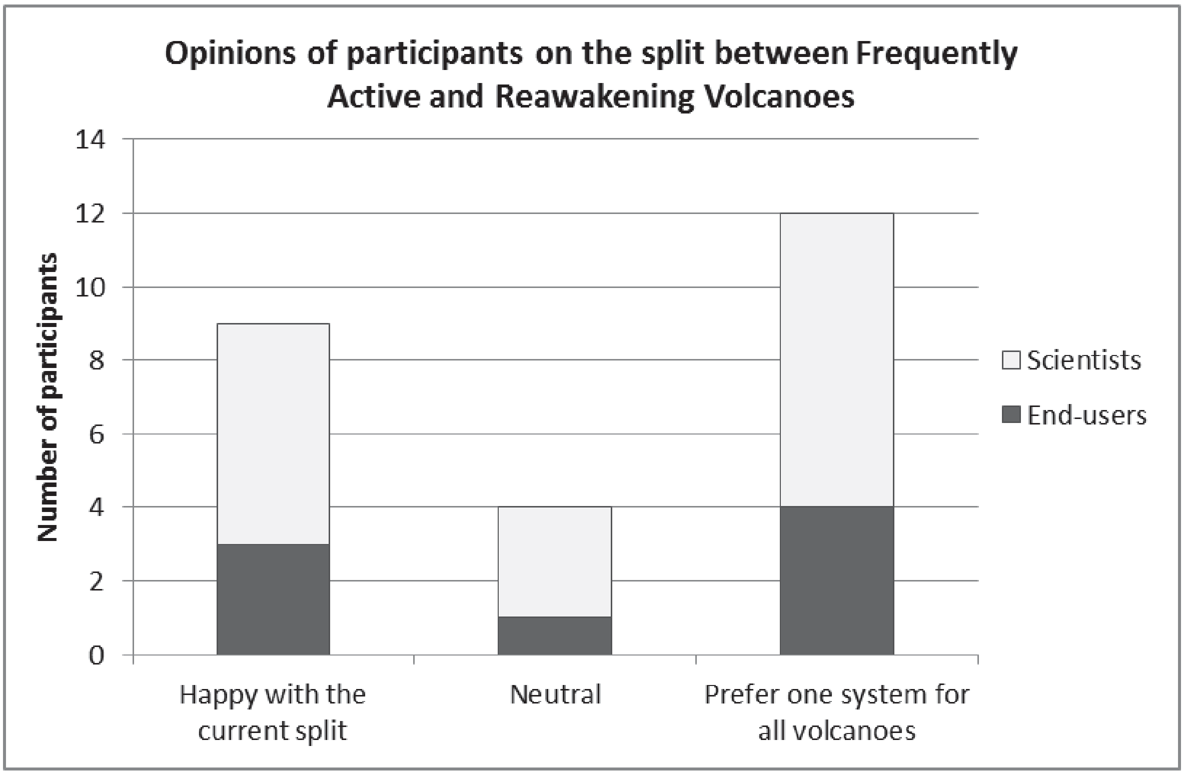


Figure 4.4. The opinions of the interview participants (N=25) regarding the split in the current VAL system between frequently active and reawakening volcanoes.

One of the main concerns over 'the split' is the unnecessary complication of a system intended to be a simple communication tool.

> "The Alert Level Table is designed to give information to the public in a kind of easily readable format. [If] you have two Alert Level tables you confuse the issue and make it more complex than it needs to be" (Sc6).

Another concern was the confusion that may occur when a reawakening volcano reaches an alert level which has a different meaning to the corresponding level on the frequently active system. For example, if Taupo Volcanic Centre (TVC) experiences "confirmed" unrest and is allocated VAL 2, and Ruapehu is experiencing minor eruptions and was also allocated VAL 2, end-users are likely to question why TVC is not also erupting.

Reawakening volcanoes changing sides of the VAL table as they become more frequently active was also identified as a potential issue. The dynamic criteria used to place volcanoes in either group increases the likelihood for this to occur. The threshold used to place volcanoes within the frequently active and reawakening systems, and whether it was intended to be a recurrence interval or dependent on the most recent date of eruption, is undefined. Alternatively, the threshold could relate to 'open' or 'closed' vent systems, however, models of volcanic systems were largely non-existent at the time of the VAL system creation. As eruption recurrence intervals have a much higher uncertainty (especially because smaller eruptions are not preserved in the geological record), it is likely that the date of the most recent magmatic eruption was the parameter used. That date is estimated next.

Okataina was last active in 1886 AD and was placed in the reawakening volcanoes system. At the formation of the VAL system, the most recent eruption at Tongariro was thought to be in 1897 (e.g., NZ Herald, 20 Oct. 1897), and it was placed in the frequently active system – possibly due to its relationship with Ngauruhoe, which last erupted in 1977 (Scott, 1978). If Tongariro is disregarded for this reason, the next oldest eruption date of a 'frequently active' volcano (at the time of the VAL formation) was this eruption of Ngauruhoe in 1977 (since Raoul Island in the Kermadecs was originally placed in the reawakening system). Therefore the threshold used for volcano placement based on the date of the last eruption was either somewhere between 1886 and 1897 AD, or if disregarding Tongariro (and Raoul), somewhere between 1886 and 1977. Some interview participants identified this "arbitrary date boundary" (Sc9) threshold as being potentially misplaced considering the typical dormancy periods of volcanoes – in other words, 1886 AD was not that long ago, and therefore Okataina should be a frequently active volcano. Another participant suggested the threshold could be moved much closer (e.g., to the 1980s) so that Ngauruhoe (and Tongariro) could become a reawakening volcano. If this latter change had been made to the VAL system immediately following the interviews (2011), Tongariro would have had a very short stay in the reawakening volcano system before presumably being moved back to the frequently active system after the eruptions in August and November 2012.

Raoul Island (Kermadecs) was originally placed in the reawakening volcanoes VAL system. A short-lived eruption occurred on 17 March 2006, and the VAL (or Scientific Alert Level, as it was referred to then) was increased to two "as a result of the eruption" (GNS Science Bulletin RAO-06/01, available on the GeoNet webpage[9]). Level 2 was not defined in this VAB, and the VAL system used was not specified (despite this being the first 'reawakening volcano' to have erupted since the system was put in place). Three weeks later, in VAB #4 (RAO-2006/04[10]), it was stated

> "Now that volcanic activity is occurring at Raoul Island it has been decided that it is more appropriate to class the island as a frequently active volcano on the Volcano Alert Level table. This does not change the level of alert, which remains at level 2."

What was not stated relates to the meaning of VAL 2 in the two systems. As can be seen in Table 2.4, level 2 in the reawakening system is "confirmation of volcano unrest. Eruption threat" and level 2 on the frequently active side is "minor eruptive activity" – two very different meanings. This suggests that at the time of eruption, the wrong VAL system (for frequently active volcanoes, despite its listing as a reawakening volcano) was used for Raoul Island. After three weeks the mistake was realised, and the volcano was formally switched to the frequently active VAL system to match the VAL descriptions which were already in use for that volcano. This allowed the (probably more correct) alert level of minor eruptive activity or VAL 2 to be allocated. No "long and involved debate" (Sc7) was recalled by GNS Science participants in the making of this decision. In VAB #5, approximately 6 weeks after the eruption, the VAL was reduced to 1, and after an additional 4.5 months, the VAL was reduced to 0 (VAB #7). Also in this final VAB (RAO-2006/07[11]), it was stated

> "Following the Raoul Island eruption on 17 March the Scientific Alert Level was increased to 2 (*minor eruptive activity*). By 26 April there had been no further

[9] http://info.geonet.org.nz/pages/viewpage.action?pageId=1474811, accessed on 11 April 2013
[10] http://info.geonet.org.nz/pages/viewpage.action?pageId=1474823, accessed on 11 April 2013
[11] http://info.geonet.org.nz/pages/viewpage.action?pageId=1474843, accessed on 11 April 2013

> eruptions and unrest was declining, so the Alert Level was reduced to 1 (signs of unrest)" (author's emphasis).

This statement confirms that the VAL 2 initially allocated in March 2006 was intended to mean an eruption had occurred, and that it was utilising the frequently active system instead of the reawakening system. No records of the public, media, or end-users reaction to the use of the wrong VAL system at Raoul Island in 2006 has been found, and as one participant stated,

> "it sort of fitted with what people's expectations were, I think, and so they probably didn't look into it in too much detail" (Sc9).

However it is a concern identified by some participants that a negative reaction could be the case in the future.

> "When Raoul erupted … we were on reawakening [and] we had to switch to frequently active. And that switch over, it was less important for Raoul but if it was on Taupo or Okataina [and] we suddenly changed from one to the next, that would cause a lot of confusion" (Sc5).

This discussion describes the fluidity of which volcanoes move between the current two systems due to the reliance on a parameter which changes over time. It seems likely that when a reawakening volcano, particularly a caldera, shows signs of unrest or erupts it would not be long before the question is raised of 'at what point does a reawakening volcano become a frequently active volcano?' Movement of volcanoes between the systems is likely to cause confusion, in part due to the use of hard copies of the VAL system in response plans by emergency managers, which describe which system each volcano is currently allocated to.

As the date of the most recent eruption is a moving threshold, other, more rigid and perhaps more appropriate parameters can be explored. The grouping of the volcanoes is a difficult task, "because every volcano is its own beast" (Sc17). The current grouping of the volcanic fields with the calderas is not supported by many participants, as the volcanic processes which influence the potential eruption size and likely length of unrest prior to the onset of eruption are completely different. More robust parameters that could be used to create multiple VAL systems, if this was desired, were identified by participants and have been grouped into the following options:

- Potential size of eruption
- Type of volcano
- Tectonic setting
- Typical speed of eruption onset following unrest
- Risk from a typical eruption
- One for each Volcanic Advisory Group (VAG)
- One for each volcano.

These suggestions are explored further here, with estimated values for these parameters for each active volcano in New Zealand described in Table 4.2. The level of risk has been subjectively determined in this table, taking into consideration the density of the local population for life safety, potential infrastructural and economic impact, and the potential magnitude and frequency of eruptions. If relative risk was to be used in the future to divide volcanoes into similar groups, further in-depth investigation would be required. The 'threat' imposed by each volcano is provided based on Miller (2011) who uses the method documented by Ewert et al. (2005) for monitoring capability assessments and includes hazard and exposure factors. A different grouping of volcanoes results from applying each of the parameters listed above (Figure 4.5). It needs to be recognised, however, that clustering volcanoes together is likely to reinforce the generalisation of their future activity, despite the recognition in scientific literature that all volcanoes are inherently complex, largely unpredictable and associated with high levels of uncertainty (e.g., Newhall & Hoblitt, 2002; Sparks, 2003). For example, "there isn't the knowledge-base to be confident of the lead-in times" (Sc20) before eruptions at rhyolitic volcanoes, which may have long periods of unrest with or without a resulting eruption, or they could very rapidly erupt with little warning (e.g., Castro & Dingwell, 2009; Phillipson et al., 2013).

Table 4.2. Comparison of generalised parameters for New Zealand's active volcanoes. The purpose of this table is to explore potential parameters on which to base the grouping of similar volcanoes for multiple VAL systems.

Volcano	Date of last eruption as of 2013 (and as of 1995)	Maximum VEI of eruptions[12]	Speed of eruption onset[13]	Type of volcano	Predominant magma type	Tectonic setting	Risk level[14]	Threat ranking[15]	Volcanic/Science Advisory Group
Rotorua Caldera	>20,000 yrs B.P.[16]	7+	Slow	Caldera	Rhyolite	Subduction	High	Moderate	Caldera Advisory Group (CAG)
TVC	~232 ± 5 AD[17]	8	Slow	Caldera	Rhyolite	Subduction	High	Very high	CAG
Puhipuhi-Whangarei	0.26 Ma[18]	3	Fast	Volcanic Field	Basalt	Intraplate	Moderate	Very low	None
Kaikohe-Bay of Islands	0.06 Ma[18] or 200–500 AD[19]	3	Fast	Volcanic Field	Basalt	Intraplate	Moderate	Low	None
Mayor Island	Later than 1000 AD[20]	5	Moderate	Stratocone caldera	Rhyolite	Subduction	Moderate	Low	None
AVF	~1450 AD[21]	3	Fast	Volcanic Field	Basalt	Intraplate	High	High	Auckland VSAG
Taranaki	1755 AD[22]	5	Moderate	Stratocone	Andesite	Subduction	High	High	Taranaki Seismic and VAG
OVC	1886 AD	7	Slow	Caldera complex	Rhyolite	Subduction	High	Very high	CAG
Ngauruhoe	1977[23]	3	Moderate – fast	Stratocone	Andesite	Subduction	Moderate	High	Central Plateau VAG (CPVAG)
Kermadecs[24]	2006 (1964)	6	Moderate – fast	Stratocone caldera	Dacite	Subduction	Low	Moderate	None
Ruapehu	2007 (1995)	5	Moderate – fast	Stratocone	Andesite	Subduction	Moderate	Very high	CPVAG
Tongariro	2012 (1897[25])	5	Moderate – fast	Stratocone	Andesite	Subduction	Moderate	High	CPVAG
White Island	2012–2013 (1995)	3	Moderate – fast	Stratocone	Andesite	Subduction	Moderate	Moderate	None

[12] Based on tephra volumes in the literature where VEIs are not published. Puhipuhi-Whangarei VF and Kaikohe-Bay of Islands VF information based on AVF data
[13] Very generalised – all are thought to have the potential to erupt within days of the onset of recognised volcanic unrest
[14] See description in text for factors considered in ascertaining the risk level
[15] Based on Miller (2011) (using the NZ grouping).
[16] Leonard et al. (2010)
[17] Hogg et al. (2012) and Wilson and Walker (1985)
[18] Smith et al. (1993)
[19] Kear and Thompson (1964)
[20] Houghton et al. (1992; 1995b)
[21] Needham et al. (2011)
[22] Druce (1966)
[23] Scott (1978)
[24] Raoul Island and Macauley Island only considered here
[25] E.g., NZ Herald, 20 Oct. 1897

Date of most recent eruption	
Post-1900 AD (Frequently Active)	**Pre-1900 AD (Reawakening)**
White Island Tongariro Ruapehu Kermadecs Ngauruhoe	OVC Taranaki AVF Mayor Island K-Bol P-Wh TVC Rotorua

Tectonic setting	
Subduction	**Intraplate**
Ruapehu Taranaki Ngauruhoe White Island Kermadecs Mayor Island OVC TVC Rotorua	AVF K-Bol P-Wh

Type of volcano	
Stratocone	**Caldera**
White Island Tongariro Ruapehu Taranaki Ngauruhoe	OVC Mayor Island TVC Rotorua Kermadecs
	Volcanic Field
	AVF P-Wh K-Bol

Predominant magma type	
Andesite	**Rhyolite**
Ruapehu Taranaki Ngauruhoe Tongariro White Island	OVC Mayor Island TVC Rotorua
Dacite	**Basalt**
Kermadecs	AVF P-Wh K-Bol

Speed of eruption onset*	
Fast	**Moderate**
AVF P-Wh K-Bol	Taranaki Mayor Island
Moderate - Fast	**Slow**
White Island Tongariro Ruapehu Ngauruhoe Kermadecs	OVC TVC Rotorua

*however all have the potential to erupt within days of the onset of unrest

Estimated risk from a typical eruption	
Low	**High**
Kermadecs	TVC OVC Rotorua Taranaki AVF
Moderate	
White Island Ruapehu Tongariro Ngauruhoe P-Wh K-Bol Mayor Island	

Potential size of eruption	
Small	**Large**
AVF P-Wh K-Bol	Taranaki Ruapehu Mayor Island
Moderate	**Very large**
White Island Tongariro Ngauruhoe Kermadecs	OVC TVC Rotorua

Volcano/Science Advisory Group	
Caldera AG	**Central Plateau VAG**
TVC OVC Rotorua	Ruapehu Tongariro Ngauruhoe
Auckland VAG	**Taranaki SAG**
AVF	Taranaki
No V/SAG	
White Island P-Wh K-Bol	Mayor Island Kermadecs

Threat rating				
Very high	**High**	**Moderate**	**Low**	**Very low**
OVC TVC Ruapehu	AVF Taranaki Ngauruhoe Tongariro	Rotorua Kermadecs White Island	K-Bol Mayor Island	P-Wh

Figure 4.5. Groupings of volcanoes based on a variety of generalised parameters (from Table 4.2) to explore the basis for multiple VAL systems. OVC = Okataina Volcanic Centre, TVC = Taupo Volcanic Centre, AVF = Auckland Volcanic Field, P-Wh = Puhiphui-Whangarei Volcanic Field, K-BoI = Kaikohe-Bay of Islands Volcanic Field.

The separation of reawakening volcanoes from frequently active volcanoes may cause end-users to over-generalise the behaviour of reawakening volcanoes, and imply that an eruption (should one occur) will be bigger than end-users are familiar with (which is likely to be untrue for both caldera and volcanic field volcanoes). Unrest at a volcano in the 'reawakening' list on the VAL table may therefore cause more significant socio-economic impacts than unrest at a volcano on the 'frequently active' list. The separation of the two types of volcanoes also implies that unrest episodes at reawakening volcanoes will be different to those at frequently active volcanoes. For example, there is the impression amongst some end-users that the duration of caldera unrest will be long enough that there will be time to undertake planning once unrest has begun. This latter assumption is unwise as sufficient time to develop the necessary systems and capabilities before an eruption may not exist (Paton et al., 1999).

The complexity of volcanic environments and "personalities" of volcanoes promote the need to have a separate VAL system for each volcano, in some participants' minds. This would enable specific hazards for each volcano to be recognised, enhance the "micromanagement of a crisis" (Sc4) and would incorporate a local context to meet the needs of each community. Other participants specifically mentioned they would not want to "overcomplicate it, by having too many" (Sc14) VAL systems.

In summary, the division of volcanoes into separate systems should be considered very carefully. The need for the VAL system to be used as a simple communication tool very likely outweighs any benefits of multiple tailored and more detailed VAL systems. The ICAO Aviation Colour Code would need to be considered in addition to any other VAL systems in New Zealand, in accordance with the standards set by the international civil aviation industry (Lechner, 2012). The volcanic areas in New Zealand cover a relatively small area, and the management of a volcanic crisis originating from any of these volcanoes generally involves the same group of people (for scientists and end-users). It is likely that having multiple systems in this situation is more likely to lead to confusion and mismanagement than in a larger country where separate groups are responding to the same, familiar volcano over time. In general, and with respect to information requirements to the public and most end-users, volcanic processes and unrest activity have similarities at every volcano regardless of its type or frequency of activity.

Based on interview responses by participants, my observations at GNS Science, and knowledge gained during this research, it is recommended that any future VAL systems in New Zealand combine all volcanoes into one system provided the language can be simplified to accommodate the range of potential volcanic activity. Any division of volcanoes into separate systems based on a single parameter is likely to reinforce inaccurate generalisations, which may increase negative impacts on society by over-emphasising the likelihood of that outcome. For example, if volcanoes were separated into different VAL systems based on their potential eruption size, and unrest commenced at a volcano in the 'very large' eruption category, there may be a higher level of anxiety in the local community than there would be if all volcanoes were using the same VAL system. This is because the potential for a 'very large' eruption is overstated, when, generally speaking, most volcanoes (at least in New Zealand) that have had very large eruptions in the past have more frequently had small eruptions. The VAL will always need to be accompanied by supplementary information, which will include volcano-specific details.

4.4.1.3 Number of levels

The interview participants were mixed in their opinions regarding the overall number of levels in the current phenomena-based VAL system. No participants supported an increase in the number of levels; as suggested by one end-user participant, any more levels and the scientists are "going to start getting lost in debate over what, in the end, are fairly minor changes" (EU7). Some participants (mainly end-users) believe it is important to retain three levels relating to eruptions. It is thought this would enable emergency managers to position the level of 'threat' at any time into perspective with what the maximum event could be when communicating with the public. This view likely perceives the VAL system as a linear equal-interval scale in terms of levels of threat, rather than using the words in the system at face value. If the current VAL configuration of two systems is utilised, limiting it to three levels of eruptions results in a zero to five scale for reawakening volcanoes, and a zero to four scale for frequently active volcanoes (as the latter currently has four levels of eruption).

Other participants (particularly scientists) thought fewer levels would be beneficial, for instance by combining levels four and five, because

> "once you've got a reasonable size eruption happening, you know, it doesn't really matter if it's bigger or smaller one day or the next, it's still a seriously large eruption, [and] impacts have virtually already happened" (Sc7).

The number of levels of unrest vs. eruption was recognised to be an issue. The frequently active system has just one level relating to unrest (VAL 1) and the reawakening system has two (VALs 1 and 2). Having only one level of unrest for frequently active volcanoes was stated to be "a big, big issue" (Sc5), and the most important flaw in the current VAL system for some participants. A large portion of the interview participants thought that an additional level relating to heightened unrest would be beneficial for the frequently active volcanoes as "it's too eruption top-heavy" (Sc1), and there was not enough "leeway" with only one level containing a large range of unrest intensity. This is particularly the case for those frequently active volcanoes that currently sit or could remain on VAL 1 for a long period of time (such as Ruapehu and White Island). Having an additional level would enable a heightened state of unrest that is more likely to lead to an eruption to be recognised and effectively communicated. The need to have more levels relating to unrest is thought to enable emergency managers to undertake decision-making, preparations, and evacuations before an eruption occurs. In order to easily communicate the level of unrest activity using the current system, scientists fairly often use an informal, undefined, and subjective decimal point system, particularly between levels 1 and 2 (e.g., 1.5 or 1.9). This was mentioned by many of the participants, both end-users and scientists, and was identified as being a useful, albeit informal method in the absence of a more gradational system.

Those who did not support the additional unrest level at the time of the interviews cited reasons which included the tendency for scientists to "micromanage" within one VAL if the volcano had been showing that level of activity for an extended period of time. It was thought that VABs could be used to communicate changes in unrest activity adequately without an additional alert level. The desire for an additional unrest level was attributed by one participant to the influence of a lack of 'experience and knowledge' on their scientific decision-making (i.e. if a voting scientist is inexperienced, they are more likely to want an additional unrest level; this influence is discussed further in section 4.5.2). Other participants stated that an additional level would only be beneficial if either an element of eruption forecasting, or levels of hazard were introduced to the system.

In determining the number of levels overall and the number of levels relating to unrest vs. eruption in future VAL systems, the perception of using the system as a linear, equal-interval scale needs to be considered. How close each level is to the highest level in the table may well have more influence on behaviour than the words used to describe each level. Labelling levels with words rather than numbers may be a method to dispel the perception of the system being a linear, equal-interval scale (however the use of the colour-coded ACC as a linear scale, discussed in section 4.2.2, may dispute this).

4.4.1.4 Indicative phenomena column inclusion

The need for the inclusion of the indicative phenomena column within the VAL system was questioned during the interviews. The majority of the participants who expressed an opinion either way supported its inclusion, although some would like the words to be changed. The wording of this column is discussed further in section 4.4.2 below; the results and discussion presented here focus on the higher level inclusion of this information in the VAL system. The purpose of its inclusion was identified by participants to be 1) for scientists to use as a guideline for which alert level is most appropriate, and 2) to provide end-users with more information on what the volcano status means.

It was recognised by some of the scientist participants that the indicative phenomena descriptions are used to assist in determining the VAL. For this reason, some participants would like to retain the column. The indicative phenomena column inclusion is strongly linked to the influencing factor of using the system as a guideline or prescriptively (discussed further in section 4.5.5). Due to the often lengthy discussions and delays in decision-making caused partly by this relationship, some participants thought it would be appropriate to remove the column, at least from the VAL system communicated with end-users. By removing the column, scientists would have more flexibility in determining the most appropriate VAL without feeling they have to wait for activity to match the words in this column. Additionally, an issue identified by some scientist participants is that the current indicative phenomena descriptions are based on observable monitoring data with very little sense of interpretation regarding underlying volcanic processes. In reality, it is thought that these processes cause indicative phenomena to overlap between levels instead of being clearly segregated. Monitoring technologies and scientific knowledge develop over time, prompting a science participant to suggest generalising the descriptions to reflect this (to allow for future flexibility). Another option suggested was to create a separate list of indicative phenomena for each volcano.

Some end-user participants were interested in retaining the indicative phenomena column, as they felt it helped them interpret what the volcano status and VAL mean. Participants felt that this inclusion of further information helped them to answer media questions, provide more transparency of scientific knowledge and help inform end-users on what they can expect to see the volcano doing at that alert level. It was also thought to help control rumours, and minimise misinterpretations of the volcano status by end-users. However some end-users did struggle with the terminology used in this column and would prefer a simpler approach.

A suggestion made by participants was replacing the indicative phenomena columns with information deemed more useful for end-users. Specifically, information directly relevant to help end-users respond appropriately, information regarding likely hazards at each level of activity, and inclusion of forecasted activity were suggested. These are discussed further in section 4.6.

The section above explored aspects related to the structure of the current VAL system. The focus of the next section is on the content.

4.4.2 Review of VAL content

In a response situation the regional CDEM decision-makers, including those that determine whether to evacuate the community or not, are not scientists and are generally unfamiliar with specific natural hazard phenomena and the jargon used in scientific information communication. They tend to rely on their emergency management colleagues to interpret the information received from scientists, at least until a scientist can be contacted to discuss the situation in person. Additionally, the duties of CDEM employees at district and regional level often involve communicating information on the current situation to a wide range of other responding agencies (who are a step removed from direct communication with scientists). Therefore non-scientists are communicating science during a crisis based on their understanding of the information they have been given. This requires those CDEM personnel, and anyone else in a similar communication role, to accurately and quickly comprehend complex scientific information. In part this can be developed through education, training, and open communication with scientists prior to a crisis, however it is also greatly influenced by the information these end-users receive during a crisis. Often, instead of the (usually important) scientific details, it seems the overall impression of the level of threat, and little phrases and analogies remembered by an end-user are quite influential to the overall multi-agency response to the situation. The content of scientific communication tools such as the

VAL system is an important element of maintaining consistent messages across all levels of communication.

4.4.2.1 "Everyone wants it as simple as possible"

Many participants stated that the current VAL system is complex, "verbose", and requires detailed reading to understand it – and "everyone wants it as simple as possible" (EU3). End-users would prefer a simple tool to quickly comprehend the level of activity, otherwise they are unlikely to read the table at all.

> "If there's too much in there, to be honest with you, you're not going to read it... It needs to be probably a one or a two liner with very clear basic description of what the issue is and where it's at, rather than going into the scientific literature. We can do that. We can drill down later on if we need that" (EU4).

This is particularly the case due to the infrequency of volcanic eruptions limiting the end-users' knowledge and experience, as identified by this end-user participant:

> "Volcanoes don't [erupt] very often, [so] it is easy to be complacent about it. So when it does happen, the message … needs to be simple, clear, and easily understood so people can actually act on that information. Because there is a risk if you have that information in too complex a form, that people miss the message" (EU2).

The simplification of the VAL system relates not only to the content, but also to improvements to the structure, as discussed in the previous section. Suggestions by the participants to simplify the content include shortening the volcano status descriptions to around three words each, investigating the need for the indicative phenomena column (discussed in section 4.4.1.4), and assessing the jargon used in the current system. It was identified that a balance between descriptions being short enough but as unambiguous as possible is required. The research findings indicated that words currently used in the VAL system, including 'geodetic', 'seismicity', 'heat flow', 'magma', 'deformation', 'quiescent' and 'dormant', are not likely to be easily understood by the majority of end-users, and it is recommended that they should be removed if possible.

4.4.2.2 "People will be looking at the detail"

Some of the words used in the VAL system were identified as an issue, particularly by scientists. As "people will be looking at the detail" (Sc5), careful consideration of the words in the VAL system is required. Some described the words in general as "ambiguous" and open to interpretation (for example 'minor', 'large', 'typical' and 'surface activity'). Specific examples of words or phrases needing attention, as identified by participants, are:

1) The words 'significant' and 'hazardous' in the frequently active system are in need of definition.
2) The terms 'possible unrest' and 'confirmation of unrest' were identified by some participants as problematic. During an unrest crisis situation at a reawakening volcano the scientists are thought to be very likely to raise the VAL to 1 only once unrest has been confirmed as magmatic (due to the influencing factors described in section 4.5), not just when there is 'possible' unrest as it currently states.
3) To be able to justifiably state that there is 'no eruption threat' is thought to be difficult in reality, since even very low levels of unrest may result in an eruption (as seen at Ruapehu and Tongariro in the past few years). Therefore an 'eruption threat' is valid at all levels of activity, and it is the probability of an eruption within a certain timeframe that changes with different VALs. As it stands, it is thought that it will be "very difficult" (Sc7) to decide at what level of unrest activity there is a 'threat of eruption'.
4) The phrases 'real possibility of hazardous eruptions' and 'large scale eruption now possible' are seen as ambiguous and in need of a time- or probability-based definition. The inclusion of this forecasting terminology in the reawakening system and not the frequently active system is inconsistent.
5) A scientist participant pointed out that unrest prior to an eruption may suddenly decrease, not just 'increase' (or be 'sustained') as stated in the indicative phenomena column of the current VAL system.
6) In the reawakening system, VAL 3 states minor 'steam' eruptions in the indicative phenomena. This level of detail was thought to be unnecessary, and fuels decision-making difficulties, particularly in relation to the guideline vs. prescriptive use of the system (discussed in section 4.5.5). The discrepancy between 'minor steam eruptions' and 'minor eruptions commenced' in the volcano status column of the same level may also cause issues, as an 'eruption' (without the steam qualifier) is defined as "the arrival of volcanic products at the surface of the Earth" (Simkin & Siebert, 2002-), which steam eruptions may not cause.

An end-user participant discussed the possibility of including common words throughout the system, such as stating 'no eruption' in pre-eruption levels, in addition to the 'eruption in progress' currently used in the eruption levels, as well as level-specific descriptions. This was thought to allow consistency across the system to avoid confusion. However a science participant disagreed with this, stating that VAL 0 (no unrest) is so far removed from being an eruption that it would be better to keep the word 'eruption' out of its description.

One end-user participant proposed the inclusion of a statement describing when the next update of the VAL would be issued, in a similar way to weather forecast statements. However it is thought this might promote the perception that there is more certainty in the situation than there is in reality, and it adds to the fine print text on the VAL system. Nonetheless, it could be considered in the future.

Creating content appropriate for de-escalation is also an important consideration, and discussed further in section 4.5.4. The issue of interpreting the meanings of words (such as 'background' and 'unrest') is discussed further in section 4.5.6. It is likely that regardless of the words selected in any future VAL system, it is inevitable that different interpretations will be applied. However, careful consideration of terminology used in scientific communication, including researching common understanding of terms (especially relating to uncertainty and probabilities), would decrease the chance of misinterpretation and confusion. Defining terms used in a publically accessible domain will also help consistent interpretation of terms.

The above section reviewed the structure and content of New Zealand's current VAL system and explored various alternatives suggested by participants. The improvement of future scientific information communication using a VAL system will take into consideration the aspects recognised here. The next section investigates the factors which influence the determination of the VAL by the scientists at GNS Science.

4.5 Theme 4: Influences on scientists' determination of the VAL

By statutory obligation, the responsibility to determine the VAL for New Zealand's volcanoes lies with GNS Science. Regardless of the content and structure of future VAL systems, the scientists will continue to have difficulties and delays in determining the VAL due to influences associated with determining the VAL. This section explores those influences and the relationships between them (depicted in Figure 4.6), and is Theme 4 of this research. An example of relationships between influences in Figure 4.6 is that the purpose of the VAL, as perceived by a VAL voter, is related to whether they include a hazard/risk and eruption forecasting perspective in determining the VAL. In turn, the inclusion of a hazard/risk and eruption forecasting perspective is related to the desire to maintain credibility. All three of those factors are influences on the determination of the VAL; the factors and their relationships are described further below. The influences recognised here were either directly identified by the participants, or interpreted during analysis based on the data and my observations.

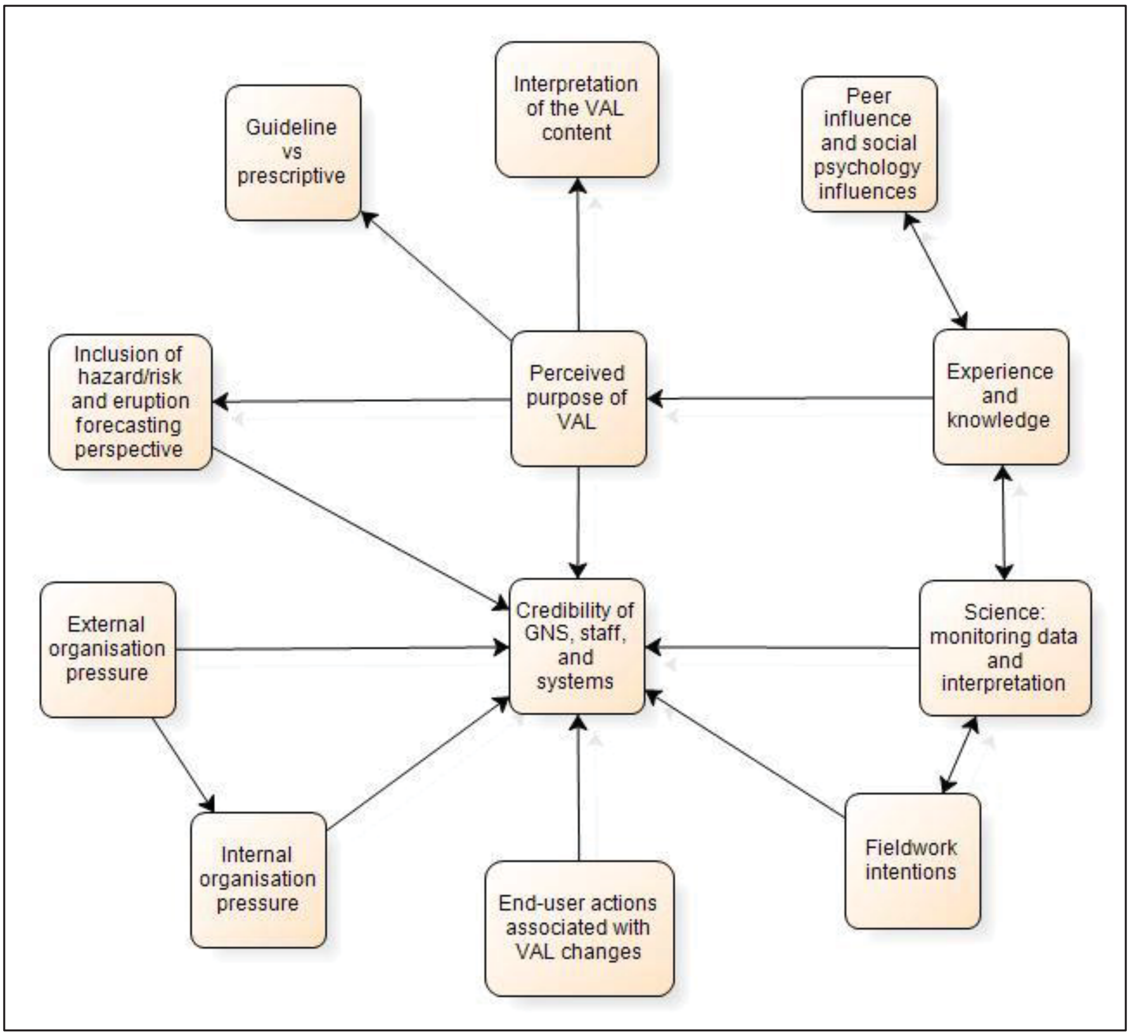


Figure 4.6. Influences on scientists' decision-making to determine the VAL, and the relationships between them.

4.5.1 The science: monitoring data and interpretation

The current VAL system is phenomena-based, with very little inclusion of forecasting or underlying processes involved (identified as an issue and disconnect by some of the science participants). Therefore, monitoring data and scientific interpretation are key influences on determining the VAL, as would be expected. The high level of uncertainty associated with volcanic processes provides a degree of difficulty in determining the most appropriate VAL.

Monitoring and observational data are informally presented and discussed for each volcano during weekly surveillance monitoring meetings. The phenomena are delivered in a variety of formats in the categories of visual observations, seismicity, geodesy, geochemical, and hydrothermal changes. Each of these categories can be at odds with the others with respect to level of intensity, causing difficulties in determining what the overall level of activity (and therefore the VAL) is. The scientists, with the occasional inclusion of scientists external to GNS Science who are unable to vote, discuss their understanding of potential volcanic processes, and develop, test, or constrain conceptual models based on the data. Models do not currently exist for most of New Zealand's volcanoes, generally take a long time (months to years) to determine with any confidence, and often prompt rigorous debate amongst the scientists. Some of the (voting) science participants are concerned that they quite often do not understand the conceptual model conversations, and yet these can be used as a basis for VAL decisions. However the process of interpretation is seen as important because it contributes towards developing an understanding of the situation.

Once the discussion has taken place, the voters must individually transfer these complex four-dimensional models and often contradictory opinions of their peers into the 'linear' VAL system with predefined constraints, and decide what level they think is appropriate. The scientific data and interpretations are most likely the largest influence on determining the VAL, however the subjective nature of this decision allows an influence by many or all of the other factors described in this section. As data interpretations are presented by scientists, an element of influence is involved, particularly regarding their (perceived) experience, knowledge, and personality in general. The current meeting process does not allow a separation of these influences (for example receiving votes anonymously in written format).

4.5.2 Experience and knowledge

A diverse range of experience and knowledge is considered beneficial by the scientists, as different ideas are brought to the table. Experience and knowledge has been found to influence the VAL decision-making process in a number of ways. Scientists' experience and knowledge is limited by the infrequency of eruptions, and this potentially influences their decisions. For example, as the VAL for reawakening volcanoes has never been raised to 1, the scientists are likely to be more hesitant to do so than if this had occurred in the past. It is an unprecedented action, and perceived consequences may become inflated. The documentation and recollection of experiences during previous events is considered vital to not lose the lessons, and to maintain familiarity of the concept and consequences of infrequent events. A number of participants remarked how regular exercises are beneficial and important even if the "exercise is never going to be quite the same as the real event" (Sc18). Holding regular exercises and simulations is supported by a number of previous publications (e.g., Flin, 1996; Taylor et al., 1997; Paton & Flin, 1999; Bird et al., 2010), as well as by MCDEM (2009).

The decision to change the VAL is made quite rapidly once the scientific discussion has been completed, and the experience of the scientists may help them process the conversation and reach a robust decision more quickly than inexperienced scientists.

There is a perception amongst some of the scientists that their relative levels of experience and knowledge influence the scale of their reactions to the situation and potentially VAL decision-making. It is thought that experienced scientists have been "calibrated" by being subjected to effects of past eruptions, such as feeling repeated earthquakes, seeing large pyroclastic flows and feeling ash rain down on their heads, which other scientists have not experienced. Some of the more experienced scientists believe that this influences the relative level of concern felt by each scientist during episodes of volcanic activity, where inexperienced scientists have an inflated perception of event significance. The perception implicitly correlates this level of concern with VAL decision-making. While this research does not definitively test this hypothesis, observations during numerous VAL votes and multiple discussions with voters indicate that other factors (such as the perceived meanings of the levels, the inclusion of a hazard perspective, or whether the VAL system is used as a guideline or prescriptively) are more influential to the decision than experience and knowledge.

The current voting system is dependent on the people present in the meeting. The distribution of the experience and knowledge of the voters was identified by both scientists and technician participants as a possible way to inadvertently skew the results of a VAL vote. The weighting of expert elicitations (as described by Aspinall & Cooke, 1998) in accordance with the voter's experience and knowledge has been considered by GNS Science, but is not currently in place. At GNS Science, the head of the Volcanology Department (HOD) makes the VAL and ACC decision if a supermajority (two thirds of the group present) is not reached in the group voting process. In this situation the HOD, who is generally an experienced and knowledgeable individual, effectively has a highly weighted vote. It is also recognised that while some of the technicians feel they may be lacking in scientific understanding, some of them do have a lot of experience in and around the volcanoes from regular visits, which contributes to the decision-making process. A suggestion by a technician participant was to instigate a lag period between joining the volcanology team and contributing to the voting. The interim discussions would help to increase a technician's understanding of volcanic systems before voting.

The knowledge of the scientists involved in the voting process is greatly enhanced by the combined experience and knowledge of all other scientists actively involved in the scientific discussions. Additionally, the knowledge of the scientists incorporates the experience and knowledge of scientists who have been in similar situations in the past and/or overseas, which is communicated mainly through the literature.

4.5.3 Peer influence and social psychology influences

The influence of a scientist's peers is recognised as an influencing factor on VAL decision-making. The group responsible for the VAL decision-making consists of a wide range of personalities and levels of experience and knowledge. The attendance of GNS Science managers and other GNS Science scientists from related fields (e.g., seismology) has been identified as a potential influence on the decisions made. Additionally, the presence of scientists external to GNS Science who contribute to the scientific data interpretation discussion prior to the voting may influence the decision-making process.

During the first 1.5 years of observations for this research, the VAL decision-making process at GNS Science occurred fortnightly (or more often during a volcanic crisis) during volcano monitoring meetings. A vote was taken for the VAL after the presentation of background information and new data, and a discussion with the aim of interpreting the data. The same person chaired the meeting virtually every week (depending on availability). The voting process usually involved the chair stating something similar to "is everyone happy to stay at alert level 1?" This would inevitably result in a verbal response from a minority and a few silent nods, resulting in affirmation. Only during rare episodes of heightened activity was a hands-up vote prompted (usually by the HOD), and the question changed to something similar to "who wants to vote for VAL1?" The former style of questioning relies on scientists to literally speak up, within a very short time period, and usually against what is perceived to be the opinions of the majority of their peers. The conservative nature of many of the scientists results in an automatic desire to remain quiet. Silence implicitly results in a positive vote, and no abstentions were recognised. The latter style of phrasing the question and method of voting is much more neutral and less likely to result in an erroneous result.

After the restructuring of the Volcanology Department and related GeoNet systems in June/July 2012, meetings became weekly, the chair changed every week (usually the departing duty officer, although the HOD would chair during a crisis, if available), and the voting process predominantly changed. Most chairs began to elicit a hands-up vote using the more neutral style of questioning as phrased above. This may have been influenced by on-going eruptive crises and more frequent evenly split votes. Some chairs continued to phrase the question (with an apparent view to save time, and usually only for volcanoes with apparent steady levels of activity) in a way that required voters to speak up (e.g., "would anyone like to change the VAL?"). In early 2013, this phrasing was questioned during a monitoring meeting by one of the voting scientists, and after a short discussion, the chair agreed to rephrase the question and a hands-up vote ensued. Clearly the potential influence of the phrasing of questions and style of voting is becoming a recognised issue at GNS Science, one which is resulting in an improvement in the neutrality of the process.

Even with the change in voting style to a hands-up vote, there is the potential for peer-influence on the VAL decision. This was identified as an issue by a number of interview participants, who were concerned that inexperienced, less qualified, or less confident voters may vote in agreement with more experienced or outspoken scientists. The influencing scientists are most likely not deliberately trying to sway the votes of their peers, and are probably unaware that their actions may be having these results. In addition to the neutral phrasing of the question as discussed above, allowing a fair and uninfluenced vote to take place without peer influence is important. Specifically, as was observed during the meetings, visibly shaking or nodding of the head, or audibly consenting or disagreeing while the question is being asked, or during the subsequent vote may influence the decision of others.

During Exercise Ruaumoko the VAL votes were perceived to be influenced by two scientists from GNS Science who do not normally take part in the voting. Due to their backgrounds in hazards and risk, and working closely with end-users during past events, they incorporated consideration of "Civil Defence and broader things… not just the science" (Sc18). They promoted the view that in that specific situation involving Auckland city, the VAL should be raised earlier than the rest of the group had been intending. The rise in VAL was thought to be necessary to prompt end-users to initiate response actions that had been delayed. The influence of the incorporation of hazard and risk in the VAL decision-making process is discussed further in section 4.5.7.2, however this is an example of how peer-influence can result in a change in the VAL. Instances of one scientist's opinion influencing others were observed multiple times during monitoring meeting discussions, however it is difficult to determine whether the influence was due to peer influence resulting from their personality, experience, and level of respect from their peers, or if 'their' branch of science and the data relating to it were the more important influences.

A suggestion by the participants to combat negative impacts of peer influence was to undertake blind voting, either by writing votes on a piece of paper anonymously, or by emailing votes to the HOD. But it was also recognised by the interview participants that there are benefits in attaining the opinions of their peers, in order to consider alternative viewpoints – peer influence was seen as positive. This was seen by some to outweigh the potential negative influences of open hands-up voting.

While it was beyond the scope of this research to investigate the influences of social psychology processes involved in the VAL decision, at times biases recognised in the literature were observed or indicated by interview participants. In particular these included the desire for scientists to conform to the group (Asch, 1952), the groupthink phenomena (Janis, 1982), obedience to authority (Milgram, 1974), the presence of an audience affecting performance (in this case external scientists potentially affecting VAL decisions) (Dashiell, 1930), and the influence of a minority (Crano & Chen, 1998). Further research on these and the potential difference between group and individual decisions relating to risk (e.g., Stoner, 1961) in a volcanic environment would be beneficial.

It is suggested that while open discussions and hands-up voting may continue to be the most effective means of scientific debate and style of voting, the scientists should be more aware of the potential influence they are having on their peers by refraining from verbal and visual offerings of opinion during the voting process (other than putting their hand up to vote), and with neutral phrasing of the question, as described above. Another option for rapid blind voting is trialling an electronic means of multiple-choice voting with remote controls (difficulties with incorporating the votes of participants joining the meeting by phone or videoconference would need to be overcome). It is recommended that information on social psychology influences on decisions such as determining the VAL be presented to the scientists to minimise these effects.

4.5.4 Credibility

The credibility of GNS Science, its staff, and the VAL system is perceived by the participants as important as it is associated with trust, and influences the response behaviour of end-users and their use of the information provided. As can be seen in Figure 4.6, the desire to maintain credibility is a key influence on the determination of the VAL, and related to many of the other influencing factors.

Seven factors were identified by the participants relating to how the end-users' sense of trust in the scientists, GNS Science and the system can be threatened (Figure 4.7). 'Fieldwork intentions' is an eighth factor identified from observations after the interviews took place, and is discussed at the end of this section.

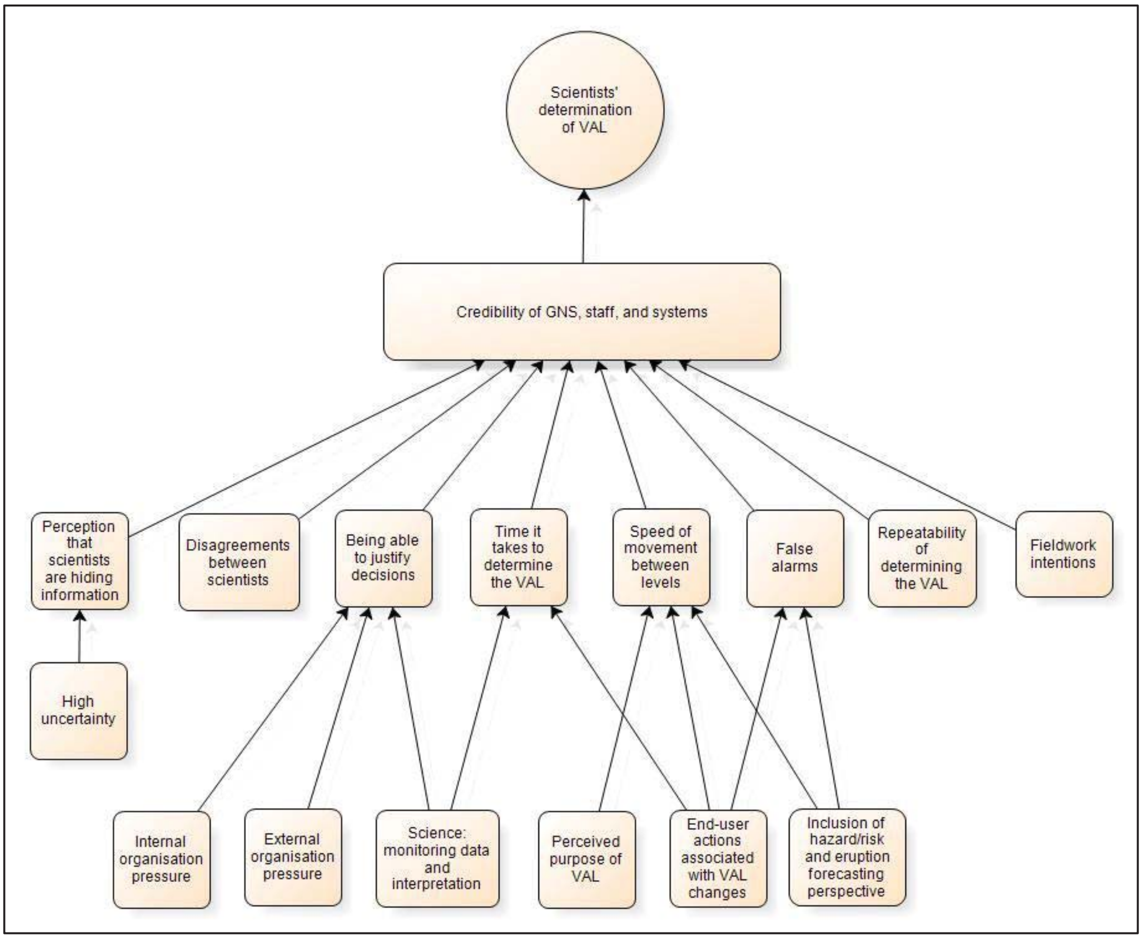


Figure 4.7. Factors associated with the credibility influence on scientists' determination of the VAL.

1) The speed of movement between the levels of the VAL system.

Many of the science participants mentioned their concern about the speed at which VALs are changed. Some were worried that they are changed too fast, or that levels are missed completely in rapidly evolving situations.

According to these participants, the concern lies predominantly with the end-users not necessarily understanding that volcanic situations may call for this rapid movement, and that their response plans being tied to the alert levels restrict their adequate preparation. If the levels change too rapidly (primarily back and forward between two levels), there is a concern that the end-users will think the scientists "can't make up their minds" (Sc5).

Other science participants, however, stated that they were concerned with how slowly the VALs changed, particularly during de-escalation. For very short eruptions (on the order of minutes), the VAL cannot be moved fast enough to accurately match the currently occurring phenomena. Consequently, the VAL is raised as soon as possible (generally on confirmation of the event occurring, which is often after it has finished), and left at that level for an undefined "lag period". This situation, and some of the reasons why the lag period exists were well described by a scientist participant involved in the Ruapehu 1995–96 eruptions.

> "A fundamental problem is you can't respond rapidly enough with [the current VAL system] because it has political consequences if you declare a level five alert, Civil Defence will go to a National Emergency State (sic) which has all sorts of downstream consequences, and then drop back [down] the next day. So automatically in the way volcanoes erupt and behave there is a time buffer that renders very problematic [in] accurately reflecting the state of the volcano in the alert levels. So we were criticised [during the Ruapehu 1995–6 eruption] – we had the volcanoes still at level three when nothing was coming out of the crater. [The end-users asked] "why haven't you dropped it back to level two?" Well, because there is a real possibility of another rapid outburst, and we debated this at length […and we] agreed there was no simple way. You either had to speed this up so it was an instantaneous reaction to some pre-set, machine-determined threshold like seismic intensity or something else, 'til we go from nought to one to two to three to two to one in the space of two hours as there was an eruption outbreak. You can understand that Civil Defence would be just left bewildered by it, so you have to have a time buffer of the order of days to a week. [And] if you're going to change the level up or down

> you have to be reasonably confident that nothing is going to disturb the horses for that length of period" (Sc20).

This extract identifies some of the reasons why rapid de-escalation of the VAL is difficult and hence a lag period is used. It refers to allowing time for likely end-user actions (such as calling a state of National Emergency and associated “downstream consequences”), and the allowance for future eruptions (“a real possibility of another rapid outburst”) without further rapid and frequent changes of VAL (to “disturb the horses”), which incorporates a sense of prediction and hazard. The allowance of these factors caused an inconsistency between the observed events and the wording (and perceived meaning) of the VAL, which prompted the question “why haven’t you dropped it back to level two?”, provoking the need for justification to maintain credibility. The scientists’ desire to use the VAL system to communicate the current situation (the commonly perceived purpose of the system) conflicts with their desire to not fluctuate between levels, which is perceived to maintain credibility. Conflicts between influencing factors such as this can cause difficulties in the decision-making, and result in lengthy discussions.

2) The time it takes to determine the VAL

The time it takes to determine the VAL was identified during this research as an issue:

> "We’re just too damn slow to decide what we’re going to do and whether we should go up or down" (Sc7).

The integration of complex data by scientists through discussion and interpretation, and ‘confirmation’ of trends is often very time consuming and can delay VAL other communication product decisions (“just one more data point” was a common catchphrase). Additionally, the consideration of all of the competing factors that are described in this section influence the time it takes to determine the VAL. During Exercise Ruaumoko the lack of timely decisions impacted end-users' decision-making, according to one of the GNS Science scientist participants:

> "I think it was early on the last afternoon of the exercise, and the group was sitting there and just going round and round and round, about some [wanted to] go to level three or to four or, I can’t remember what it was, and Civil Defence said “we’ve got to put something out, we’ve got to put something out”

> … they ended up basically ignoring us because we hadn't made a decision" (Sc9).

The inability to provide timely information is likely to be an influence on GNS Science's credibility, and therefore on the VAL decision-making process. End-user participants described the reliance they have on the scientists to provide them with the scientific information, resulting in a trust relationship. If the event occurs without prior warning from the scientists and the councils cannot react in time, the trust is likely to be threatened. This is particularly the case if the end-users discover the event has occurred from sources other than the scientists, such as the public and media, who are likely to be demanding answers. This is a difficult situation for both the end-users and the scientists, who often are not able to accurately forecast volcanic eruptions.

One participant stated that

> "in Ruaumoko, I think it was one thing that I got frustrated with was how slow the meetings would be. People would just take forever discussing really fine points when you knew the emergency managers wouldn't give a stuff about that particular point" (Sc18).

In order to not lose credibility and provide information quickly, this participant suggests "we have to have a system that forces us to come to a decision" by placing time limits on discussions, even if it is "slightly military" and "against science".

It should be recognised, however, that the interpretation of complex scientific information is seen to greatly benefit from discussions. The resulting decisions by GNS Science to determine the VAL are generally seen as robust. During a volcanic crisis, time pressures and the influence of maintaining credibility will require the finer details of scientific discussions to be kept to a minimum when determining VALs. A balance between making robust and timely decisions should be sought.

3) Disagreements between scientists on the appropriate VAL in the public arena

While the careful management of disagreements between scientists has been identified in the literature as being an important aspect of effective scientific management of a volcanic crisis (e.g., Fiske, 1984; Peterson, 1988), it was only identified briefly by a small number of the participants in this research. This is likely to be due to the robust statutory obligation for GNS Science to make the VAL decision, and the inclusion of external institutions in preliminary scientific discussions. This has resulted in an effective strategy for all scientific debates to be held away from the media, and a united front with "consistent messages" presented (along with uncertainties). It is a GNS Science practice that the spokesperson (usually a scientific duty officer and the appointed media staff member) supports (and defends, if needed) the resulting VAL decision, even if they voted against it. The potential threat to their credibility through public disagreements may influence the scientists' VAL decision-making by promoting conformity; however, in reality it is likely that any influence in this regard is slight.

4) The perception that scientists are hiding information

Many scientists mentioned the need for scientific information to be "transparent", including reasons behind the determination of the VAL. This is largely due to their awareness of the concern of a number of the end-users who wonder during a volcanic event "is there something going on they aren't telling us?" (EU4). This is fuelled by the inability of scientists to give definitive answers due to the high level of uncertainty. End-user participants identified the need to have close relationships with scientists as it is very important to build trust. Trust helps to overcome the perception that information is being hidden, thus maintaining credibility. While not identified by any of the participants in the interviews, this threat to the scientists' credibility may have a slight influence on their VAL decision-making by encouraging a vote for a change in the VAL to acknowledge changes in activity.

5) The repeatability of determining the VAL

The credibility of GNS Science, the VAL system and the scientists who determine the VAL is influenced by the consistency of the decision.

> "The decision must be transparent and... for it to be scientifically credible it's got to be repeatable; it's not repeatable at the moment" (Sc16).

In order to be consistent over time, the scientists require the same overall level of activity to go to a certain VAL. This repeatability is judged by what end-users (including the media and public) observe at the volcano. For example, there is an expectation that what can be seen at a volcano on VAL2 on one day is the same as another day, and that what can be seen at that volcano is the same as another volcano on VAL2. This expectation has been identified as a serious potential issue in the future due to the difference in levels of activity between the 'frequently active' and 'reawakening' sides of the current VAL system. The desire to have a repeatable decision according to the overall level of activity for each VAL, in order to maintain credibility, is thus an influencing factor on VAL decision-making.

6) "False alarms"

There is a perception that there will be a loss of trust in the scientists if the VAL is increased and no eruptions occur, referred to by participants as "false alarms" (most likely to occur during 'failed eruptions', Moran et al., 2011). This is despite the VAL system not being a forecasting tool (at least as perceived by the scientists). This loss of credibility is thought to be more likely in 'high stake' situations where infrastructural, social, and economic impacts are perceived to be likely to result from a VAL change. Loss of trust due to 'false alarms' was also identified as an expected factor if the VAL system was used as a forecasting tool, likely to be due to the implied increase in certainty followed by a 'failure'. Caldera unrest was recognised as a particularly likely type of 'false alarm' event where scientific credibility will be difficult to maintain if societal expectations are not met. Other examples given were airline rerouting and cessation of major infrastructure supplies due to the change in VAL. The likelihood of failed eruptions and the threat to scientific credibility is seen as a strong influence on VAL decision-making. Due to this threat, the scientists will be hesitant to increase the VAL at volcanoes associated with high risk, most likely at least until unrest has been confirmed as magmatic.

7) The ability to justify decisions

Scientists place importance on being able to justify why certain VALs have been determined, to maintain credibility. This is due to questioning they receive from end-users, particularly the media, on their reasoning and the underlying evidence, and the desire to maintain trust. However, the decision often is not easily justifiable, as identified by this GNS Science participant:

> "The difficult thing is sometimes people go on their gut feeling [to vote for the VAL] and the problem is that you can't take your gut feeling out into the wider community. You do actually need, this is the difficult thing, you actually need some phenomena that you can point to or boxes that you can tick to justify why you've gone to a particular alert level, because if we start playing with the alert levels at [a] reawakening volcano, with the particularly large ones or near

> population centres or something, all the people are going to get quite bothered by it in one way or another" (Sc9).

This is particularly the case if the decision goes against expectations or the situation is unfamiliar to the end-users:

> "If we start doing something that they're not familiar with or it doesn't seem quite logical, we'll get the media on us; that's fine, the media can ask questions. But if we then can't front up to the media and explain why we've done something in a way that people can understand then we'll lose credibility, and more importantly, the system will lose credibility, and if the system has no credibility then the system doesn't work, and it doesn't matter what we think about it" (Sc9).

This desire to be able to justify the decision and maintain credibility is an influence on the resulting VAL decision, especially where there is no supporting evidence to justify the change.

I experienced first-hand this influence on my VAL (and commonly ACC) decision-making on a number of occasions. For example, in one monitoring meeting the majority of the group voted for the VAL to be lowered from 1 to 0, which I disagreed with (I was in the minority). In the next meeting, no further changes to the phenomena at the volcano had occurred and I still wanted the VAL to be 1. But if I voted for 1 and was part of a majority, the VAL would be raised to 1 and we would have to justify why this decision was made when no change in volcanic activity had occurred. This resulted in a conflict of influences between my interpretation of the VAL content, my understanding of the scientific data, awareness of time pressure and many other influences, with this need for GNS Science to be able to justify the decision and maintain credibility – so I abstained from the vote.

Associated with this justification factor is the use of the current VAL (or ACC) as a 'peg' to compare whether the level of activity has changed or not, regardless of the meanings of the words in the system. This was exemplified during a monitoring meeting when the ACC was mistakenly recorded in the meeting minutes as being changed to a lower level. In subsequent weeks, the group voted to retain that mistaken level because the overall level of volcanic activity had not changed. There is, of course, the additional possibility that the majority of the group believed the ACC should have been at that lower level at that point in time, but this isn't supported by my observations or a change in the overall intensity of activity. It is recommended that the face value of the words in the system be carefully considered prior to voting to ensure an accurate level is determined, enabling justification and continued credibility.

Another potentially influencing factor on the VAL decision, and linked to the desire to maintain credibility, is the fieldwork intentions of the scientists. That is, one scientist participant mentioned that it was possible that VAL votes by other scientists were lower than they potentially could be in order to allow fieldwork to take place on volcanoes that were showing signs of activity. Increasing health and safety regulations at GNS Science had been causing scientists to have restricted access to the volcanoes. It should be noted that the VAL is not directly linked to health and safety regulations; however, both the VAL and the regulations are influenced by the common factor of the interpreted state of a volcano, which is determined by group discussions. If those discussions are influenced by the desire to conduct fieldwork, this may in turn influence the VAL decision. This influence was identified after the interviews took place. It is difficult to extract how much of an influence this factor has on the final VAL vote, compared to other factors, as the decision is made internally by each scientist. The influence of fieldwork intentions on the VAL decision is described further in section 4.5.7.5 and is perceived to be linked to credibility (Figure 4.7). This is because the inability for scientists to carry out fieldwork due to the high level of hazard during a volcanic crisis, despite tourists having permission to visit, is seen to threaten the scientists' credibility.

As stated by participant Sc9 above, preserving the credibility of GNS Science, the system, and the scientists through the factors described in this section is seen as an important influence on overall effective management of a volcanic crisis, and an influence on the VAL decision. By remaining credible and maintaining trust, advice and warnings disseminated by the scientists are more likely to be heeded by end-users (e.g., Haynes et al., 2008).

4.5.5 Guideline vs. prescriptive

One of the issues with determining the VAL that was most frequently identified by the participants was the inconsistency between some voting scientists using the words in the VAL system 'prescriptively' (i.e. the description for each level must match the observed phenomena in order to vote for that level), and other voting scientists using it as a guideline (i.e. the system is used more flexibly, and the description for a particular level does not need to match the observed phenomena to receive a vote). The majority of GNS Science scientists consider the VAL system as a guideline (Figure 4.8).

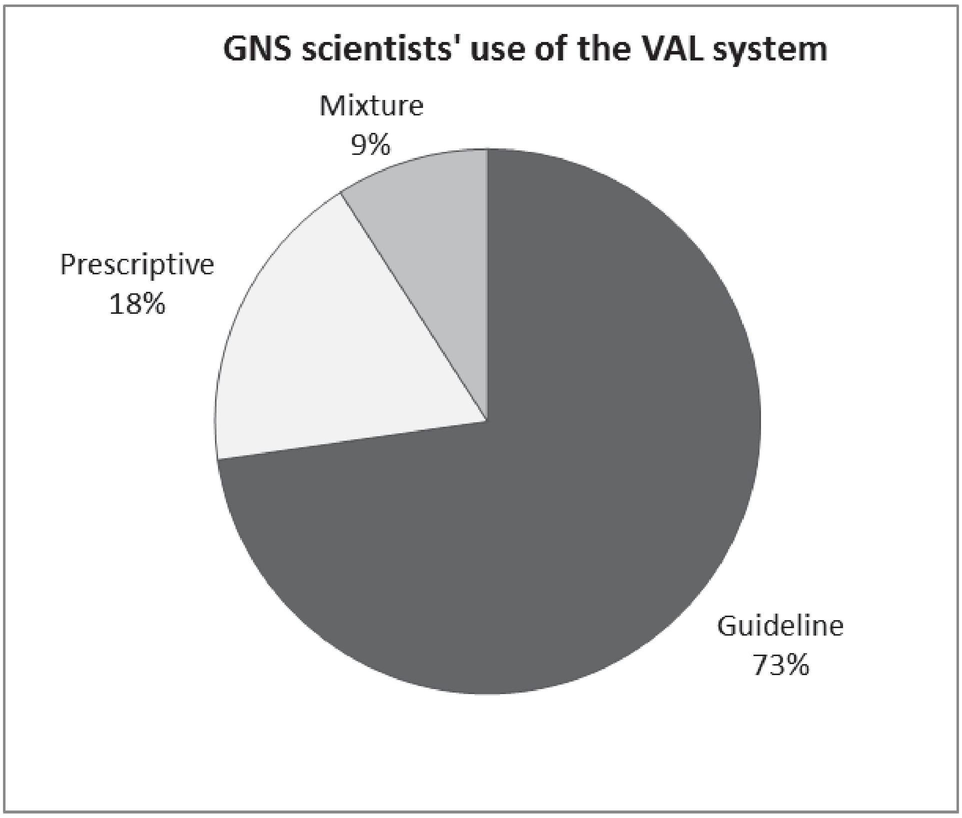


Figure 4.8. The proportion of GNS Science scientists using the VAL system as a guideline, as a prescription or as a mixture between the two (N=11).

Scientist participants' opinions on the use of the VAL system as a guideline or prescriptively (i.e. as a 'check list') tended to be fairly strong, and is likely to be a major reason for lengthy debates in the past. A widely referred to occurrence of this was during Exercise Ruaumoko, where some scientists from GNS Science wanted to raise the VAL up to 3 ('minor eruptions commenced') as a signal to the authorities that the perception of the hazard had increased despite the lack of eruptions occurring at that time (i.e. using the VAL as a guideline), whereas others were strongly opposed since the eruptions were not occurring (demonstrating a prescriptive use of the VAL system). This discussion was seen as excessively lengthy (linked to the 'time it takes to determine the VAL' credibility factor). So what are the reasons behind the scientists' use of the VAL system as a guideline, a prescription, or a mixture of the two? While the preference may be due simply to personalities, the reasons suggested by the participants are listed below.

Reasons for using the current VAL system as a guideline:

- To incorporate subjective interpretation and "gut feeling"

- Because it is one system covering a range of volcanoes, some of which very seldom exhibit certain phenomena
- Due to the belief that the intent of the system should be used ("the spirit of the thing"), rather than the written words ("the letter of the law"; Sc18)
- To be able to incorporate a sense of increased (or decreased) hazard or risk (as occurred during Exercise Ruaumoko)
- Due to the high level of uncertainty over what phenomena will occur, particularly at reawakening volcanoes
- Because there are not enough indicative phenomena included to be able to use it as a check list.

Reasons given by the participants for using the system prescriptively include:

- For the communication of consistent information, particularly due to the inclusion of the VAL system in emergency management legislation
- If it is not used as written it can "convey incorrect information" (Sc6)
- Because the inclusion of indicative phenomena descriptions creates the perception that they should be used as a check list.

Reasons for the use of the VAL system as a mixture between a guideline and a prescription are:

- In order to retain consistency (such as using the 'volcano status' column prescriptively) as well as flexibility (by using the 'indicative phenomena' as a guideline)
- Flexibility is needed for the 'indicative phenomena' as not all of these phenomena occur at the level represented by the 'volcano status' description.

It was suggested by a participant that a check list system could be beneficial (as used in Vanuatu), if it is used as a guideline.

The use of the VAL system as a guideline or prescription is an important influence on the VAL decision-making process. Differences in its use between scientists can result in lengthy debates and delays in decision-making. Obtaining a group consensus regarding how it should be used would be beneficial in both saving time and for robust decision-making, if this is possible. In making this decision, the use of the system by end-users and the purpose of the system should be given a heavy weighting.

4.5.6 Interpretation of the VAL content

The meanings of levels were found to be based on an individual's interpretation of the content of the VAL system, on the perception of what the meanings were originally intended to be when the system was formed in the mid-1990s, and the use of the system as a linear equal-interval scale with little emphasis on the wording. The meanings placed on the levels are obviously very important influences on the VAL decision-making process. The content and structure of the VAL system itself is reviewed in section 4.4.

The interpretation of the content by each scientist is a particularly influential factor for determining the VAL. Definitions of individual words are a case in point, as was observed multiple times during VAL meetings, and identified as an issue by a number of interview participants. For example, the definitions of 'background' and 'unrest' are open to interpretation. This influences VAL votes as 'typical background surface activity' is the definition of VAL 0, and 'signs of volcano unrest' (or 'initial signs of possible volcano unrest' for the reawakening system) is the definition of VAL 1. VAL 0 is where most of New Zealand's volcanoes spend the vast majority of time, and fluctuations in activity cause the threshold between 'background' and 'unrest' to become debated – at what point is the VAL raised to 1? Is 'background' interpreted to mean there is no unrest occurring whatsoever, or is it relative to the volcano's usual state (which for some, is constant unrest)? The time period considered in determining 'background' levels becomes an important factor. If a short period of time is used, the scientists may become like frogs in hot water, not realising the activity is increasing over a longer time period, or that the volcano is in a constant state of unrest. Defining unrest has also been a difficulty associated with decreasing the VAL at the recently active Mount Tongariro. Should a short time span of a few months be considered in ascertaining the background level (i.e. post-eruption activity at Tongariro, which consists of open-vent degassing), or should a longer time period be considered (i.e. decades of activity prior to the eruption)? The ambiguity of the VAL content causes differences in interpretation and results in voting variances.

Similarly the interpretation of 'minor eruptive activity' for some scientists is different to others, and even when the definition of 'eruption' is sought, it also becomes subject to interpretation. If a mud geyser is occurring in a crater and it is thought to be a result of the heat from near-surface magma (as seen at White Island during 2012–13), is it 'unrest' or 'minor eruptive activity'? Once ash is entrained in an eruption column, how big does the column have to be before becoming a 'significant local eruption', a 'hazardous local eruption' or a 'large hazardous eruption' (as stated in the current VAL system)? 'Large' compared to what – previous eruptions at that volcano, eruptions at other volcanoes in New Zealand, or eruptions at similar volcanoes worldwide? The threshold between every VAL is seen as open to interpretation and undefined (but perhaps more flexible).

The meanings behind each level of the current VAL system, according to an interview participant who helped create the system, are described in Table 4.3. This participant stated that "the words 'significant' and 'hazardous' were used to give a dimensionless scale factor, so the table could be applied to several volcanoes" (Sc3).

During the latter stage of my observations it became increasingly apparent that the VAL system and the ACC were being interpreted in different ways by some people, despite similar wording in both (Tables 2.2 and 2.4, and discussed further in section 4.2.2). This indicates that the meanings applied to the two systems (by a majority of voters) are not necessarily related to the words used in the systems.

When this difference in meanings was investigated further through an informal chat with a voting scientist from GNS Science, it came to light that this scientist was mapping a conceptualised linear equal-interval scale onto the four-level ACC scale, giving the words it contains and 'face value' meanings less emphasis than expected. The ACC has been reinterpreted so each colour contributes towards an approximately equal-interval scale. In this conceptualised scale, the levels are given a new or alternative interpretation of the meaning, where

- Green = no unrest, OR 'background' level of unrest, OR unrest, but a low (subjectively determined) likelihood of ash being erupted into the air in the next few hours to days
- Yellow = the volcano has very recently erupted but is not currently, OR heightened unrest which may result in an eruption soon
- Orange = occasional ash eruptions or small continuous eruption with relatively low volumes of ash
- Red = large scale (sustained) ash eruptions, with tall eruption columns and wide dispersal of ash.

Table 4.3. Interpretation of the original meanings of the current VALs, according to a GNS Science participant involved in its creation.

Frequently active volcanoes	VAL	Reawakening volcanoes
Volcano is not showing any signs of unrest, that is, no magmatic signatures in water/geothermal chemistry, temperatures below boiling for altitude, no primary volcanic gas signatures, etc.	**0**	Volcano is not showing any signs of unrest, that is, no magmatic signatures in water/geothermal chemistry, temperatures below boiling for altitude, no primary volcanic gas signatures, etc.
Some form of unrest signature from a volcanic source: heat flow, gas, chemistry, etc. For example SO_2 at White Island, or the heat flow needed to warm Crater Lake at Ruapehu.	**1**	Allowing an acknowledgement of unrest phenomena that have been noticed by the public (or recorded by monitoring), but is unlikely to result in an eruption in the near future.
Eruptive activity attributed to a magmatic source is occurring in the active crater. Impacts of the activity do not extend beyond the crater.	**2**	"Scientifically we become concerned about the volcano". The monitoring data indicate or confirm a magmatic source; there is an eruption threat for the near future.
A significant eruption is occurring which is creating ash columns or explosions, etc., which reach beyond the crater. When people are in their 'normal locations' (e.g., on roads, well-formed tracks/ski fields, in accommodation) they will not be injured or killed, however someone standing at a crater edge is considered outside their 'normal location' and thus at risk of death or injury.	**3**	Small eruption(s) most likely of a phreatic nature in progress. A hazardous eruption is likely to develop. Typical examples are Mount St. Helens, Pinatubo, Montserrat, and Unzen as they started to erupt.
Eruption in progress which is hazardous to people in their 'normal locations'.	**4**	A hazardous eruption is now in progress; hence people in their 'normal locations' would be affected.
Large hazardous eruption is now in progress	**5**	Larger hazardous eruption is now in progress

Based on this interpretation, if a volcano was experiencing heightened unrest, the ACC would receive a vote for Yellow (not Orange as my interpretation of the wording indicates), and low to moderate levels of unrest (if the volcano is deemed not likely to erupt in the next day) would receive a vote for Green (not Yellow). Additionally, a shorter time period is considered when setting the ACC than when setting the VAL, attributed to the purpose of the ACC being for aviation and therefore including whether or not ash is currently in the air. The interpreted meanings of the levels fit a linear equal-interval scale ranging from the lowest level (Green) meaning no unrest, to the highest level (Red) meaning large-scale eruption occurring. This is different to the face value of the words. Additional complications result from two different meanings within each ACC level.

During the White Island and Tongariro eruptions, at times the majority of the voters would vote for VAL 1 and also for ACC Green, so it is likely the scientist above was not alone in applying this interpretation. It is quite possible similar equal-interval interpretations are applied to the VAL system, and if combined with interpretations of the content (wording and definitions) and consideration of the meanings behind the formation of the VAL system, significant differences in meanings are placed on each of the VALs, influencing the scientists' decision-making.

4.5.7 Other influences

A number of other influences on the decision-making process were identified based on the responses given by interview participants. While these factors have been included here with a general description, they have not been investigated further at this point; this is a potential avenue for future research.

4.5.7.1 End-user actions associated with VAL changes

The decisions made by some of the scientists to determine the VAL are influenced by the end-users' actions based on the VAL system and the potential socio-economic impacts of a VAL change. If the scientists are aware of these consequences and they believe them to be inappropriate in response to the situation, they may become hesitant or "reluctant" to change it, especially at a high risk volcano. It was suggested by a participant that this is particularly the case for situations where there is high uncertainty relating to the outcome of the event (and therefore the risk of 'false alarms'), and at levels of activity close to the thresholds between VALs, where scientists are likely to wait for "confirmation". An example given by a participant was the potential influence on determining the VAL by scientists knowing gas production would be terminated in the Taranaki region once the VAL is raised to 2 at Taranaki/Egmont volcano, causing widespread disruption throughout the North Island. This knowledge may cause hesitation amongst the scientists to raise the VAL to 2. In some cases the level may be changed sooner to prompt response actions the scientists think are necessary (imposing a hazard perspective on the system), as seen during Exercise Ruaumoko.

During an unrest crisis, this influence on scientists' decisions may be linked to whether the unrest phenomena can be felt or seen. If there were numerous felt earthquakes at a caldera such as TVC, according to some participants, the scientists are more likely to increase the VAL from 0 to1 at an earlier stage than if the unrest consisted solely of unnoticeable gas or deformation phenomena. This in turn is a result of the need for scientists to maintain credibility – one influence outweighing another. The influence on the scientists' decision-making of end-user actions caused by VAL changes demonstrates the subjectivity imposed on what at first glance appears to be a relatively objective VAL system.

4.5.7.2 Incorporating a hazard or risk perspective and eruption forecasting

In determining the VAL, a small number of participants incorporate a sense of the level of hazard in an attempt to reduce the risk. An example is increasing the VAL before the physical phenomena-based criteria have actually been met (as occurred during Exercise Ruaumoko to communicate the heightened sense of risk). A second example is retaining the VAL at a heightened level (e.g., VAL 2, or 'minor eruptive activity') despite the activity decreasing, if future additional eruptions are considered likely. That is, following the precautionary principle by keeping the VAL higher during high uncertainty to contribute towards increasing life safety. This inherently includes a sense of what may happen in the future. The incorporation of a sense of hazard and risk would tend to result in higher VAL votes on average than if this factor was not an influence.

4.5.7.3 Internal organisation pressure

Pressure to change the VAL from management levels within GNS Science was perceived as a possibility by a minority of the participants. This is thought to be particularly the case if there were increased levels of funding or other assistance associated with higher VALs, and if funding source (external) agencies were seeking justification for the increased expenditure. This conflicts with the scientists' desire to justify their VAL decision to maintain credibility. For GNS Science to maintain credibility, it seems very unlikely management would impose pressure on VAL decisions.

4.5.7.4 External organisation pressure

Scientists' decisions to determine the VAL may be influenced by pressure applied by external organisations, either directly or through the media. Examples given by participants were hypothesised to include major land management agencies, tourist operators, and others with a vested interest in the hazardous and therefore potentially access-restricted area (however, GNS Science does not stipulate areas for restricted access for any agency other than itself for health and safety of employees). MCDEM was also considered to be a potential source of pressure to change the VAL by some of the scientist participants. However the MCDEM interview participant was certain this would not happen due to the science – policy separation in New Zealand. It was indicated that MCDEM may converse with GNS Science (seeking justification) if there were perceived discrepancies between what the selected VAL descriptions indicated and what could be seen at the volcano, or if it was thought they needed to contribute to the scientific communication process. The former example could be perceived by the scientists as indirect pressure to change the VAL, especially if funding hinged on the VALs.

4.5.7.5 Fieldwork intentions

Permission from GNS Science management to carry out fieldwork (i.e. health and safety regulations) is perceived to be partly associated with the VAL system, where low VALs are linked with permission to conduct fieldwork. This may influence the votes of a number of scientists who are keen to gather data in the field. In reality, the VAL and permission to do fieldwork are not directly linked, however they are both based on the interpretation of the overall level of activity (indicated by the monitoring data) and underlying conceptual model. These are in danger of being 'downplayed' to enable fieldwork, influencing the resulting VAL.

4.5.7.6 Perceived purpose of the VAL

Differences in the perceived purpose of the VAL system that are held by voting scientists, as described in section 4.2.4, are likely to influence their votes. If a scientist emphasises the purpose of the VAL system to be for end-users' decision-making, they might be more likely to use the system as a guideline, and incorporate a sense of hazard and risk with elements of forecasting. Whereas a scientist focussing on communicating only the physical science may be more likely to use the system prescriptively, and seek firm confirmation of activity indicating each level before it is changed. The perceived purpose of the system may also influence how the scientist interprets the VAL content (including definitions of terms, and interpreting the content at face-value or as an equal-interval system). Experience and knowledge are likely influences on the perceived purpose of the VAL system (in addition to personalities).

In summary, numerous factors influence scientists' determination of the VAL. This research was exploratory and focussed on the identification of the factors, in addition to a discussion of why and how the factors are an influence. Further investigation into some of the influences could be undertaken in the future to ascertain more clearly the extent and relative impact of these factors on decision-making. Despite the perception of many participants that the decision is (or should be) "professional without fear or favour and not influenced by any assumption of effect" (EU11), this section has suggested that the decision is subjective and therefore influenced by many factors. Recognition of these factors allows them to be minimised (if this is desired) and more effectively managed in future volcanic crises in New Zealand.

4.6 Theme 5: Possibilities for future VAL systems

Significant potential changes relating to future VAL systems were identified by interview participants, including questioning the foundation on which the current VAL system sits. Alternative options are explored in this section, which comprises Theme 5 of this exploratory review of New Zealand's VAL system, and relates to research aims 2 and 3 ('explore New Zealand's VAL system, and how it is used' and 'identify ways to make New Zealand's VAL system more effective', respectively). Establishing the purpose of the future VAL system is a central focus going forward and will aid the determination of the foundation of the system. The inclusion of forecasting volcanic activity and response advice is also discussed. This theme draws upon the previous four themes in suggesting the best possible alternatives for a future VAL system. By ascertaining potential foundations of future systems, and whether to include key types of information, the best possible VAL system can be created to contribute towards the effective management and communication of scientific information during a volcanic crisis.

4.6.1 A shifting of foundations

New Zealand's VAL system is predominantly based on currently occurring phenomena, such as 'apparent seismic, geodetic, thermal or other unrest indicators' and 'minor eruptions commenced'. It also acknowledges hazards and risk, such as 'hazardous local eruption in progress' and 'significant risk over wider areas' (although risk in this context was undefined). This section discusses five potential foundations underpinning future VAL systems. Some were suggested directly by participants (and have been member-checked), while others are the result of my interpretation of interview and observation data. The strengths and weaknesses of each system are described, along with an example of a system based on each of the foundations. The 'foundation' of the VAL system is essentially the theme used to divide the levels.

4.6.1.1 Phenomena-based

The current VAL system's foundation is based on volcanic phenomena largely due to the era in which the system was formed, according to one of the participants involved in its creation. The focus on hazards, risks, and social impacts by volcanologists that can be observed currently was not emphasised in the early to mid-1990's, and volcano-specific models were few and far between, at least in New Zealand. Volcano scientists at various branches of DSIR had only recently been combined into one organisation (now known as GNS Science), with a less cohesive nature of working as a team than is apparent now. All-in-all, basing the VAL system on currently observable phenomena was the most "comfortable" foundation for a scientific group not yet confident in eruption forecasting. Aspects of volcanology and scientific knowledge have developed substantially in the 20 years since the VAL system's formation, along with a paradigm shift of acknowledging societal needs in the communication of scientific information. These developments prompt the need to carefully consider whether the foundation of current phenomena, containing little to no eruption forecasting or hazard information, is still adequate – some participants think it is not (although it may still be the most "comfortable" foundation).

The benefits of retaining the phenomena basis to the system were identified as including a lower level of uncertainty in communicating physical monitoring data than in communicating either hazard or risk information that is associated with societal systems, or underlying magmatic models. The phenomena-based system is thought to be "the system that is truest to the science and conveys what the volcanoes are doing without added layers of interpretation" (Sc23).

Another benefit is that descriptions of the physical phenomena can be seen as the first step in the communication process, prior to their interpretation and relationship to hazards and possible future activity. By communicating this first step, the subsequent interpretation, hazards, and future activity information can be tailored to suit the wide range of end-users, volcanic environments, and situations. Additionally, by basing the VAL descriptions directly on the observable phenomena, the opportunity for subjectivity to influence the VAL decision is minimised, and the time it takes to determine the VAL may be shorter.

An example of a phenomena-based VAL system is presented in Table 4.4. An additional column relating to (simplified) indicative phenomena may be added, and there are six levels included in this example in accordance with the end-users' wishes.

Table 4.4. Hypothetical VAL system for New Zealand based on a foundation of currently occurring volcanic phenomena. This example demonstrates the use of a numerical system, from low (at the top) to high (at the bottom).

Hypothetical Phenomena-Based Volcanic Alert Level System	
Volcanic Alert Level	**Description of volcanic activity**
0	No volcanic unrest
1	Minor volcanic unrest
2	Moderate to heightened level of volcanic unrest
3	Minor volcanic eruption has recently occurred or is in progress
4	Moderate volcanic eruption has recently occurred or is in progress
5	Large volcanic eruption has recently occurred or is in progress

Potential issues with retaining the phenomena foundation as identified by interview participants are:

1) some end-users find it difficult to interpret the current phenomena into meaningful information for hazard planning and decision-making
2) the reliance on summarising observable phenomena at various levels of activity, when a wide range of activity is possible (including for the volcanoes that have not had witnessed eruptions, and for de-escalation)
3) the grouping of volcanoes with a range of hazard environments and possible behaviours into one system based on currently observable activity
4) it is very difficult, if not impossible, to accurately set the VAL during a short-lived eruption (where observable phenomena are rapidly changing) using the current phenomena-based system (discussed further in section 4.5.4). This is the reason the example VAL system in Table 4.4 contains the words 'has recently occurred or is in progress'.

As a result of these identified issues, participants considered shifting the foundation of the system to other options, and including response advice and eruption forecasting.

4.6.1.2 Hazard-based

Some parts of the current VAL system are based on hazards 'in progress' (e.g., 'hazardous local eruption in progress', the original meaning of which was based on a subjective level of hazard in a spatial area (Table 4.3). It was suggested by interview participants that the foundation of the future VAL system could be based entirely on the level of hazard, and referred to as a 'Hazard Level' instead of a VAL system. Hazard assessments are based on information of past activity (from the geological and historical records), and the understanding of underlying processes and models. The method used to ascertain the level of short-term hazard may include the interpretation of monitoring data, and its application to conceptual models. This in turn would suggest styles of potential future eruption activity with associated hazards. The level of hazard can then be based subjectively on this understanding.

Having an indication of the hazards associated with various levels of volcanic activity is an important influence on the planning and response decisions made by end-users in various roles and risk environments. By creating a VAL system with a foundation in hazards, one system could be applied to all of New Zealand's volcanoes, as a hazard system is thought to make all volcanoes "directly comparable" (Sc4). Using this foundation, response advice and systems incorporating spatial zonation of hazards could be associated with each level, depending on the volcano and situation. An example of a hazard-based system is provided in Table 4.5, and includes a description for each Hazard Level, largely based on the spatial extent of the volcanic hazards. A simpler Hazard Level could be used consisting of solely the left hand column (extremely high to very low), to remove the influence of the spatial extent.

Potential issues with a hazard-based system, as identified by interview participants, include:

1) Identifying appropriate terminology to enable applicability to the wide range of New Zealand's volcano types and spatial extents may be a challenge. For example, if a general hazard description of 'hazardous on the volcano' is used, it may be difficult to define the perimeter of 'the volcano' at a caldera or in a volcanic field where the location of the new volcano is highly uncertain. It is a similar situation for the terms 'crater' and 'vent'. Predefining these terms and associated spatial extents for each volcano will be beneficial.

Table 4.5. Hypothetical VAL system for New Zealand's volcanoes based on a foundation of hazards. This example demonstrates the use of ordinal words instead of a numeric system, with a high to low order of activity from top to bottom.

Hypothetical Hazard-Based Volcanic Alert Level (or 'Hazard Level') System	
Hazard Level	
Extremely high	Very hazardous on and near volcano (hazards depend on eruption style) e.g., widespread ash, lava flows or domes, pyroclastic flows, lahars, flying rocks
High	Hazardous on volcano (hazards depend on eruption style) e.g., ash, lava flows or domes, lahars, flying rocks
Moderate	Hazardous at areas near crater e.g., unpredictable small eruptions, poisonous gas, flying rocks, hot geysers
Low	Low level of hazard, associated with volcanic unrest e.g., unpredictable small steam eruptions, gas emissions, earthquakes
Very low	No volcanic hazards

2) Having a Hazard Level in addition to maps with associated spatial hazards may be confusing, particularly as they are both dynamic systems which change over short periods of time.
3) A wide range of volcanic activity would be included in each level due to the emphasis on hazard rather than magnitude of activity. For example, an 'extreme' level of hazard is likely to include an eruption at Raoul Island, a pyroclastic flow on Ngauruhoe, or an eruption at AVF. The level of risk (described further in section 4.4.1.2), on the other hand, would be comparatively low at Raoul Island and Ngauruhoe compared to AVF due to the relatively low level of exposure of human life and property to the volcanic hazards.
4) Defining the terminology used will be important to reduce ambiguity and subjectivity in the decision-making process. For example, defining at what point a situation is deemed 'hazardous' will influence the outcome. The 'moderate' Hazard Level in Table 4.5 may include heightened unrest (in progress), or rapid fluctuations between geyser

activity in a crater lake and heightened unrest, where no further warning of a sudden eruption can be given. Due to the subjective nature of the hazard-based system, intentions for every level (potentially for every volcano) should be defined to retain consistency in the scientists' decisions over time.

5) To retain simplicity, it will not be possible to include all types of hazards in the VAL system, particularly with levels defined by the spatial extent of hazards. As identified by one science participant,
"[in] the case of Ruapehu you can have a minor eruption … down one particular valley [where] the impacts could go a hundred kilometres, but … I think if you try and allow for every possible permutation and combination you'll get your hands tied up in knots" (Sc9).

In the future, the situation might arise where a new or additional system is required to deal with a continuously high level of volcanic eruption activity from one volcano. In this situation, specific hazards over time that may occur in various locations become a pressing issue, rather than a reliance on VALs stating the current level of activity. This occurred at Montserrat during the 1990's and 2000's, according to interview participants involved in the revisions of the VAL system there. While eruptive activity continued at a fairly steady state, the areas impacted changed requiring the combination of a colour-coded VAL system with a hazard map associated with evacuations. This situation may occur at a New Zealand volcano, and may cause complications due to the existence of other volcanoes also in the nearby area, which would presumably use the original, more generic VAL system. Whereas Montserrat communities just had one volcano and VAL system to understand. In this case it is hypothesised that the overall VAL system could remain the same, but a volcano-specific hazard map be utilised. Consideration should also be made for the development of a more detailed localised warning system (which may cause difficulties if used in conjunction with a hazard-based VAL system) in this situation to suit the needs of the local end-users.

4.6.1.3 Process-based

As discussed in section 4.5.1, once volcanic monitoring data have been collected at a volcano, they are interpreted to understand the underlying processes and used to develop a theoretical, conceptual model of the volcanic system. As further data are collected, the model is tested and refined until it becomes as accurate as possible. Accurate models, along with an understanding of volcanic processes, contribute greatly towards eruption forecasts and hazard predictions. According to one interview participant, this is similar to the diagnosis of a sick patient by doctors to ascertain the outcome of a disease. An initial diagnosis of a disease is based on the patients' symptoms, and over time, the diagnosis is tested as new symptoms occur. The diagnosis may be used to predict what the outcome is for the patient, and the symptoms which may be likely along the way. Likewise, a volcano model is based on the observable phenomena, and tested over time. Forecasts of future activity can then be made with increasing accuracy. By basing the future VAL system on underlying volcanic processes, it is thought by participants that determining resulting phenomena and associated hazards may be possible, and can therefore be included in the system.

An example of a potential process-based VAL system based on one participant's thoughts is presented in Table 4.6. An additional level could be added representing 'moderate extrusion of magma' to bring the number of levels into alignment with the majority of participant's wishes. During the feedback process, a number of participants suggested changes to the wording of these levels – if it is to be used in the future, further investigation of the terminology is needed, with consultation of the system's users.

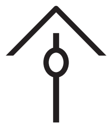
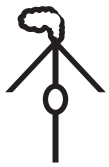
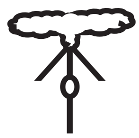
Other scientist participants identified a number of issues relating to this potential VAL foundation. These consist of:

1) A reliance on having accurate models for all volcanoes in New Zealand. Most volcanoes do not have a model at all, and those that do are highly uncertain. It is thought by a number of GNS Science participants that "we haven't got enough science and understanding of the volcanoes to create those models" (Sc3). It was also identified that using this system "would imply that at any time we know where the magma is", whereas it is thought GNS Science has not "ever been confident that magma is in a particular place underground until it is virtually at the surface" (Sc8). However, regardless of the existence of models, the ability to transfer the understanding of volcanic processes may permit the use of this foundation.
2) Due to the uncertainty associated with processes and models, it is thought that there would be significant delays for the scientists to decide on the most appropriate model, and therefore on the VAL. "This is too dependent of knowledge of process. As we saw at Te Maari it might take months to get a handle on that. Adequate knowledge may come well after the time an alert system is most needed" (EU12). Monitoring sample results (e.g., of magma inclusion in eruption deposits or crater lake chemistry changes to determine the eruption classification as phreatic (VAL 2 in Table 4.6) or

phreatomagmatic (VAL 3)) can take days to weeks to be analysed, contributing to delays in determining the model and thus the VAL.

Table 4.6. A hypothetical VAL system with a foundation of volcanic processes, designed with input by an interview participant. The levels of 'hazard' and 'activity' are based on the 'underlying process' column.

Hypothetical Process-based Volcanic Alert Level System

VAL	Hazard	Activity	Underlying process	Model
0	No volcanic hazard	No unrest or eruptions	No magma	
1	Low level of hazard, associated with volcanic unrest e.g., steam eruptions, gas emissions, earthquakes	Minor volcanic unrest with no eruptions	Shallow, stable magma in rock beneath volcano	
2	Hazardous at areas near vent e.g., small eruptions, poisonous gas, flying rocks, hot geysers	Heightened unrest with possibility of minor eruptions	Intrusion of fresh magma into rock beneath volcano	
3	Eruption hazards on volcano and downwind (hazards depend on eruption style) e.g., ash, lava flows, lava domes, pyroclastic flows, lahars, flying rocks	Minor to moderate volcanic eruption	Extrusion of magma (explosive or effusive)	
4	Very hazardous near volcano (hazards depend on eruption style) e.g., widespread ash, large lava flows, unstable lava domes, pyroclastic flows, lahars, flying rocks	Large volcanic eruption	Large extrusion of magma	

3) Models can be difficult to understand – even senior scientists can have difficulties comprehending the discussions around specific phenomena outside of their specialities, and the impact they have on the model. All staff involved in the voting

(which includes technicians) would need to be able to comprehend the models; the "system needs to be based around something they can understand" (Sc9). Additionally, the inclusion of underlying volcanic processes and models are likely to be incomprehensible to the vast majority of end-users, leading to questioning the purpose of their inclusion in the system. However, the 'underlying process' and 'model' columns could be decoupled from the system, removing it from the public arena, whilst being used by the scientists to determine the level. Voters who may not understand the models or who have an empirical focus could use the 'activity' column to determine the VAL, which should be predominantly cohesive with the 'underlying process' column.

4) Systems based on interpretations have much more room for error than those based on the observable data, and can be proven retrospectively to be incorrect. It is thought, however, that scientific decisions are mainly based on the currently available information (and therefore defensible), as would be the case for this VAL foundation. It is unlikely that scientists would be comfortable with this increased likelihood of being proven 'wrong' retrospectively.
5) There is a concern that a process-based system will be very difficult to use during de-escalation, largely due to lengthy magma residence times. Adopting a process-based system would therefore require a change in the concept of how a VAL system is used. The lower levels of the process-based system would be fairly static, more of a label for each volcano than a system reflecting short-term changes, as the underlying system would take in the order of years to de-escalate after an eruption using this system. Allocating a lower level after an eruption using this system would be problematic due to the use of categories such as 'stable magma'. Levels may also be missed during escalation (e.g., going straight from VAL 0 to 2), which may go against expectations of end-users with response planning repercussions.
6) A range of hazards will be apparent for each level, but particularly levels 1 and 2 in Table 4.6. Level 1 (shallow, stable magma) may involve a range from no hazard at all to hydrothermal eruptions and poisonous gas emissions. Level 2 could include periods with no signs of unrest or associated hazards, through to unpredictable phreatic eruptions (or even magmatic eruptions until the magma inclusion results are obtained, by which stage the eruption may be over). This wide range of hazards within each level may not be very useful for end-users, although it is not too dissimilar to the range of hazards in the current frequently active volcanoes system for VALs 1 and 2. During the feedback process, one end-user participant described it as "the scientists' system, and

> not focussed on the end results of what the likely consequences are. Focussing on the processes makes sense from a science perspective but is quickly lost in the world of non-scientists" (EU14).

While scientific knowledge relating to volcanology strives towards understanding processes and developing accurate models, as a basis for a simple communication tool aimed at non-scientists, it may not be the most effective tool at this stage. There is no doubt that these themes will continue to provide the basis for scientific discussion in volcanology. Once more certainty is developed relating to understanding volcanic processes and models, and when these theories can be tested more rapidly (particularly with developing technology for rapid sample analysis), VAL systems may benefit from considering a process-based foundation.

4.6.1.4 Risk-based

As described earlier, New Zealand's volcanoes lie in a very wide range of risk environments. For the purposes of this section, the definition of risk stated by New Zealand's CDEM Act 2002 is used: "risk means the likelihood and consequences of a hazard" (MCDEM, 2002). The consideration of hazard and risk was identified in this research as an influencing factor on the determination of the VAL. The incorporation of risk in scientific decision-making is a difficult challenge as uncertainties remain high, and volcano scientists are often not particularly knowledgeable about societal elements or influencing factors relating to risk. If the future VAL system is based on the level of hazard, according to a number of participants in this research, eruptions at similar levels of hazard may have entirely different levels of risk due to the inclusion of socio-economic consequences and variations of likelihood.

As suggested by interview participants, a risk-based VAL system could be utilised in New Zealand to communicate relative levels of risk associated with volcanic activity (such as the simple qualitative Risk Level presented in Table 4.7). The Risk Level would be based on the potential consequences of a specific hazardous volcanic event, and incorporate an estimated likelihood of occurrence within a certain timeframe. Probabilistic (i.e. likelihood) thresholds based on consequences (e.g., life safety) could be pre-determined for each volcano in collaboration with CDEM for each level of risk. Thresholds for acceptable and tolerable levels of risk could then be ascertained and related to the Risk Levels to potentially assist with decision-making.

Table 4.7. A hypothetical qualitative Risk Level, which could potentially be used to communicate the level of risk resulting from volcanic activity in New Zealand.

Risk Level
Extreme
Very High
High
Moderate
Low
Very Low

The representation of risk remains highly uncertain. Multiple risk assessments would need to occur for various impacts at a range of locations, whilst incorporating estimates of uncertainty. Those risk assessments would then need to be integrated or at least considered in parallel to set the Risk Level. Significant further investigations would be required if using a Risk Level is seen as a viable option, for example to determine which risk metric to use (e.g., consequences involving life safety, built environment, and/or economic impact), whether to have a qualitative, semi-quantitative, or quantitative risk analysis process (e.g., AS/NZS, 2004), and whether any Risk Index or assessment method already exists and could be applied to volcanoes with respect to warnings. Additionally, terms used in the Risk Level (such as those in Table 4.7) would need to be defined so that end-users and scientists have a common understanding of the meanings. Examples of existing indices which could be further investigated, combined and/or modified (particularly to focus on a localised area) include the Disaster Risk Index (Peduzzi et al., 2009), the Disaster Deficit Index (incorporating an economic focus, Cardona et al., 2004), the Local Disaster Index (incorporating social and environmental factors and the impact of volcanic eruptions, applied at a nationwide impact scale by Marulanda and Cardona, 2006, cited in Cardona & Carreño, 2011), the Prevalent Vulnerability Index (reflecting the susceptibility of an area to impacts from hazards, Cardona & Carreño, 2011), and the Risk Management Index (which measures a city, region or country's risk management performance, Carreño et al., 2007).

Coordination with end-users will be crucial, including when selecting the risk-metric. Terminology used in risk communication would need to be defined and kept consistent between scientists and end-users to avoid misinterpretations and confusion. A Risk Level may not be a viable option for New Zealand at this stage due to the high level of uncertainty and lack of experience with a system such as this. However, it could be developed and tested in the future.

4.6.1.5 Multi-foundation

Combining multiple foundations may be possible to draw on the benefits of each system and minimise their individual weaknesses. Conversations with participants and analysis of their written statements of an ideal system were explored and developed further, resulting in the multi-foundation system presented here. Desires expressed by interview participants to focus on the state of activity during unrest and then change the focus to the spatial constraints of hazards during eruptions (particularly long-term eruptions) were particularly considered in the creation of this system.

The example system shown in Table 4.8 has a foundation in phenomena for levels zero to two, and a hazard foundation for the levels three to five. Had this system been entirely based on a foundation of hazard, levels 1 and 2 would be merged into a low level of hazard. Had this system been entirely based on a foundation of phenomena, levels 3 to 5 would be categorised using the magnitude of eruptions. However, because levels 3 to 5 are based on hazard, a state of unrest may also be included in VAL 3, if it was hazardous. Table 4.8 incorporates an element of risk by allowing the designation of Hazard Zone boundaries according to vulnerabilities and consequences, and by ascertaining levels of acceptable risk through the use of probability thresholds between levels. Along with defining 'hazard' (e.g., property damage or life safety), these boundaries and thresholds would be created in collaboration with CDEM personnel, who have more knowledge in societal factors relating to risk thresholds and land-use. This interaction was seen by participants as being a positive attribute of this system. A zone is envisaged to be deemed as 'hazardous' once the likelihood of eruption (or unrest) hazards reach a pre-determined threshold. This assessment and setting the VAL could be undertaken by GNS Science scientists using their knowledge based on the interpretation of monitoring data, conceptual models, and geological and historical events.

Probabilistic risk calculations are currently carried out to determine whether GNS Science staff can do fieldwork in hazardous areas. The extension of this process and incorporation into the VAL system would enable this valuable information relating to life safety to be communicated to the public in a simplified (and qualitative) manner. The estimation of risk involves a future component with the inclusion of likelihood of a hazardous event occurring, which, given the discussion in section 4.6.3, may be an issue with the inclusion of risk in this system. The determination of Hazard Zone boundaries and acceptable risk thresholds in conjunction with CDEM personnel (and major land managers) allows recognition of the various risk environments that New Zealand's volcanoes are situated in. Time constraints for risk assessments would also need to be determined.

Table 4.8. Hypothetical VAL system based on a combined foundation of phenomena, hazards, and risk. Each VAL change would need to be accompanied by a map depicting hazardous zones pre-determined in conjunction with CDEM personnel and major land managers.

Hypothetical Multi-Foundation Volcanic Alert Level System	
Volcanic Alert Level	
5	Hazardous in Zones A, B and C
4	Hazardous in Zones A and B
3	Hazardous in Zone A
2	Heightened unrest
1	Minor unrest
0	No unrest
Hazard Zone boundaries are shown in Volcanic Alert Bulletins and on the GeoNet website: www.geonet.org.nz	

The simplified language in Table 4.8 aims to balance the minimisation of ambiguity with generalisations between volcanoes, allowing one standardised system within New Zealand in addition to the international ACC. The multi-foundation system is designed for use during both escalation and de-escalation, and, as with all hypothetical systems presented in this chapter, allows a volcano to remain at one level for lengthy periods of time by the exclusion of time-comparative language. It also allows scientists to retain flexibility and incorporate a sense of forecasting (by moving to a level in advance of activity actually being observed). A major benefit of this system is the increase in guidance given to end-users on what actions they should take by stating the point at which life is at risk, while retaining appropriate roles and responsibilities between scientists and end-users.

The Hazard Zones incorporate a spatial component and need to be pre-determined to allow rapid use during eruptions. Maps displaying the zones would need to be carefully developed to replace the existing (or future) hazard map for each volcano, as the use of two spatial representations of hazard is likely to be confusing. The zone boundaries could be changed over time as eruption characteristics and hazard potential change or become better understood. There may be socio-economic impacts (e.g., on real estate) when hazard zone boundaries are changed.

Example Hazard Zones are depicted in Figure 4.9 for Ruapehu. Zone A includes the summit area; Zone B has a 3 km radius (typical of the ballistic range), and demonstrates the incorporation of more hazardous areas such as the Whangaehu River valley, prone to lahars from the summit Crater Lake. Further valleys could be incorporated in Zone B if desired. Zone C is a reasonably arbitrary area with a 10 km radius from the vent, and may need further adjustments with regards to localised hazards and communities, for example, to extend the zone to include additional sections of the Whangaehu River Valley. It is thought that during heightened unrest with the potential for unpredictable small eruptions, the VAL would be 3 (Hazardous in Area A). In the event of small phreatic eruptions the VAL would remain at 3 until areas within Zone B reach the pre-determined hazard or risk threshold (depending on whether consequences were included in the development of the hazard zone boundary).

A potential issue with this system is the restriction to three hazard zones (A, B, and C). The addition of more Hazard Zones into the VAL system may be problematic as the system should be limited to six levels overall, according to the participants in this research. Further details relating to sub-zones may be incorporated in the VAB to combat this issue. Additionally, this system highlights the area at risk, and not the relative levels of risk between zones. Multiple versions of maps and Hazard Zones may also be a concern over time, requiring clear dates to be written on the maps; as well as the potential for flank eruptions requiring a rapid map and zone change, but it is thought that this is similar to the updating of hazard maps as more information comes to light. The extent to which Hazard Zone boundaries are gradational needs to be investigated further. During the feedback process, participants suggested that this system overlooks the aviation industry and its need for airborne ash information. However, if the ACC is used for NZVs, this may not be an issue. It was also suggested that more specific hazard information could be added as a separate column in a similar way to the process-based system.

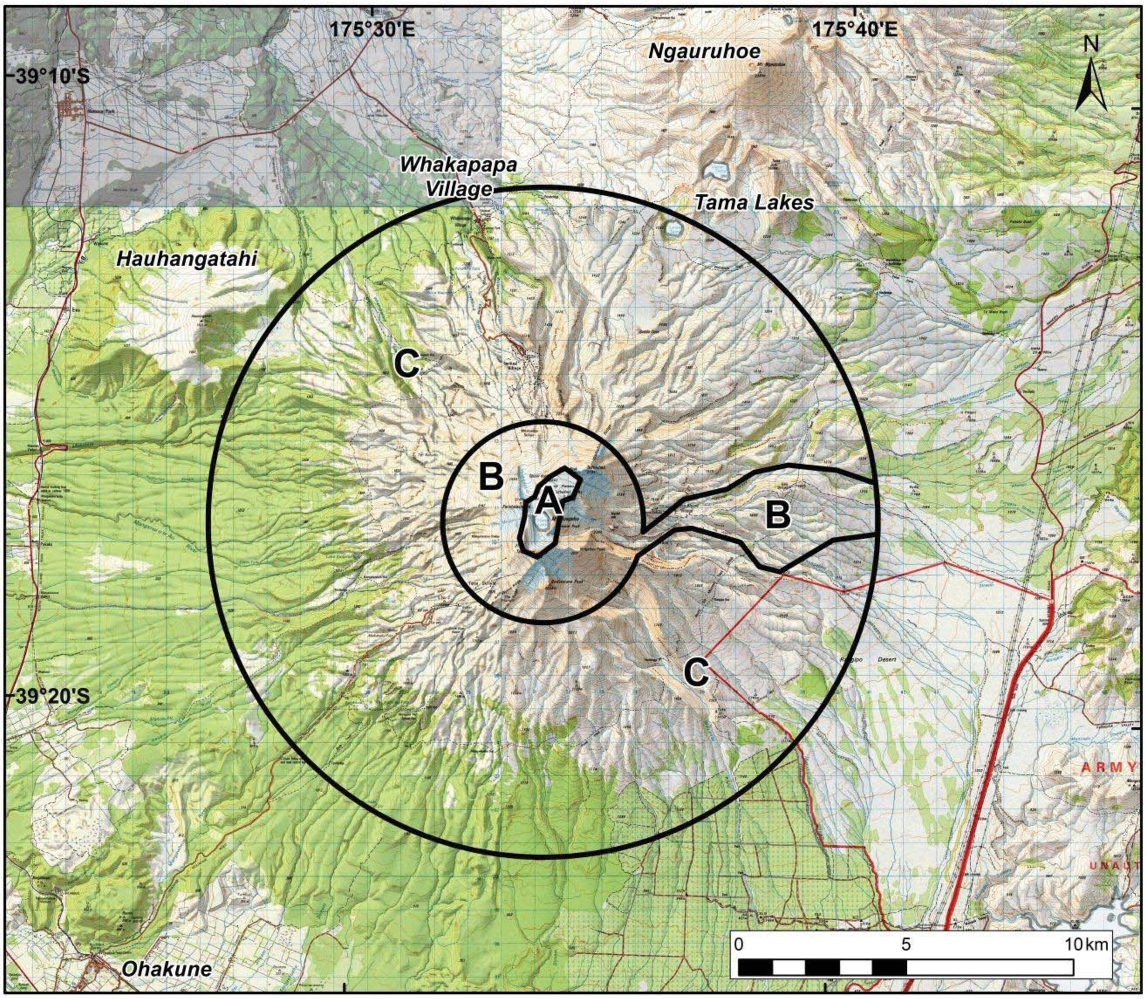


Figure 4.9. Example Hazard Zones for Ruapehu volcano, New Zealand. Zone A includes the summit area, Zone B has a 3 km radius based on typical extent of ballistic hazards and includes the lahar-prone Whangaehu Valley, and Zone C has a 10 km radius. This is an estimated hazard map used only as a demonstration of how Hazard Zones could be used within the VAL system; it should not be used out of context.

The use of coloured zones was deliberately excluded from Table 4.8 and Figure 4.9 to minimise confusion with other hazard maps. However, if this system was to replace existing (or future) hazard maps, colour may be able to be incorporated instead of the letters A, B and C (and subzones potentially labelled with letters). The colours would not change as the level of hazard increases; the different coloured zones would simply be progressively included in the area designated as 'hazardous'.

4.6.2 Foundation preference feedback from participants

The results presented in this chapter, along with a shortened summary document (Appendix 10), were presented to the research participants and other relevant individuals (including all scientists involved in volcanology at GNS Science and further end-users associated with volcanic emergency management) for feedback in 2013. They were asked to rank their order of preference for the five VAL systems in Tables 4.4 to 4.8), from one (highest) to five (lowest). 17 participants including eight end-users and nine scientists obliged, with a further three participants providing general feedback without input to the ranking. Analysis of the mean rank attributed to the five systems resulted in the recognition that end-users prefer the multi-foundation system, while scientists' prefer the phenomena-based system (Figure 4.10, Table 4.9).

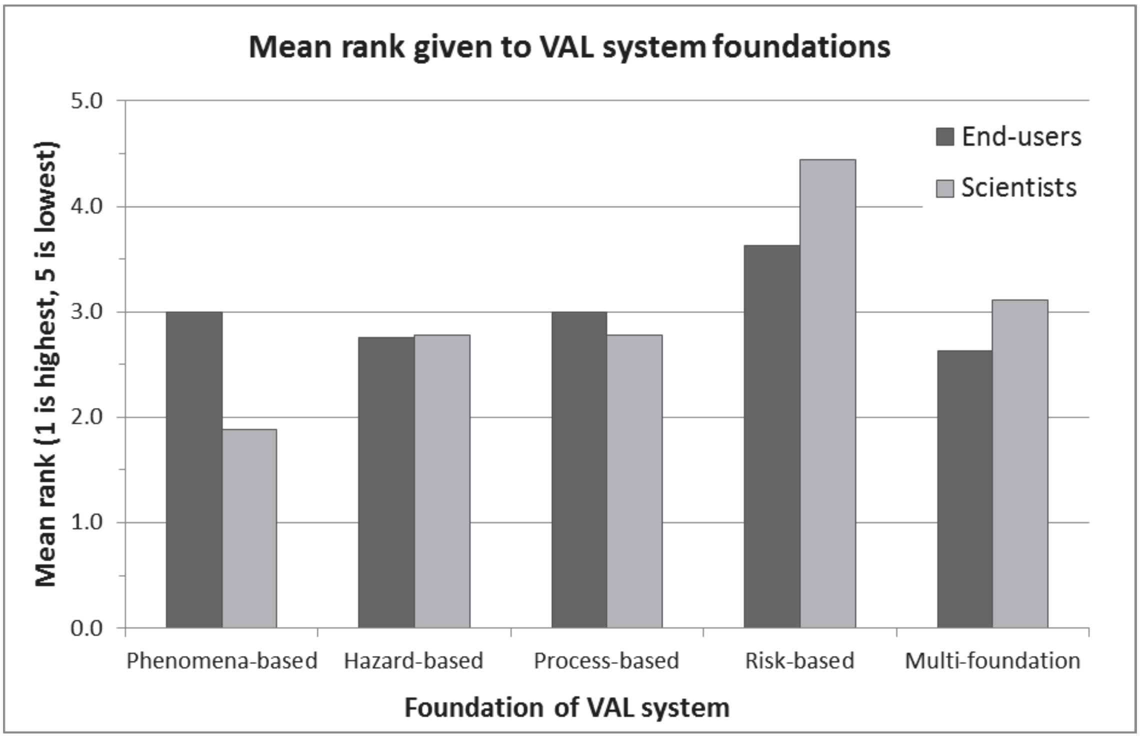


Figure 4.10. Mean ranking of VAL system foundations by end-user and scientist participants. A lower mean rank indicates a more preferred system. (End-users N=8; scientists N= 9.)

Table 4.9. Ranking analysis results for the five potential VAL system foundations. The lower the subtotal and mean of subtotal, the higher it is preferred.

		Foundation of VAL System				
		Phenomena-based	Hazard-based	Process-based	Risk-based	Multi-foundation
End-users (n=8)	Subtotal (sum of ranks)	24	22	24	29	21
	Mean of subtotal	3.00	2.75	3.00	3.63	2.63
	Number of counts in position 1	1	2	2	1	2
	Number of counts in position 1 or 2	3	3	4	2	4
	Number of counts in position 1 or 2 or 3	4	6	5	3	6
Scientists (n=9)	Subtotal (sum of ranks)	17	25	25	40	28
	Mean of subtotal	1.89	2.78	2.78	4.44	3.11
	Number of counts in position 1	5	0	2	0	2
	Number of counts in position 1 or 2	6	5	4	1	2
	Number of counts in position 1 or 2 or 3	8	6	6	1	6
All participants (n=17)	Total (sum of ranks)	41	47	49	69	49
	Overall mean	2.41	2.76	2.88	4.06	2.88
	Number of counts in position 1	6	2	4	1	4
	Number of counts in position 1 or 2	9	8	8	3	6
	Number of counts in position 1 or 2 or 3	12	12	11	4	12

Reasons cited by some end-users on supporting the process-based system was the inclusion of more information, including hazards, activity and the picture of the model, rather than focussing on the use of the process as a foundation. Potentially this may have increased the rank of this system compared to the others, without being an accurate reflection of opinions relating to the process foundation and associated changes in concept relating to how the system would be used.

End-users ranked the hazard-based and multi-foundation systems higher in their top three order of preference than the other systems, while scientists preferred phenomena-based, with an even ranking given to hazard-based, process-based, and multi-foundation systems within their top three preferences (Table 4.9). The phenomena-based, hazard-based, and multifoundational systems were selected in the top three positions the same number of times overall, and the process-based system was selected only slightly less. On average there is a preference for the phenomena-based system, with the risk-based system receiving the lowest ranking.

In addition to the ranking of example systems based on the various foundations, the participants suggested alternative combinations of systems. In particular, a phenomena-based system with the incorporation of hazard information was seen as being potentially beneficial. This is different to the multi-foundation system, which is based on phenomena only in levels zero to two (Table 4.8), before switching to a hazard-based system. Having both sets of information throughout the levels is seen to be useful, while retaining the foundation of phenomena. One end-user participant described the reason for this preference, which was to provide the context surrounding the hazard information:

> "The phenomenon-based system helps me understand what is going on and the relative severity of the event. The hazard-based system sets out clearly what needs to be done as a consequence. In terms of my CDEM responsibilities, we need both – people get twitchy about instructions given without context and justification – in today's world expert authority is treated with suspicion. So you need to be able to say 'why' as well as 'what'" (EU7).

A system with a foundation of phenomena accompanied by hazard information could resemble that given in Table 4.10, which combines the systems given in Tables 4.4 and 4.5. This example demonstrates a system which contains hazard information, yet has a foundation on currently observable phenomena. This is likely to be more useful for end-users, as it provides them with the interpretation of the intensity of volcanic activity, i.e., what it means for them.

Having two systems was another suggestion by participants, one targeted at specific information for the CDEM sector (and presumably other key stakeholders), and the other for the public, incorporating more general information. It was also proposed that this could occur with VABs. Taking this further, one participant suggested that the various end-user sectors (such as major land managers, infrastructure, insurance etc.) could identify what information they require from the scientists, support and fund the creation and dissemination of that information, and build their own responses and procedures around it.

Table 4.10. Example of a phenomena-based VAL system which incorporates hazard information.

<table>
<tr><th colspan="3">Hypothetical phenomena-based Volcanic Alert Level system,
which incorporates hazards</th></tr>
<tr><th>Volcanic Alert Level</th><th>Volcanic activity</th><th>Potential hazards</th></tr>
<tr><td>5</td><td>Major volcanic eruption
has recently occurred or is in progress</td><td>Hazardous on and near volcano
Hazards depend on eruption style and may include widespread ash, lava flows or domes, pyroclastic (hot ash) flows, lahars (mudflows), and/or flying rocks</td></tr>
<tr><td>4</td><td>Moderate volcanic eruption
has recently occurred or is in progress</td><td>Hazardous on volcano
Hazards depend on eruption style and may include ash, lava flows or domes, pyroclastic (hot ash) flows, lahars (mudflows), and/or flying rocks</td></tr>
<tr><td>3</td><td>Minor volcanic eruption
has recently occurred or is in progress</td><td>Hazardous at areas near vent
Hazards depend on eruption style and may include unpredictable eruptions, ash, lava domes, hydrothermal activity, lahars (mudflows), and/or flying rocks</td></tr>
<tr><td>2</td><td>Moderate to heightened level of volcanic unrest</td><td rowspan="2">Low level of hazard, associated with volcanic unrest
Hazards may include unpredictable eruptions, hydrothermal activity, lahars (mudflows), and/or earthquakes</td></tr>
<tr><td>1</td><td>Minor volcanic unrest</td></tr>
<tr><td>0</td><td>No volcanic unrest</td><td>No volcanic hazards
Hazards which may not be directly related to volcanic unrest or eruptions may still occur, such as hydrothermal activity, lahars (mudflows), and/or earthquakes</td></tr>
<tr><td colspan="3">The Volcanic Alert Level is determined by GNS Science. For more information on volcanic hazards, see gns.cri.nz/volcano.</td></tr>
</table>

In conclusion, there are a number of possible foundations on which to build future VAL systems in New Zealand, which is the fifth theme of this qualitative research. The selection of the basis of a future VAL system requires consideration of the end-users' information needs, and what scientists can reasonably achieve with the current state of knowledge and monitoring techniques. There is a strong preference by scientists to retain a phenomena-based VAL system in the future, whereas end-users show a preference for a multi-foundation system based on a mixture of phenomena and hazards.

The next concept to be investigated is the incorporation of forecasting and predictive language in the VAL system.

4.6.3 "What is going to happen next?"

It was identified by a number of participants that the current system already includes predictive language, or implies future events may occur (e.g., 'large-scale eruption now possible', 'no eruption threat', and 'eruption threat'). However, it was recognised that there are numerous issues with this terminology, and that the VAL system should incorporate a much higher degree of eruption forecasting. End-users in particular would like to have an element of eruption forecasting included in the VAL system in order to give prior warning and enable an adequate response. It was implied by participants 'what use is a system where the VAL is increased after it erupts, when there is a possibility of interpreting the monitoring data and putting it up before it erupts?'

One of the questions perceived to be most commonly asked of the scientists during a volcanic crisis is 'is the volcano going to erupt, and if so, when?' While this level of accuracy in forecasting is yet to be achieved, participants from both scientist and end-user groups suggested incorporating whether the activity is trending up or down, or is stable.

> "Although the current alert level is not designed to [communicate what is going to happen] ..., during the volcanic crisis we're always trying to find out what someone's opinion is, some specialist's opinion – what are the trends?" (EU12).

The VAL provides a simple, effective tool to communicate this information, as recognised by the following two scientist participants.

> "What the people are telling us is they want to know what's happening next and we've got no way, using the scale, at least, of signalling that. The argument is often that we use the bulletins to flesh out that information, but the way we do it currently, I don't think many people read the bulletins necessarily or understand them or don't read between the lines. I think it needs to be a bit more explicit in which way we are going up or down on the information" (Sc5).

> "If you think that scientifically it's going in a certain direction, even if it's not quite there yet, you have some responsibility to communicate that somehow.

> You can do it in the words, but there's nothing quite as convincing as upping the alert level by one notch, sort of thing" (Sc18).

So whether the VAL system contains predictive language, whether this information is included in supplementary sources, or as a separate table or column in the VAL system, or whether the VAL system is used with a predictive sense by changing the level in advance of what the descriptions contain, communicating the scientists' sense of what is going to happen next is seen as important.

> "If there's one weakness [with the current system...] it's not in there and you can argue that it shouldn't be, but we all want it, all of us users want [to know] *what's going to happen next?*" (EU12) (authors emphasis).

It is thought, particularly by scientist participants, that end-users consider the current system as predictive, despite the original intent.

> "I think we're fooling ourselves if we say that people don't think, people other than scientists... who have written this, don't think of this as a predictive system. They are basing their response on it and the response is in the future, so they are always thinking of it as predictive" (Sc18).

It was recognised that the movement between VALs sends a signal to the end-users as to what might happen, not just what is currently happening. There is a perception that "if it's going up to one, it will be going up to two and then to three, and carry on" (EU7). This is likely to be the case regardless of the words used in future VAL systems. A decision-making strategy used by end-users, according to one participant, is anticipating future events in order to respond.

The incorporation of forecasting information into the VAL system would be challenging due to the high level of uncertainty involved in forecasting, and different interpretations which can be applied to predictive language. Interview participants considered the need to clarify the meaning of the forecasting phrases used in the current reawakening system, particularly those relating to eruption threat. A number of scientist participants stated that they are in favour of the phrase 'eruption threat' because it reflects that an "eruption may be imminent" (Sc4). Others mentioned that the language used for these terms was ambiguous:

> "how do you define what an eruption threat is, [...] if you've got probability of 10% does that make it an eruption threat, or is it 50[%]?" (Sc5).

It is thought that if you have unrest there is always a possibility of eruption, so the use of 'no eruption threat' would need to be changed to 'little eruption threat' or 'little likelihood of eruption' or similar, according to scientist participants. Additionally, it is thought that determining whether there is a 'threat of eruption' or not during unrest would be a very difficult decision to make. The phrase 'large scale eruption now possible' was also seen as problematic as a large scale eruption is possible anywhere in the system. It was suggested this phrase be changed to 'large scale eruption more likely', however this in turn raises the question of 'more likely than when/what?' The ambiguity of language potentially used in the system needs very careful thought.

It is fairly widely accepted by end-user participants that it is very difficult for scientists to provide forecasts and predictions. It is thought there is "conservatism" by most scientists to forecast volcanic activity due to the high level of uncertainty, and the fear of being proven incorrect retrospectively (which relates to the credibility factor influencing scientists decision-making, discussed in section 4.5.4):

> "Civil Defence and Emergency Management and the public don't want to know necessarily what's happened they want to know what is likely to happen. And this is where many scientists feel uncomfortable because they don't want to predict something and then find themselves being wrong. But on the other hand if you don't predict what could be a calamitous situation then you might be held in contempt for not doing that" (Sc22).

One of the difficulties with incorporating predictive language in a VEWS is the likelihood of 'false alarms', particularly if there is a timeframe relating to the onset of eruptive activity associated with the VALs. Language reflecting uncertainty can be incorporated, but is often difficult to interpret and keep consistent between groups (e.g., as reviewed in Doyle et al., 2011). Accurate forecasts need to include a timeframe, however uncertain, but this will be a challenge in a generic VAL system for all volcanoes, particularly those which have had no witnessed eruptions. The inclusion of forecasts with a timeframe in the VAL system may be too inflexible, with a high level of uncertainty. It is more likely that should predictive language be included in the future VAL system or supplementary information, time periods will not be used (and thus they will not be forecasts) to minimise the possibility of 'false alarms' and associated threats to scientific credibility. It was recommended by participants that there should be "great clarity" between what is currently being observed and forecasting language used. Some volcanologists insist that in the short term, volcanoes are not predictable, and thus no predictive language should be included in future VAL systems.

In summary, it seems there is a general desire by both scientists and end-user groups to include volcanic forecasting and predictive language in future VAL systems, yet the associated challenges described above may be too difficult for the scientists to overcome to maintain credibility. This research is inconclusive with regards to the inclusion of eruption forecasting in the VAL system. If it is decided that this information will not be included in future VAL systems, it is recommended that it is included in supplementary information, potentially in scenario format. It was acknowledged by end-users that information regarding the potential for future events can usually be extracted from the scientists during person-to-person conversations, depending on the scientist on duty. The VAB provides an optimal vehicle of information such as eruption forecasting. Recent VABs generally include a statement relating to potential future activity, for example "eruptions could occur with no warning" and "the likelihood of a sudden eruption, substantial enough to affect aircraft around the volcano, has decreased" (VAB RUA-2013/02[26]). It is recommended that the scientists attempt to include forecasting estimates in VABs whenever possible in order to communicate this information with the widest possible audience, rather than relying on individual person-to-person communication. As many end-users do not read VABs when the VAL has not been changed (as it is seen as "re-confirming" the VAL), this forecasting information should be explicit, and placed in an obvious position, such as in the summary sentences at the top of the VAB with the VAL and ACC. Should the determination of probabilities of scenarios during unrest and eruption events continue to develop at GNS Science, future VAL systems may be able to include forecasting language without jeopardising scientific credibility too seriously. It is likely that this will require uncertainties to be substantially decreased from their current levels, and forecasting would need to become possible for all of New Zealand's potentially active volcanoes.

4.6.4 Response advice inclusion

One of the most frequent statements by end-user participants during the VAL interviews was "what does it mean for us?" Often end-users find the interpretation of VALs difficult with respect to determining appropriate response actions.

[26] http://info.geonet.org.nz/pages/viewpage.action?pageId=4292767, accessed on 17 April 2013

> "It is more about the 'well what does that mean', what do we need to do now, in the way of actions more than anything else, or what do we need to communicate... to the community about what they should be doing in different places?" (EU1)

With a clear link to the 'relationship between end-users and the current VAL system' theme, it was suggested that future VAL systems incorporate not only the volcano status and scientific information if necessary, but also basic response advice for emergency managers and the public. This information would act as a "trigger" for emergency managers to make the appropriate response actions. Examples given by participants were those used by the MetService in severe weather warnings, which, prior to the event occurring, include 'move stock to higher ground' and 'exercise caution while driving'. Translating this to a volcanic crisis, advice could include 'prepare emergency plans and kits' and 'emergency managers are advised to monitor the situation for changes' (because although there is an assumption by scientists that emergency managers always monitor the situation for changes and read the VABs in detail, this is often not the case). During an eruption, generic advice might include, 'evacuate from hazardous zone' (within a stated timeframe), and how to live and work in an ash environment. These messages and many more are described in the unpublished draft document *community behaviour-based communication framework* prepared for Exercise Ruaumoko by GNS Science and MCDEM in January 2008. Due to the wide range of end-users and volcanic environments, careful consideration of the content of response advice would be required, and the information will likely be kept quite general. The decision on whether to evacuate or not remains with the emergency managers, and based on the interview results, this is generally well understood in New Zealand. Some participants did not support this idea due to the potential confusion of responsibilities between science and politics, and the legal consequences – "a road paved with litigation!" (EU11). The MetService response advice is issued within the information bulletin and is not part of the alert system itself. GNS Science may find this type of general response advice could be issued within VABs and not in the VAL system. This way situation-specific advice could be included in the more flexible accompanying supplementary information and in person to emergency managers, as is currently done.

4.7 Recommended changes to New Zealand's VAL system

The findings of this exploratory review of New Zealand's VAL system are summarised in this section. These findings are based on the opinions of end-users and scientists gathered during interviews and conversations in this ethnographic research, along with interpretations from document analysis and observations over three years. Based on this research, it is recommended that a number of aspects of New Zealand's VEWS be developed, including the VAL system and how it is used. These aspects are summarised here for ease of access.

4.7.1 Establishing the context of the VAL system

- Person-to-person communication should continue to be given high priority in the future, particularly to provide local context.
- Scientific information should be disseminated regularly and in a timely fashion, regardless of the level of uncertainty.
- Descriptions in the ACC should be taken at 'face-value' to ensure consistent use internationally and when compared to the VAL, and because it was designed and intended for the aviation industry so no further interpretation is required.
- If deemed appropriate by organisations involved, the ACC could be used to determine the NZV rather than the VALs. The template for future activity that is used by the aviation industry could be reconfigured to incorporate the VAL systems for both frequently active and reawakening volcanoes *if* the current VAL system continues to be used.
- The ACC could be taken out of the public arena, or at least not issued with a VAB. This is to minimise confusion over inconsistent messages from having two systems with similar wording, and the use of colour may cause complications with coloured hazard maps. Information relating to the ACC could continue to be made available to the interested public and other end-users by the Wellington VAAC.
- Supplementary information sources (such as the VAB) could meet most of the needs of end-users. These needs were identified as:
    - Details of the current situation, e.g., why the decision to change the VAL was made.
    - Potential hazards resulting from the current situation, and their impacts (including on society, human behaviour, and the economy). Clear and specific information needed on who may be affected.
    - Possible future activity, which could be based on what has happened in the past or elsewhere. E.g., is the situation trending upwards or downwards? How long is the situation expected to continue for? This information could be presented as scenarios.

  - What is known? What is unknown? Clear statements on uncertainty needed. Probability estimates are welcomed by end-users.
  - What should the public and other end-users be doing in this situation (to the extent that separate roles and responsibilities allow it)?

It is recommended that the purpose of the current VAL system is adopted to be *a communication tool used by the scientists at GNS Science to enable end-users to quickly understand the current state of activity at the volcanoes, from which they can decide their response*.

4.7.2 Relationship between end-users and the current VAL system

- It is recommended that the link between end-user actions and specific VALs be kept flexible, and lead-in times to events considered.
- It is recommended that the VAL system be simplified for ease of use for end-users, with a balance struck between short descriptions and minimising ambiguity.

4.7.3 A review of the current VAL system

- The layout and appearance of the VAL system on the GeoNet webpage should be consistent with the official version in the Guide to the CDEM Plan.
- Consideration should be given to ordering the alert levels from highest (top) to lowest (bottom).
- Either numbers or words (not different colours) should be used as labels in the future VAL system, however the words should not be similar to those used by MetService.
- It is recommended that all volcanoes in New Zealand should use a single VAL system.
- It is recommended that two levels relating to unrest should be included in the future system (suggested to be minor unrest and moderate to heightened unrest).
- End-users preferred three levels relating to eruption (most likely due to the perception of the system being a linear, equal interval scale), resulting in a zero to five system if retaining a phenomena-based foundation.
- It is recommended that the type of information currently contained in the indicative phenomena column be removed from the VAL system and included in the VAB for those wishing to know the specific monitoring data behind the decision (as is currently done), provided scientists have a common basis to ground their VAL decision in other documentation.

- The future VAL system needs to avoid jargon and have careful consideration of all terminology used to minimise ambiguity and the chance of misinterpretation and confusion.

4.7.4 Influences on scientists' determination of the VAL

The influences on the determination of the VAL (and ACC) are summarised here, and include:

- The science: monitoring data and interpretation
- Experience and knowledge
- Peer influence and social psychology influences
- Maintaining credibility, influenced by:
    - The speed of movement between the levels of the VAL system (particularly during de-escalation)
    - Delays in determining the VAL
    - Disagreements between scientists on the appropriate VAL in the public arena
    - The perception that scientists are hiding information
    - The repeatability of determining the VAL
    - 'False alarms'
    - The ability to justify decisions
- Use the system as a guideline (i.e. flexibly) or as a prescription (i.e. inflexibly) by the scientists
- Differences in interpretation of the VAL content, based on:
    - an individual's interpretation of the content of the VAL system
    - the perception of what the meanings were originally intended to be when the system was formed in the mid-1990s
    - using it as a linear numbered system with little emphasis on the wording.
- End-user actions associated with VAL changes (including socio-economic impacts)
- Incorporating a hazard or risk perspective and eruption forecasting
- Internal organisation pressure
- External organisation pressure
- Perceived purpose of the VAL
- Fieldwork intentions

Recommendations made in this section are that:

- Regular exercises take place due to the infrequency of eruptions.
- Lessons and experiences should continue to be recorded following an event for the future, so lessons are not lost.
- A 'lag period' could be considered before new technicians (and scientists?) vote on the VAL during monitoring meetings, while they increase familiarity and knowledge of the volcanoes.
- Research could be undertaken on the social psychology influences on expert and group decision-making in a volcanological context, to maximise the effectiveness and appropriateness of decisions made.
- Scientists should be made aware of the potential influences occurring during the voting process. Increasing awareness of the potential biases can reduce the influence on decision-making.
- The VAL voting process should exclusively use neutral phrasing of the question eliciting a response (e.g., "who would like to vote for VAL 1?" as opposed to "is everyone happy with the VAL staying at 1?"). A hands-up vote rather than a verbal vote should be used.
- Alternative options for voting could be considered (e.g., electronic means of multiple-choice blind voting with remote) in the future.
- The use of a time limit in which to decide on a VAL (and ACC) could be considered during future crises when time is an important factor in provision of scientific advice. This will help maintain end-users' trust and credibility, while balancing making a robust and timely decision.
- It is recommended that the face-value of the words in the system be carefully considered prior to voting to ensure an accurate VAL (or ACC) is determined, rather than relying on the decision made in the previous meeting. By taking the descriptions at face-value, the interpretations of the meanings of the levels will be more consistent between scientists and end-users. However, the incorporation of a forecasting or hazard/risk perspective may require the system to be used more as a guideline, prompting the need for further details (e.g., justifications) in supplementary information sources.
- Obtaining a consensus amongst voting scientists at GNS Science regarding whether the VAL system should be used as a guideline or as a prescription when determining the VAL would be beneficial, although it may not be possible. In making this decision, the

use of the system by end-users and the purpose of the system should be given a heavy weighting.

- Developments in assigning probabilities to scenarios during volcanic unrest and eruptions could result in the incorporation of forecasting into future VAL systems.

4.7.5 A recommended future VAL system for New Zealand

The purpose of the future VAL system is suggested below. It is similar to the purpose of the current system, and is based on the integrated findings of this research.

The VAL system is a communication tool used by the scientists at GNS Science to enable end-users to quickly understand the current state of activity and the potential hazards at the volcanoes, from which they can decide their response.

It is recommended that New Zealand retains a phenomena-based VAL system. This is based on the findings presented in this thesis, particularly the preferences expressed during the feedback process in the latter stages of this research (discussed in section 4.6.2). It is recommended that the currently used indicative phenomena column be replaced by hazard information, as in general, it is seen as more useful for end-users. The details of the unrest and eruption activity (i.e. the indicative phenomena), which specifically relate to each situation, can be described in the VAB, as is currently the case. The benefits of both the phenomena-based and hazard-based systems as described in sections 4.6.1.1 and 4.6.1.2 apply to this recommended system. The inclusion of hazard information helps mitigate some of the issues described for phenomena-based systems. For example, phenomena-based systems can be difficult for end-users to interpret to understand potential hazards they may need to respond to. The inclusion of this hazard information negates this issue.

Through the incorporation of the recommendations listed above, it is envisaged that the new system could be similar to Table 4.11. It is reproduced from and identical to Table 4.10. It has one level for no unrest, two levels relating to unrest, and three for eruptions. The order of the levels has been reversed from the current system to be high (5) at the top of the table, to low (0) at the bottom of the table. The use of numbers has been retained here, however in the future, adequate words may be found to replace the numbers to minimise the perception of a linear, equal-interval scale. Further research is needed to assess the possibilities. To meet the expressed opinions of some of the participants to simplify the system, this table would have fewer words and detail in it. However, during the feedback process end-users generally preferred the VAL systems which had a high level of detail (including for hazards) for clarity, hence the inclusion of this information in Table 4.11. The high level of wording is the reason the potential hazards for VAL 1 and 2 are not repeated. If this is thought to increase the chance of confusion, however, separate entries for VALs 1 and 2 may need to be created.

Table 4.11. Recommended VAL system for New Zealand, based on the findings of this research. It is a phenomena-based system with hazard information, where to go for further information, and would contain a version number or year.

Recommended Volcanic Alert Level system for New Zealand		
Volcanic Alert Level	**Volcanic activity**	**Potential hazards**
5	**Major volcanic eruption** has recently occurred or is in progress	**Hazardous on and near volcano** Hazards depend on eruption style and may include widespread ash, lava flows or domes, pyroclastic (hot ash) flows, lahars (mudflows), and/or flying rocks
4	**Moderate volcanic eruption** has recently occurred or is in progress	**Hazardous on volcano** Hazards depend on eruption style and may include ash, lava flows or domes, pyroclastic (hot ash) flows, lahars (mudflows), and/or flying rocks
3	**Minor volcanic eruption** has recently occurred or is in progress	**Hazardous at areas near vent** Hazards depend on eruption style and may include unpredictable eruptions, ash, lava domes, hydrothermal activity, lahars (mudflows), and/or flying rocks
2	**Moderate to heightened volcanic unrest**	**Low level of hazard, associated with volcanic unrest** Hazards may include unpredictable eruptions, hydrothermal activity, lahars (mudflows), and/or earthquakes
1	**Minor volcanic unrest**	
0	**No volcanic unrest**	**No volcanic hazards** Hazards which may not be directly related to volcanic unrest or eruptions may still occur, such as hydrothermal activity, lahars (mudflows), and/or earthquakes
The Volcanic Alert Level is determined by GNS Science. For more information on volcanic hazards and what to do to mitigate them, search 'volcanic hazards' on www.gns.cri.nz. Version x.		

Terms have been carefully selected for both simplicity and clarity to avoid ambiguity. The use of the terms 'volcano' and 'vent' have been used in the hazard column, and it is acknowledged that this may be difficult to use at volcanoes where sites of future eruptions are uncertain.

However, the 'volcanic activity' column could still be used to base VAL decisions on. A hazard map would most likely also be disseminated to describe the areas near the possible vent sites that are most at risk. The difference between minor, moderate, and major volcanic eruptions intentionally remains fairly subjective. It is envisaged that volcanoes only capable of relatively small eruptions, such as AVF, would reach VAL 5 during a major eruption, even though it would not reach the same eruptive volume as a caldera volcano may be capable of (hence the use of the term 'major' instead of 'large' volcanic eruption). This enables flexibility and the potential for incorporating risk in determining the VAL.

Time comparative language (e.g., background activity, changes, or increases in activity) has not been incorporated in this system to enable the consistent use of a single level for a long period of time. For example, continuous minor volcanic unrest from Mt. Ruapehu observed as a warm crater lake and sizeable gas flux is expected to sit at VAL 1 in this recommended system, without needing to consider whether this level of activity is now the normal, background level of activity. This way, the level of activity at all volcanoes in New Zealand can be compared using the VAL system. The use of graphics in the VAL system, similar to the Japan Meteorological Agency VALs, could be beneficial. This would require further research if it were to be used in New Zealand.

It was initially proposed that the decision to allocate the VAL could be based on either the volcanic activity column or potential hazards column. However, it was decided the risk of mixed messages and the threat to scientific credibility is too high, so common practice will be to determine the level based only on the 'volcanic activity' column. This minimises the possibility of raising the level in advance of activity occurring, but the language in the table is still less restrictive than the current system, in case this decision changes in the future.

Issued VALs should be accompanied by supplementary information sources, with additional details available on volcanic hazards, potential impacts, and mitigation measures (or where to find further information on these aspects); specific situation information in VABs; and appropriate hazard maps containing spatial information. Forecasting language is not incorporated in this recommended VAL system, for reasons stated earlier in this chapter. However, forecasts can be incorporated in the VAB or other supplementary information in the future. If forecasts were 'hard wired' into the new VAL system, scientific credibility may be jeopardised in situations where forecasts remain highly uncertain, or raising the VAL may be delayed until the forecast is more certain. It is recommended that forecasts, such as in the form of probabilities or scenarios, be communicated whenever possible to a wide audience, and stated in a clear and explicit manner. This should be accompanied by context, comparative language, and/or analogies, and risk language carefully considered, to ensure consistency in interpretation and ease of understanding. Together, this package should provide users with the majority of their information needs.

4.8 Impacts of changing the VAL system

End-users were asked ‘in the event that the VAL system changes in the future, what impact would this have on your organisation?’ They predominantly thought that as long as they were made aware of the change, and what the meanings of the levels in the new system are, the change would not be "earth-shattering". In fact it was seen as potentially beneficial as it would prompt volcanic hazards and response planning to be brought to the forefront of end-users’ minds, and response plans might be updated. The VAL system in the Guide to the National CDEM Plan (MCDEM, 2006) would also need to be updated. This document is routinely updated every couple of years, and according to one end-user participant, it may be processed more quickly if necessary, such as during a volcanic crisis. The information would still be delivered through the Ministry's Datasquirt advisory bulletin system. MCDEM would then need to raise public awareness of the change and re-educate the CDEM sector.

The aviation industry and any other end-user with actions associated to specific VALS would need to reassess their thresholds, and while it would need attention it was not seen as a barrier to updating the VAL system. It was thought if the new system is easier for end-users to understand or interpret, end-users and GNS Science would get fewer follow-up phone calls for clarification.

It was suggested that the new VAL system should clearly state a version number, or year of publication to ensure all end-users are using the correct version. Similarly, end-users should be prompted to throw out any hard copies of the out-dated version or mark on them that it has been superseded.

4.9 Post-research implementation of the VAL system

This research ended in August 2013 with the recommended VAL system presented in Table 4.11. In the months following, this recommended system was presented to volcanologists at GNS Science, end-users, and MCDEM representatives, and it went through multiple iterations, and graphics department consultations. Throughout this process, the findings of this research were maintained. The final version of New Zealand's new VAL system was implemented on 1 July 2014, and is presented in Figure 4.11. It is included in an amendment of MCDEM's Guide to the National CDEM Plan, and is on the GeoNet website.

Reasons for changes made between Table 4.11 and Figure 4.11 include:

- Levels 1 and 2 in the hazard column were split for simplicity.
- The fine print in the hazards column was removed, and eruption and unrest hazards described once at the bottom of the table, for simplicity.
- Various caveats were included, relating to the potential spatial extent of hazards, the possibility for levels to be skipped out, or not follow a sequential pattern, and, most importantly, that an eruption can occur from any level. It was recognised that the hazards in each level describe the most likely hazards that may be observed, but that an eruption of any size could occur before the level can be raised.
- The phrase "potential for eruption hazards" was added to the hazard column of VAL 2, to reinforce the increased potential for an eruption to occur at heightened unrest. Careful choice of language was made to enable decreasing VALs and remaining at that level for long periods of time.
- A column to the left of the table was added and colour used to emphasise parts of the table relating to eruption vs. unrest. Increasing strengths of the same colour was added under the number labels to aid the interpretation of the different levels.
- The colour was changed to purple to avoid the colours used in the ACC, and those likely to be used in future volcanic hazard maps. It was selected to be balanced between not overly reassuring or concerning. The version in MCDEM's Guide to the National CDEM Plan is grey-scale due to their colour restrictions (it looks the same as a black and white photocopy of the purple version).

New Zealand Volcanic Alert Level System

	Volcanic Alert Level	Volcanic Activity	Most Likely Hazards
Eruption	**5**	**Major volcanic eruption**	**Eruption hazards on and beyond volcano***
Eruption	**4**	**Moderate volcanic eruption**	**Eruption hazards on and near volcano***
Eruption	**3**	**Minor volcanic eruption**	**Eruption hazards near vent***
Unrest	2	Moderate to heightened volcanic unrest	Volcanic unrest hazards, potential for eruption hazards
Unrest	1	Minor volcanic unrest	Volcanic unrest hazards
	0	No volcanic unrest	Volcanic environment hazards

An eruption may occur at any level, and levels may not move in sequence as activity can change rapidly.

Eruption hazards depend on the volcano and eruption style, and may include explosions, ballistics (flying rocks), pyroclastic density currents (fast moving hot ash clouds), lava flows, lava domes, landslides, ash, volcanic gases, lightning, lahars (mudflows), tsunami, and/or earthquakes.

Volcanic unrest hazards occur on and near the volcano, and may include steam eruptions, volcanic gases, earthquakes, landslides, uplift, subsidence, changes to hot springs, and/or lahars (mudflows).

Volcanic environment hazards may include hydrothermal activity, earthquakes, landslides, volcanic gases, and/or lahars (mudflows).

***Ash, lava flow, and lahar (mudflow) hazards may impact areas distant from the volcano.**

This system applies to all of New Zealand's volcanoes. The Volcanic Alert Level is set by GNS Science, based on the level of volcanic activity. For more information, see geonet.org.nz/volcano for alert levels and current volcanic activity, gns.cri.nz/volcano for volcanic hazards, and getthru.govt.nz for what to do before, during and after volcanic activity. Version 3.0, 2014.

Figure 4.11. New Zealand's new VAL system, based on the findings of this research. This system is in an amendment of the Guide to the National CDEM Plan (MCDEM, initially published in 2006), produced in July 2014.

Prior to the use of the new system on 1 July 2014, a communication strategy was developed at GNS Science to introduce it to stakeholders and the public. The first step, in May 2014, communicated that the system was going to change in six weeks' time. It involved targeted messages to the VAB and VONA distribution lists (which include media), and to key stakeholders such as DoC and tourist operators. Multiple presentations were given and are planned for future meetings and conferences that are attended by stakeholders. A news story was added to the GeoNet website[27], which included Frequency Asked Questions, and it was publicised on social media. The new system was added to the GeoNet website, beneath the current VAL system. Frustratingly, this prompted the recognition that adding the VAL system as an image is not ideal for websites due to resizing on various devices and lack of compatibility with read-aloud software. The new system was therefore added as text in a table, and formatted to look as similar to Figure 4.11 as possible. MCDEM organised the integration of the new VAL system into the Guide to the National CDEM Plan, trained their duty officers, and disseminated further information to the CDEM sector. Joint messages between GNS Science and MCDEM were distributed using the MCDEM Impact magazine and E-Bulletin.

Another message was disseminated through these avenues on 1 July stating that the new system had come into effect, and listing the new VALs for each of New Zealand's monitored volcanoes, as voted by the GNS Science volcanologists. It is likely that the demand for information relating to the new system will not come until a VAL changes during an unrest or eruption in the future.

Guidelines were developed within GNS Science to aid establishing a common interpretation of the meanings of the alert levels between voting scientists. The guidelines for each alert level include a brief description and 'type examples' of activity from New Zealand's volcanoes, and some from overseas. Establishing a common understanding of each level was a major undertaking, and an enlightening exercise in itself.

4.10 Link to Chapter 5

This chapter presented and explored the results of research into New Zealand's VAL system. The context of the VAL system was set, the relationship between end-users and the current VAL system described, the content and structure of the current VAL system explored, and factors influencing scientists' determination of the VAL identified. Options for future systems were suggested, and the new version of the VAL system that will be implemented in New Zealand based on the findings of this research was presented.

The interpretation of the content of VAL systems, particularly between 'background' and 'unrest' activity requires further exploration and definition to ascertain the point at which the

[27] http://info.geonet.org.nz/pages/viewpage.action?pageId=9502734, accessed on 23 June 2014

VAL would be raised at a caldera volcano. The next two chapters address this issue by describing the development of the Volcanic Unrest Index, discussing the concept of unrest, and defining unrest for TVC. These relate to research aim five. Chapters 5 and 6 are presented in the form in which they were submitted to the international journal called Bulletin of Volcanology, and as such, contain some information that is repeated elsewhere in this thesis. However, as it is part of a thesis, it contains cross-references to other chapters, and cited references and appendices are positioned at the end of the thesis with those from other chapters.

CHAPTER FIVE

INTRODUCING THE VOLCANIC UNREST INDEX (VUI): A TOOL TO DEFINE AND QUANTIFY THE INTENSITY OF VOLCANIC UNREST

This paper has been submitted to the Bulletin of Volcanology:

Potter, S.H., Scott, B.J., Jolly, G.E., Neall, V.E., Johnston, D.M. Introducing the Volcanic Unrest Index (VUI): a tool to define and quantify the intensity of volcanic unrest. Submitted to the Bulletin of Volcanology.

5 INTRODUCING THE VOLCANIC UNREST INDEX (VUI): A TOOL TO DEFINE AND QUANTIFY THE INTENSITY OF VOLCANIC UNREST

5.1 Abstract

The accurate observation and interpretation of volcanic unrest phenomena contributes towards better forecasting of volcanic eruptions, thus potentially saving lives. Volcanic unrest is recorded by volcano observatories and may include seismic, geodetic, degassing, and/or geothermal phenomena. The multivariate datasets are often complex, and can contain a large amount of data in a variety of formats. Low levels of unrest are frequently recorded, causing the distinction between background activity and unrest to be blurred, despite the widespread usage of these terms in unrest literature (including eruption forecasting probabilistic models) and in Volcanic Alert Level (VAL) systems. Frequencies and intensities of episodes of unrest are not easily comparable over time or between volcanoes. Complex unrest information is difficult to communicate simply to civil defence personnel and other non-scientists. The Volcanic Unrest Index (VUI) is presented here to meet these needs. The purpose of the VUI is to provide a definition of unrest and a semi-quantitative rating of unrest intensity relative to each volcano's past and potential level of unrest. The VUI is based on a framework of observed phenomena. Ranges for each phenomenon within the framework can be customised for individual volcanoes, as demonstrated in the companion paper for Taupo Volcanic Centre, New Zealand (Chapter 6). The VUI can be retrospectively estimated for historical episodes of unrest based on qualitative observations, as well as for recent episodes with state-of-the-art monitoring. This enables a long time series of unrest occurrence and intensity to be constructed and easily communicated to end-users. The VUI provides a definition of background activity and unrest, which can assist with VAL decision-making. Two approaches to the concept of unrest are presented and discussed.

Keywords

VUI, earthquakes, deformation, hydrothermal, caldera unrest, volcanic unrest, communication

5.2 Introduction

Volcanic unrest is the key indicator of an impending eruption. Unrest can include a wide range in intensity of phenomena and duration of episodes, and can cause a variety of social and economic impacts (e.g., Barberi et al., 1984; Mader & Blair, 1987; Lowenstein, 1988; Hill, 1998; Johnston et al., 2002). It may occur frequently and often does not result in an eruption (e.g., Newhall & Dzurisin, 1988; Moran et al., 2011). A robust understanding of the frequency and intensity of unrest is limited by the lack of evidence in the geological record. This restricts the extent of the record to historical times, with a reliance on observations that have been recorded. Very few long-term unrest catalogues have been created at volcanoes worldwide, particularly in the case of no resulting eruption; the emphasis is predominantly on eruptions (Moran et al., 2011). A notable exception is WOVOdat (www.wovodat.org), still under development but opened for public use in July 2013. The identification and classification of past unrest can inform the potential outcomes of future unrest.

Early historical volcanic unrest observations tended to be qualitative, which are difficult to compare to routine and precise modern monitoring data. Volcanic hazard forecasting is becoming more quantitative, and is based on an understanding of volcanic system processes (Sparks, 2003). However, there is currently no simple numeric summary of the overall intensity of multivariate volcanic unrest phenomena, which might be used to compare the intensity or frequency of unrest over time or between volcanoes. We propose a solution in the form of a Volcanic Unrest Index (VUI), based on a scale of 1 to 5 of observed unrest. Since it is defined flexibly, the VUI can be estimated from any information on unrest, however sparse.

5.3 Volcanic unrest phenomena

Volcanic unrest may include seismic and geodetic phenomena, degassing, and/or changes to geothermal systems (e.g., Scarpa & Tilling, 1996).

5.3.1 Seismicity

Volcanic earthquakes, defined by McNutt (2000, p. 1016) as "earthquakes which occur at or near volcanoes, generally within 10 km, or are related to volcanic processes", are a fundamental indicator in forecasting volcanic eruptions (e.g., McNutt, 1996, 2000; Kilburn, 2003; Zobin, 2003). A variety of seismic signals are produced by volcanoes, caused by processes such as rock fracturing from the movement of magma, groundwater, and hydrothermal fluids; changes in stress and pore pressure (e.g., from deformation, regional events, and gravitational loading); tectonic processes; and/or surficial events (e.g., McNutt, 2000). These seismic signals can be interpreted to contribute towards understanding magma chamber properties and evolution, indicating physical volcanic processes in order to forecast eruptions, as well as to identify the actual onset of an eruption, and understand eruption characteristics (e.g., Chouet, 1996; McNutt, 2000, 2005; McNutt & Nishimura, 2008).

Drawing on findings in the international literature, a number of seismic parameters may indicate whether or not an eruption might follow. Earthquakes typically occur in swarms near volcanoes (McNutt, 2000). An earthquake “swarm” is defined by McNutt (2000) as “a group of many earthquakes of similar size occurring closely clustered in space and time with no dominant main shock”. The duration of pre-eruptive earthquake swarms tends to be longer than the duration of non-eruptive swarms (e.g., Benoit & McNutt, 1996; Sandri et al., 2004; Kilburn & Sammonds, 2005). Earthquake hypocentres are often located at moderate depths beneath the volcano edifice (McNutt, 1996), and may also cluster in a location offset from the central vent area (e.g., Harlow et al., 1996; McNutt, 1996; Hurst & McGinty, 1999; Kilburn, 2003). Hypocentres sometimes move towards a vent prior to an eruption, as fractures in the rock caused by migrating magma unite (e.g., Umakoshi et al., 2001; Kilburn, 2003; Kilburn & Sammonds, 2005). Additionally, the rate of seismicity tends to increase prior to an eruption (e.g., Zobin, 2003; Kilburn & Sammonds, 2005; Bell et al., 2011). The maximum magnitude of earthquakes may not be significantly different in pre-eruptive unrest than non-eruptive unrest (Benoit & McNutt, 1996; Sandri et al., 2004). However, an increase in the rate of seismic energy release can indicate an impending eruption, as can a sudden (over hours to days) decrease (e.g., Malone et al., 1983; Voight, 1988, 1989; Voight & Cornelius, 1991; Endo et al., 1996; Zobin, 2003; Kilburn & Sammonds, 2005). Seismicity with a low frequency component, including hybrid earthquakes and volcanic tremor, indicate pressure changes induced by fluid movement through fractures (e.g, McNutt, 1992; Chouet, 1996; McNutt, 2000, 2005). Tremor is often particularly indicative of an impending eruption (e.g., Newhall & Dzurisin, 1988), and contributes to the release of seismic energy, which can be monitored with real-time seismic amplitude measurements (RSAM; Endo & Murray, 1991; Voight & Cornelius, 1991).

5.3.2 Deformation

Deformation of a volcano can indicate a future potential eruption due to, for example, movement of magma or pressurisation of geothermal systems (e.g., Decker, 1986; Toutain et al., 1995; Van der Laat, 1996; Murray et al., 2000). An increasing rate of deformation precedes some eruptions (e.g., Swanson et al., 1983; Voight, 1988, 1989). Along with ground fracturing, uplift was recognised as one of the most important pre-eruption indicators at silicic calderas by Newhall and Dzurisin (1988). Deformation can be monitored by GPS, interferometric synthetic aperture radar (InSAR), surveying levels, and tilt measurements (e.g., Murray et al., 2000; Otway et al., 2002; Scott & Travers, 2009). The location of a deformation source, and whether it is inflating or deflating can be hypothesised, modelled, and compared against observable data to give an indication of subsurface processes (e.g., Mogi, 1958; Lowry et al., 2001; Langbein, 2003; Folch & Gottsmann, 2006; Newman et al., 2012). Measuring gravity and magnetic changes can also contribute towards recognising magma body locations (e.g., Rymer, 1994; Davy & Caldwell, 1998; Murray et al., 2000). While the interpretation of data measured on the surface to indicate subsurface processes still involves a fair amount of uncertainty, it is an important component of interpreting volcanic unrest and possible outcomes (Murray et al., 2000).

Groundwater level and spring flow changes reflect pore pressure increases and decreases in a confined aquifer (Price, 1985). Pore pressure changes can be caused fairly rapidly by magma injection resulting in mechanical compression and extension of surrounding areas, or a slower increase in pressure from rising fluid temperatures (Newhall et al., 2001). Sudden groundwater level drops have been noted on numerous occasions as a result of inflation and draining of confined reservoirs, including at Kilauea (Hawaii, U.S.) in 2001, (Hurwitz & Johnston, 2003); Mt. Usu (Japan), prior to an eruption in 2000 (Shibata et al., 2008); and elsewhere in Japan and the Philippines (e.g., Koto, 1916, cited in Newhall & Dzurisin, 1988; Albano et al., 2002). Increases in spring flows have also been noted prior to eruptions (e.g., Omori, 1914 and Koto 1916, both cited in Newhall & Dzurisin, 1988; Guidoboni & Ciuccarelli, 2011). Groundwater level changes are particularly useful for consideration in historical periods, prior to modern deformation monitoring technology, and at volcanoes with a low monitoring capability.

5.3.3 Geothermal systems and degassing

Changes in geothermal systems and degassing can also indicate volcanic unrest (e.g., Martini, 1996). 'Geothermal systems' are described by Hochstein and Browne (2000, p. 835) as a "natural heat transfer within a confined volume of the Earth's crust where heat is transported from a 'heat source' to a 'heat sink,' usually the free surface". Volcanic systems, hydrothermal systems, and combination volcanic-hydrothermal systems (which differ depending on the fluid signature, and recharge and convection processes) are types of geothermal systems (Hochstein & Browne, 2000). The activity of surface manifestations (which include fumaroles, solfataras, hot steaming ground, hot mud pools, hot springs, and hot acid lakes) depends on parameters such as the tectonic regime, temperature of the geothermal system, source of heat, characteristics of the crustal rock including permeability, and the processes of heat transfer (Hochstein & Browne, 2000). As magma is injected into shallow levels of the Earth's crust, surface temperatures and heatflow often increase, and surface manifestations may become hotter, more active, and unstable (e.g., Bonneville & Gouze, 1992; Rothery et al., 1995). Hydrothermal eruptions and phreatic eruptions may also occur. Hydrothermal eruptions are defined by Browne and Lawless (2001, p. 300) as "an eruption ejecting at least some solid material and whose energy derives solely from heat loss and phase changes in a convecting hot water or steam-dominated hydrothermal system" (this is similar to the definition given by Barberi et al., 1992). The definition of a phreatic eruption used in this research is "an eruption which is caused by heating and flashing of water produced when magma comes into contact with water but only country rock or overburden is ejected (i.e. no juvenile magmatic material)" (Browne & Lawless, 2001, p. 300).

Degassing is defined by Jaupart (2000, p. 237) as "the process by which magma loses its dissolved volatile species as pressure decreases", and is monitored by many observatories as an indication of subsurface processes. Magma degasses (CO_2 and SO_2 increases are particularly common) as the pressure drops at shallow depths, and convection assists the movement of gas to the surface (e.g., Allard et al., 1991; Kazahaya et al., 1994; Martini, 1996; Moran et al., 2011). Therefore, changes in gas flux may indicate the presence of shallow magma (e.g., Daag et al., 1996; Delmelle & Stix, 2000). A sudden decrease in gas emissions may also occur prior to an eruption caused by the blocking of the conduit, or from quenching of magma resulting in scrubbing magmatic gases (Moran et al., 2011). The emission of high concentrations of poisonous gases can cause animals (including humans) and trees to die (e.g., Blong, 1984; Baxter et al., 1989; Rabaul Volcano Observatory, 1990; Farrar et al., 1995; Sorey et al., 2000; Umakoshi et al., 2001; Durand, 2007).

Changes in the geochemistry of gas and fluids, often interpreted using ratios, are influenced by the interaction of a magma body and its fluids with groundwater and surrounding rocks (e.g., Newhall & Dzurisin, 1988; Sparks, 2003). Geochemistry of volcanic gases and fluids can be interpreted to determine whether the source has a meteoric, hydrothermal, or magmatic signature (e.g., Delmelle & Stix, 2000). An increasing disequilibrium state can indicate unrest in a magmatic-hydrothermal system (Martini, 1996).

The integration and interpretation of these unrest parameters contributes towards an increased understanding of magmatic and volcanic system processes, and potential outcomes.

5.4 Volcanic unrest challenges

5.4.1 A complex multivariate dataset

The interplay of large-scale tectonics, regional deformation, local tectonic fault belts, and geothermal systems, together with coexisting volcanic systems, creates a highly complex dataset. Identifying the phenomena that specifically indicate magma-induced volcanic unrest is a difficult but important challenge, as a magmatic eruption is likely to have a more significant consequence than non-magmatic unrest. As magma enters existing country rock, the geophysical and geochemical response can vary in intensity and spatially according to the range of mechanical properties and structures of the rock, stress variations, pore pressure, and the temperature and chemistry of the magma (Sparks, 2003). These factors cause differences between volcanoes in the variety and intensity of unrest phenomena generated. Many of these factors also change over time, as rates of deformation, strain, magma movement, crystallisation, and degassing vary (Sparks, 2003). Therefore, a complex array of phenomena requires interpretation. The dataset can be large, received in a variety of formats, and is often collected at different monitoring frequencies. Observations which were described by the local population qualitatively in the past are now predominantly recorded quantitatively on monitoring equipment at volcano observatories, with a high level of detail. The integration of these datasets can be a challenge. The data are combined conceptually by volcanologists to determine the likely cause(s) of the phenomena, and the potential outcomes. Integrating and interpreting the various unrest parameters is key to successfully forecasting eruptions (e.g., Harlow et al., 1996; Sparks, 2003).

5.4.2 Volcanic unrest communication

Effectively communicating warnings relating to volcanic unrest is important in order to provide adequate response time before an eruption, and to maintain relationships between scientists, civil protection personnel, and the public (Ronan et al., 2000). The change in intensity of activity, for example, between 'background' (or typical) activity to 'unrest', is often communicated to end-users by a change of the VAL. The VAL commonly influences the preparation and response actions by scientific and emergency management officials (Fearnley et al., 2012). The descriptions given in VAL systems typically use the terms 'background' and 'unrest' as thresholds between levels (including in the U.S., Gardner & Guffanti, 2006; New Zealand, Scott & Travers, 2009; Philippines, as stated on http://www.phivolcs.dost.gov.ph/; and in the International Civil Aviation Organization (ICAO) aviation colour code, Guffanti & Miller, 2013). The decision to change levels is based on the subjective integration of multiple monitoring observations by volcanologists (Fearnley, 2013; and as discussed in Chapter 4).

Unrest is also used in the first node in Event Tree models for eruption forecasting and quantifying volcanic hazards (e.g., Newhall & Hoblitt, 2002; Marzocchi et al., 2004; Marzocchi et al., 2008). The term 'unrest' requires a robust, transferable, defendable and, in the opinion of some, preferably quantitative definition (Garcia-Aristizabal et al., 2013). Without a robust definition of terms such as 'background' and 'unrest', the point at which to change the VAL may become inconsistent over time and between volcanoes, negating the purpose of these systems. This is particularly the case during slowly evolving unrest situations.

Volcanic unrest phenomena can be hazardous and require a response, despite the lack of an impending eruption, as has been observed at large calderas in particular (for example at Campi Flegrei Caldera, Italy, in 1982–84, Barberi et al., 1984; Long Valley Caldera, U.S., in 1979–84, Mader & Blair, 1987; Rabaul Caldera, Papua New Guinea, in 1983–85, Lowenstein, 1988; and Taupo Volcanic Centre (TVC), New Zealand, in 1895, 1922, and 1964–65, Chapter 6). Caldera unrest may cause psychosocial, political, and economic impacts as a result of the on-going felt earthquakes, uncertainty, and the impact on tourist and investment industries (e.g., Mader & Blair, 1987; Lowenstein, 1988; Hill, 1998; Johnston et al., 2002). In these situations the distinction between 'background' activity and 'unrest', particularly in relation to determining the VAL, becomes a focus. Similarly, classifying the level of unrest at non-caldera volcanoes can also be difficult when the stakes are high – such as those frequented by tourists and relied on by businesses and local economies (for example, White Island and Tongariro Volcanic Centre in New Zealand, both of which exhibited fluctuating unrest and minor eruptions in 2012 and 2013). Developing an understanding of the relative intensity of past unrest will help end-users (and scientists) place future unrest into perspective, help to prompt the preparation of response plans, and thus reduce the risk of volcanic unrest and eruptions.

The concept of an index is to compare a quantity to a pre-specified base (Inhaber, 1976). There is not currently a simple, quantitative method to integrate and describe the intensity of unrest, no volcanic unrest index exists, nor is there a transferable and comparable definition of unrest, to assist with the effective communication of volcanic unrest with end-users.

5.5 The Volcanic Unrest Index (VUI)

Given the need to more easily and robustly compare the intensity of unrest over time, and to ensure that there is a common situational awareness between scientists and end-users, a VUI has been developed. The design and use of the VUI is described in this section.

The current state of knowledge has been ascertained regarding relationships between volcanic unrest phenomena and volcanic processes, including eruptions, through an extensive literature review. Areas of focus included research on eruption-forecasting methods, statistical analyses of unrest data, and the current understanding of volcanic processes and associated signals (including research by those mentioned in the introduction section of this chapter, as well as Newhall & Dzurisin, 1988; Voight, 1988; Benoit & McNutt, 1996; McNutt, 2000; Sandri et al., 2004; Phillipson et al., 2013; and many others). Feedback from civil defence personnel and other potential end-users of the VUI was also sought. Ten key unrest parameters were identified and classified into five levels according to intensity and potential importance as an eruption precursor. As the VUI framework was constructed, important characteristics of scales were considered, including clarity, robustness, reliability, applicability, and simplicity (Blong, 2003; and references therein). The framework was tested numerous times on a variety of volcanoes, and tweaks were made as needed. Throughout this process, feedback from international specialists in all volcano-related disciplines resulted in further modifications. The final version of the VUI framework is shown in Figure 5.1.

The structure of the VUI framework is based on the Volcanic Explosivity Index (VEI, Newhall & Self, 1982). Both are magnitude scales grounded in observable phenomena, use multiple parameters, and include both qualitative and quantitative descriptions to rate the intensity of a volcanic event (Newhall & Self, 1982; Blong, 2003). Like many other natural hazard and damage indices, the VUI is an ordinal scale with higher numbers indicating a greater intensity of unrest. While neither the absolute VUI number nor the differences between the numbers have specific meanings (Lehmann et al., 1998), each parameter within a single column has a similar level of 'concern' implied. Additionally, the relative intervals between adjacent columns are intended to be similar. Therefore, the system can be used as an interval scale for the purposes of enabling a mean calculation to be used for a final result summarising the observations (Agresti, 2010). Using the framework, the determination of the VUI is transparent; it is not a 'black box'.

The spectra of intensity for the parameters are given in rows in the framework. The number of parameters within each of the main three unrest categories (local earthquakes, local deformation, and geothermal systems and degassing), and the positions of parameter thresholds along each row determine the approximate weighting within the framework. Maximum values (e.g., the maximum rate of earthquakes observed within an episode, or the maximum gas flux measurement recorded) are used in attaining the VUI, as these are most likely reported in historical unrest episodes, and represent the highest level of activity within an episode. It is recognised that public observations of maximum values, particularly reported through the media, may be over-exaggerated. The parameters in the VUI framework are different for each volcano (discussed further below).

The requirement for different quantitative ranges of parameters for each volcano has been identified due to the large range in intensity of unrest phenomena between volcanoes, some of which are followed by eruptions, and others which are not (e.g., Moran et al., 2011). This is particularly the case for the rate of deformation, as recognised by Newhall and Dzurisin (1988), who state it would be more defensible for each volcano to have its own deformation thresholds above which an eruption may be deemed likely. To begin estimating the VUI for an unrest episode, these parameter ranges are determined, and used to fill in the blanks on the framework. A value of one to five is estimated for each parameter (row) using the available unrest data (rows with no available data are left blank). The VUI is calculated by summing those assigned values, and dividing the total by the number of rows used.

Quantitative data are used in the framework directly. In some cases, a qualitative description is given in the framework to summarise complex and multiple quantitative data, or to make use of any qualitative information available (e.g., “effects may include gas-induced vegetation kill or effect on animal life”). Some qualitative data can be translated into a number to fit within the VUI framework, such as the rate of felt earthquakes based on historical accounts, provided the method of translation is used consistently. For example, if the rate of earthquakes is described as “a few earthquakes occurred overnight”, “a few” might be interpreted as a minimum of three events, enabling this information to be used for estimating the VUI (this is discussed further in Appendix 14).

Volcanic Unrest Index (VUI)

Volcano: ______
Area used: ______
Date applied: ______
Real-time / Past episode
Time window: ______

		1 Inactive volcanic system, no unrest	2 Dynamic volcanic system, no unrest	3 Minor unrest	4 Moderate unrest	5 Heightened unrest	VUI = ____
Local Earthquakes	Duration of earthquake swarm (all frequencies)	No earthquake swarm	Short (≤ ___ time unit)	Short to moderate (___ ≤ ___ time unit)	Moderate to long (___ ≤ ___ time unit)	Long (> ___ time unit)	
	Location of earthquakes (all frequencies)	No locatable EQs or generally deep hypocentres (> ___ km)	Moderate depth (___ ≤ ___ km), or shallow depth (≤ ___ km) and distant from likely vent (___ ≤ ___ km)			Shallow (≤ ___ km) and close to vent (≤ ___ km), or unlocatable tremor	
	Maximum rate of high frequency earthquakes	Low rate (0 ≤ ___ EQs (> ___ Mc) per time unit)	Low to moderate rate (___ ≤ ___ EQs (> ___ Mc) per time unit)	Moderate to high rate (___ ≤ ___ EQs (> ___ Mc) per time unit)	High rate (> ___ EQs (> ___ Mc) per time unit)	Rapid acceleration in rate, may include sudden decrease in rate	Use only the highest of these 2 scores
	Tremor, low frequency and hybrid earthquakes	None		Weak tremor (≤ ___ units) or low rate of LF or hybrid EQs (1 ≤ ___ per time unit)	Moderate tremor (___ ≤ ___ units) or high rate of LF or hybrid EQs (> ___ per time unit)	Strong tremor (> ___ units)	
Local Deformation	Maximum rate of local deformation	No deformation	Low rate of deformation (≤ ___ units per time unit)	Moderate rate of deformation (___ ≤ ___ units per time unit)	High rate of deformation (> ___ units per time unit)	Rapid acceleration in rate of deformation, or sudden decrease in rate	
	Location of deformation source (e.g., through modelling)	No deformation	Slowly deflating source or local tectonic fault movement	Deep inflating source (> ___ km)	Inflating source at a moderate depth (___ ≤ ___ km)	Shallow (≤ ___ km) inflating source or migration towards the surface	
	Groundwater levels and spring flows	Levels and spring flows reflect that of surrounding areas	Low levels and spring flows. May include wells or spring-fed ponds drying, or streams ceasing to flow		High levels or spring flows. May include hot or cold water spouting (not geysers), or high stream-flow/lahars without corresponding rainfall or lake contribution		
Geothermal systems and degassing	Surface temperature, heatflow, and manifestations	Ambient temperatures, no heatflow, nor active surface manifestations	Above ambient temperature, heatflow or activity at surface manifestations	Heatflow or temperatures near or at boiling conditions, or moderate activity at surface manifestations	Geothermal system hotter than boiling conditions, may include hydrothermal eruptions	High heatflow, temperatures or activity, may include phreatic eruptions	
	Gas flux	Low levels of gas flux (≤ ___ t/day of CO_2 and ≤ ___ t/day of acid gases)	Moderate levels of gas flux (___ ≤ ___ t/day of CO_2 or ___ ≤ ___ t/day of acid gases) Effects may include gas-induced vegetation kill or effect on animal life			High levels or acceleration of gas flux (> ___ t/day of CO_2 or > ___ t/day of acid gases), or a sudden decrease	
	Gas and fluid composition	Meteorological signature	Hydrothermal signature	Mixed to magmatic signature	Magmatic signature		

S. H. Potter, 2014

Figure 5.1. The Volcanic Unrest Index (VUI) framework, used to make simple, semi-quantitative estimates of unrest intensity.

All monitoring and observational data should be used (assuming the data is considered trustworthy), regardless of the assumed genesis of the phenomena. For example, a mainshock-aftershock sequence from within the volcano area interpreted to be purely tectonic, or a hydrothermal eruption interpreted to be a result of exploitation (such as for geothermal power generation), or other non-magmatic factors, should be incorporated when assigning a VUI. This follows the same philosophy as Newhall and Dzurisin (1988, p. 2) in their extensive caldera unrest catalogue, who stated "we assume that changes that are temporally and spatially close to each other are related, even though we might not understand that relation". The VUI does not interpret the origin of unrest, nor does it forecast eruptions. Instead, the VUI framework is structured so that episodes consisting of phenomena created by non-magmatic processes generally only exhibit one or two high scores in the VUI framework, and so do not result in a high overall VUI result.

The purpose of the VUI is to provide a definition of unrest, which is here defined as ≥VUI 3, and a quantitative rating of unrest intensity. By providing unrest episodes (many of which are based on qualitative data) with a quantitative description, the VUI has a limitless range of uses. It covers all levels of volcanic unrest that might precede an eruption with a magmatic component. Effectively, the VEI could be placed beside the VUI framework as a continuum of volcanic activity. The VUI uses a common framework transferrable both between volcanoes and throughout the duration of the historical time period. The definition of unrest can assist in determining the VAL, as well as in any other situations that require it. In probabilistic event tree eruption forecasting models (e.g., Newhall and Hoblitt, 2002; Marzocchi et al., 2008; and the HASSET event tree structure by Sobradelo et al., 2014), the VUI applies to Node 1 (unrest or no unrest) by defining the status of unrest.

5.5.1 Determining the Volcanic Unrest Index

A five step process can be followed to estimate the VUI for an episode of activity – 1) determine a geographical area to consider, 2) determine ranges for each parameter, 3) determine a time window (or start and end dates of episodes), 4) apply data, and 5) calculate the mean score to determine the VUI. Example determinations of the VUI are provided for Mt

Ruapehu, New Zealand, prior to the 1995–96 eruptions, and for the entire unrest catalogue at TVC in Chapter 6.

5.5.1.1 Determine a Geographical Area to Consider

The process of estimating the VUI is made easier by first determining a geographical area surrounding the volcano from which to include observations. This is a fairly subjective decision to be made by the scientists for each volcano to allow consistency over time, particularly for factors such as rate of seismicity. The area may not necessarily be circular if local features need to be included (e.g., location of known distal high frequency seismicity associated with volcanic eruptions) or excluded, or if a linear vent zone requires a rectangular buffer. The area surrounding the volcano commonly considered by the scientists during their routine monitoring is adequate if defined.

5.5.1.2 Determine Ranges for Each Parameter

To accommodate the variation in unrest intensity between types of volcanoes, ranges for each unrest parameter are determined on a case-by-case basis. An example of a parameter range in the VUI framework is “low rate of deformation (≤___ unit per time unit)”. In this example, the upper threshold for the “low rate of deformation” is determined by scientists, along with a selection of a measurement unit (e.g., millimetres, microradian, or microstrain) according to the monitoring techniques used, and an appropriate time unit. A low rate of deformation at a constantly moving, dynamic volcano (such as Yellowstone, U.S.) may be higher than that of an inactive or basaltic volcanic system (such as the Auckland Volcanic Field, New Zealand). At a single-vent volcano, it may be beneficial to select parameters for a single monitoring station, as the magnitude of the signal generally varies with distance from the vent. These ranges of parameters are determined for each volcano based on its historical unrest and with consideration of unrest at analogous volcanoes. If very little historical unrest information is known for a particular volcano, the parameter ranges from an analogue volcano (with a similar magma type, tectonic setting, or eruption frequency, etc.) with a more complete dataset may be utilised until the dataset of the first volcano has developed. The ranges of parameters in the framework have been designed with contiguous values in mind, for simplicity.

Additional specific parameter ranges may be added into the existing phenomena rows of the VUI framework (for example, the flux for different species of gas, or groundwater levels in certain areas). However, they must fit within the overall low to high structure to keep each value within a column at a similar level of intensity. A comparison to the previous state (e.g., 'increasing' or 'decreasing') has been deliberately excluded from the descriptions and thresholds on the VUI framework. The reason for this is to enable a volcano to remain at any VUI for an extended period of time. The only exceptions to this 'no comparative language' rule are the inclusions of 'inflating' and 'deflating' sources in the deformation source location parameter, and the 'accelerating' and 'sudden decrease' of phenomena in column five. If any additional thresholds are added into the VUI framework, it is important the descriptions do not include comparisons to the previous state. Comparisons of state can be undertaken through a comparison of the VUI over time.

5.5.1.3 Determine a time window

When estimating the VUI for a historical episode of unrest, the start and end points of the episode require careful consideration. This is inescapably a subjective decision. A method that can be used for consistency is determining thresholds of intensity of activity for each phenomenon – when those thresholds are met, the episode of activity has begun. The episode has ended when the activity falls below the thresholds for a minimum length of time, and the VUI can be estimated for the episode. This method is demonstrated in Chapter 6 for TVC.

When estimating the VUI in real-time, a sliding time window can be selected. Data from the entire duration of the time window is considered for each parameter. For example, if the rate of high frequency earthquakes was thought to be accelerating at any stage during the time window, the rate of high frequency earthquakes row on the VUI framework would obtain a score of five, until the time window no longer includes the date on which the acceleration occurred (see the next section for more details on applying data). A time period to consider using is the longest period between regular samples, to incorporate all possible parameters in determining the VUI. The process of estimating the VUI can be completed very quickly; after setting thresholds, a scientist with a good understanding of a volcano and its range of past unrest activity can determine the VUI for an unrest episode in a matter of minutes.

5.5.1.4 Apply the data

The data from monitoring records, reports, and observations are considered for each row on the VUI framework. Only phenomena located within the predetermined geographical area should be considered. If multiple phenomena within an episode are relevant to a single row (for example, one surface feature shows a meteoric signature and another feature shows a magmatic signature), the value for that row uses the phenomena that reflects a higher score (in the above example, the magmatic signature). Some parameters contain descriptions over two or more boxes. This method was incorporated to allow an element of flexibility, and to reflect data with higher uncertainty, and gradational changes of data values. Judgement is used as to whether a lower or higher score should be awarded, according to the perceived significance of the data, and its level relative to the parameter ranges (where stated). If no data are available for a parameter, the row is left blank and is not included in the final calculation. Note, however, that if a record specifically states an event did not occur (e.g., no change noticed in the hydrothermal features), this is still a valid observation and should be included in the VUI calculation. Early historical episodes or those volcanoes with little monitoring may have very few rows able to be used. Reasoning for the selection of these parameters, and definitions for specific terms used below and in the VUI framework (Figure 5.1) are in section 5.3. Guidance is given below for determining the VUI using data from each unrest parameter in the VUI framework.

Local earthquakes

- Duration of earthquake swarm (all frequencies). Where individual events can be identified and are part of an earthquake swarm, the duration of the swarm is divided into four categories – short, short to moderate, moderate to long, and long. Episodes with only mainshock-aftershock events would receive a score of 1, as a swarm has not occurred. Care should be taken in distinguishing between swarms and both mainshock-aftershock sequences and tremor.
- Location of earthquakes (all frequencies). This parameter has two factors – the depth of the earthquakes and the distance from the likely vent. If desired, the thresholds for deep, moderate, and shallow depths may be based on the depths of the crust-mantle boundary, the magma chamber, and above the magma chamber (or above the H_2O exsolution depth), respectively. Due to the often dispersed nature of earthquake hypocentres, main clusters of hypocentres can be considered for this parameter.
- Maximum rate of high frequency earthquakes. The rate of high frequency seismicity is divided into four categories in the framework, in addition to a category recognising rapid acceleration (a likely candidate when the rate of high frequency earthquakes rapidly increases to the point where it is difficult to distinguish between individual events). This parameter is commonly considered in volcano monitoring and scientific literature, however it is dependent on monitoring capabilities, which change over time. To enable comparisons of the intensity of unrest over time, one could consider only relatively large (e.g., felt) events; however, this discounts potentially important

small magnitude events. An alternative is dividing lengthy historical records into periods with similar monitoring capabilities, and assigning different ranges on the VUI framework for each period. These ranges need to remain consistent with the associated qualitative descriptions in the framework (i.e. low rate, low to moderate rate, etc.) to keep column intensities comparable.

- The occurrence of tremor, low frequency, and hybrid earthquakes. Column two is left blank in order to increase the weighting of low frequency and hybrid events, and tremor. The rate of low frequency and hybrid events are considered in columns three and four, while tremor is considered in columns three to five. If both tremor and low frequency (or hybrid) events occur within the same episode, the highest value on this row is used. Low frequency events include tornillos. The intensity of tremor can be quantified using modern monitoring tools, such as RSAM, and parameter ranges incorporated in this row of the VUI framework for values at a specific monitoring station. A limitation of using RSAM is the tendency for the amplitude of tremor at some volcanoes to vary over time depending on fluids in the environment (e.g., a crater lake, within the hydrothermal system, or relating to rainfall). Therefore, the amplitude of tremor deemed significant at one point in time may differ from that at another point in time, leading to difficulties in using consistent RSAM thresholds. Thresholds for a single monitoring station should be used over time, if possible, as the signal varies with distance from the source. Surface noise recorded by RSAM (e.g., wind, waves, and cultural noise) would also need to be discounted when using this method.

Only one value (the highest value) from the ‘maximum rate of high frequency earthquakes’ and ‘tremor, low frequency and hybrid earthquakes’ rows is considered in the final calculation. This is to cater for the difference between open and closed volcanic systems. For example, if a volcano exhibits no high frequency earthquakes (a score of one) and strong tremor (a score of five), only the strong tremor would be included in the final calculation. The maximum number of rows used in calculating the VUI for an episode is therefore nine, since one of these two rows is not being used.

The magnitude of earthquakes is excluded from the VUI framework due to its lack of significance as an eruption precursor (Benoit & McNutt, 1996; Sandri et al., 2004). Surface seismicity that is caused by events such as rockfalls, landslides, debris flows, pyroclastic-density currents, explosive eruptions, avalanches, glacial cracking and other ice-related processes, and outburst floods and lahars (e.g., McNutt, 2000), are not included in the VUI framework. This is because these events are

1) associated with eruptions (e.g., rock falls at growing lava domes (Malone et al., 1983; Swanson et al., 1985; Mueller et al., 2013), pyroclastic density currents, and explosions);
2) not usually considered as unrest phenomena (e.g., lahars and floods (unless caused by high spring flow, which is included elsewhere in the VUI framework), avalanches, and ice-related processes); or
3) secondary events (e.g., landslides, debris flows, or rockfalls caused by ground shaking; or flooding caused by eruption products or hot ground melting ice).

Seismicity caused by these surficial events should usually not be considered when applying data to the VUI framework. Regional earthquakes, while potentially having a role in triggering increased seismicity or an eruption (e.g., Marzocchi, 2002; McNutt, 2005), are not a sign of unrest caused by the magmatic system of the volcano, and therefore are not included in the VUI framework. However, if unrest intensity is high, and a regional earthquake (or regional deformation) occurred, one might want to pay extra attention to the response at the volcano.

Local deformation

- The maximum rate of local deformation. This parameter contains ranges for the rate in columns two to four, and rapid acceleration (or deceleration) in the rate is considered in column five. The rate of deformation can be determined from any method of monitoring or observations. Monitoring methods recording millimetres, microradians, or microstrain can be used. In the case of multiple sets of results indicating different scores on the same row of the framework (e.g., due to monitoring sites at different distances away from the source of deformation), choose the higher score. The rate of deformation can incorporate subsidence or uplift. Visual observations of deformation, including ground cracking, bulging of the ground surface, and ground level changes with respect to water bodies can be included in this row in the absence of quantitative rates of deformation. This technique is used in determining a score for this row in some of the pre-monitoring episodes at TVC (e.g., in the 1922 and February 1983–March 1984 episodes, described further in Chapter 6).
- The location of the deformation source. This is predominantly determined through modelling, and is categorised by depth between columns three to five. Depth

thresholds for this parameter may follow the guidelines given for the 'location of earthquakes' parameter. Column two allows inclusion of interpretation of the deformation source, to effectively down weight tectonic movement and slowly deflating (deep magmatic) sources. Whilst adding subjectivity and uncertainty to the VUI estimation, the inclusion of modelling results for deformation is a significant contribution to interpreting volcanic unrest and potential outcomes. If the interpretation of data is improved over time, the VUI can be recalculated retrospectively using the most up-to-date understanding and modelling techniques.

- Groundwater level and spring flows. This parameter is effectively divided between 'normal', low, and high levels and flows across the five categories. Spouting and spring flow changes likely to be due to deformation are included, however, geysers and hot spring activity changes as a likely result of temperature or gas flux fluctuations are considered in the 'surface temperature, heatflow, and manifestations' parameter. The inclusion of this parameter allows both monitoring data and qualitative historical information indicating deformation to be considered. Temperature and geochemical data from groundwater should be considered in the 'geothermal systems and degassing' section.

Regional deformation is not included in the VUI framework as it is not seen to be an indicator of local magmatic processes.

Geothermal systems and degassing

- Surface temperature, heatflow, and manifestations. This parameter is divided into five categories based largely on the approximate temperature of the system. This distinguishes between cold, dormant volcanoes, those with geothermal systems, and those with superheated fumaroles, for example. Surface manifestations may include activity of hot springs or fumaroles, the overturn of crater lakes due to heating of the crater floor, and changes in the colour of a crater lake (Newhall & Dzurisin, 1988). Column four includes hydrothermal eruptions as defined by Browne and Lawless (2001), and column five includes phreatic eruptions, as defined by the same authors. The VUI framework does not include phreatomagmatic or magmatic eruptions.
- Gas flux. Low, moderate, and high to accelerating rates of gas flux are included in this parameter. CO_2 and acidic gases (e.g., HCl, HF, SO_2, and H_2S) are treated separately to accommodate differences in processes between the two groups. If other gases are

routinely monitored, new ranges can be added to the gas flux row if kept in accordance with the overall low to high structure. In the case of different gas species resulting in different scores on the framework, generally the highest level should be used. Qualitative descriptions in this row allow the inclusion of historical observations indicating high levels of gas flux (e.g., effect on animal life).

- Gas and fluid composition. Compositions can be interpreted by scientists to understand subsurface processes (Martini, 1996). This parameter includes compositions indicating meteoric, hydrothermal, mixed to magmatic, and magmatic signatures. Ratios (such as CO_2 to SO_2) can be utilised in this row to indicate the source of gas and fluids.

5.5.1.5 Mean calculation to determine the VUI

Any rows that were not given a value due to missing data are not included in the VUI calculation. The numbers given for each parameter are summed using a maximum of nine rows, due to just three of the four local earthquake parameters being used. A simple mean calculation, rounded to the nearest integer, results in the VUI. The labels along the top row of the framework are associated with the VUI numbers, and indicate the meaning of each level. These are 1) "inactive volcanic system, no unrest", 2) "dynamic volcanic system, no unrest", 3) "minor unrest", 4) "moderate unrest", and 5) "heightened unrest". These labels may be used instead of the VUI number for consistent messaging purposes, and to avoid potential confusion with number-based VAL systems.

5.5.2 Dealing with uncertainty

Allowances for epistemic uncertainties are incorporated in the VUI framework with features such as parameter descriptions overlapping column boundaries, the exclusion of parameters from the final calculation if the data do not exist for the episode in question, and by rounding the calculated mean result to an integer.

Unrest episodes may throw 'curveballs', or unexpected phenomena (potentially due to aleatoric uncertainties), which can be worrying but might not be included in the VUI framework. The flexibility of the VUI means these phenomena may be incorporated into the existing rows by volcanologists for future reference at that volcano. For example, if an earthquake swarm was often located in a specific area near a volcano, after which the volcano usually erupted, the description of the area could be included in column four or five (depending on its reliability as a precursor) of the 'location of earthquakes' parameter. The VUI is a guiding tool; it is not designed to be the only tool in the scientists' volcanic unrest crisis toolbox. Not all unrest situations will fit the VUI framework, and when applying it in real-time, other aspects need to be considered. For example, heightened magnitude of seismicity, while not included in the VUI framework, may still cause increased anxiety amongst the community, civil defence personnel, and perhaps also amongst the volcanologists. It is expected these contributing events would be considered alongside the VUI in communication plans and conceptual models of the volcanic processes.

The application of the data to the VUI framework can sometimes be difficult due to uncertainties. Due to the structure of the framework, quite often whether the level of a specific type of unrest is judged to be in one column or the column next to it does not affect the overall VUI result. When in doubt, striving for consistency in applying data makes it more robust and repeatable.

5.5.3 Limitations and opportunities

Volcanic processes tend to be complex, so creating a simple system to characterise these processes is challenging. However, the benefits of simplifying unrest into a semi-quantitative tool outweigh the limitations. Various inclusions to the VUI were considered, particularly further scientific interpretation of the data. It was decided the VUI should attempt to stay as objective as possible, and minimise subjectivity.

Including flexible ranges of parameters in the framework enables customisation to specific volcanic environments, based on scientific understanding and experience. Including parameters such as deformation modelling is thought to be an important aspect of interpreting unrest data. However, both of these factors add subjectivity and uncertainty to the process, which seems inescapable based on current scientific understanding of complex volcanic systems. They sit within a structured framework to allow consistency when estimated at different volcanoes, and over time. In the future, integrating the interpretation of multivariate observational data may be beneficial, particularly if subjectivity, uncertainty, and biases can be minimised.

It is prudent to keep in mind that eruptions may occur from a low level or even with no recorded unrest, and heightened levels of unrest may not necessarily result in an eruption. Future research will show relationships between the overall intensity of unrest through the estimation of the VUI, and the occurrence of eruptions, explosivity, eruption volume, etc., as well as societal or economical responses to the unrest (e.g., resettlement, evacuations).

A limitation of the VUI is the potential for confusion to be caused by the occurrence of numbers both in the VUI and in number-based VAL systems. It is recommended that if using the VUI to communicate with end-users in locations where VAL systems involve numbers, the labels associated with the VUI numbers (e.g., “minor unrest”) are used.

5.6 Example estimations of the VUI

The method used to determine the VUI is demonstrated using unrest prior to the phreatomagmatic eruptions at Mt Ruapehu, New Zealand, which occurred in 1995–96. Mt Ruapehu is an andesitic stratovolcano situated near the centre of the North Island of New Zealand (Figure 5.2), and has historically had moderate-sized eruptions at 50 year intervals. The 1995–96 eruption produced a dense rock equivalent (DRE) volume of approximately 0.1 km^3 (Hurst & McGinty, 1999). Small, short-lived but explosive eruptions occur more frequently, usually with very little precursory unrest. The most recent small eruption occurred on 25 September 2007, producing two lahars (Kilgour et al., 2010). Mt Ruapehu is thought to have a reasonably open-vent system, with very few high frequency earthquakes located within the volcanic cone and beneath the vent, and common occurrences of low levels of tremor (e.g., Hurst & McGinty, 1999; Sherburn et al., 1999).

The parameter ranges created for Mt Ruapehu’s VUI framework are given in Table 5.1. These were developed by volcanologists at GNS Science. The geographical boundary for the VUI estimation is an irregular polygon centred on the vent within the Crater Lake (Figure 5.2). This is in order to include the locations of past seismic swarms thought to be related to magmatic processes at Mt Ruapehu (Hurst & McGinty, 1999), and to exclude areas of on-going activity not thought to be connected to local magmatic processes (e.g., tectonic swarms attributed to regional deformation processes, and neighbouring volcanoes).

Table 5.1. Unrest parameter ranges for Mt Ruapehu, New Zealand, used in the framework to determine the VUI. DRZ is a monitoring station near the summit of Ruapehu, selected for use for tremor (RSAM) thresholds. It was used due to the tendency for maximum values for rate of earthquakes and deformation to be recorded at the monitoring station nearest the vent.

Unrest parameter		**Mt Ruapehu values**
Local earthquakes		
Duration of earthquake swarm (all frequencies)	Short	≤ 3 days
	Short to moderate	3 days ≤ 2 weeks
	Moderate to long	2 weeks ≤ 6 weeks
	Long	> 6 weeks
Location of earthquakes (all frequencies)	Deep	> 15 km
	Moderate depth	5 ≤ 15 km
	Shallow depth	≤ 5 km
	Distant from vent	10 km ≤ outer perimeter
	Close to vent	≤10 km
Maximum rate of high frequency earthquakes	Low rate	0 ≤ 2 events per day
	Low to moderate rate	2 ≤ 5 events per day
	Moderate to high rate	5 ≤ 10 events per day
	High rate	> 10 events per day
Tremor, low-frequency and hybrid earthquakes	Weak tremor	≤2000 RSAM units at DRZ
	Moderate tremor	2000 ≤ 3000 RSAM units at DRZ
	Strong tremor	>3000 RSAM units at DRZ
	Low rate of low-frequency or hybrid earthquakes	≤ 5 per day
	High rate of low-frequency or hybrid earthquakes	> 5 per day
Local deformation		
Maximum rate of local deformation	Low rate	1 ≤ 5 mm per year
	Moderate rate	5 ≤ 10 mm per year
	High rate	> 10 mm per year
Location of deformation source (e.g., through modelling)	Deep	> 10 km
	Moderate depth	5 ≤ 10 km
	Shallow depth	≤ 5 km
Geothermal systems and degassing		
Gas flux	Low levels	0 ≤ 300 t/day of CO_2 and 0 ≤ 50 t/day of SO_2 and 0 t/day of H_2S
	Moderate levels	300 ≤ 1500 t/day of CO_2 or 50 ≤ 500 t/day of SO_2 or 0 ≤ 1 t/day of H_2S
	High levels	>1500 t/day of CO_2 or >500 t/day of SO_2 or >1 t/day of H_2S

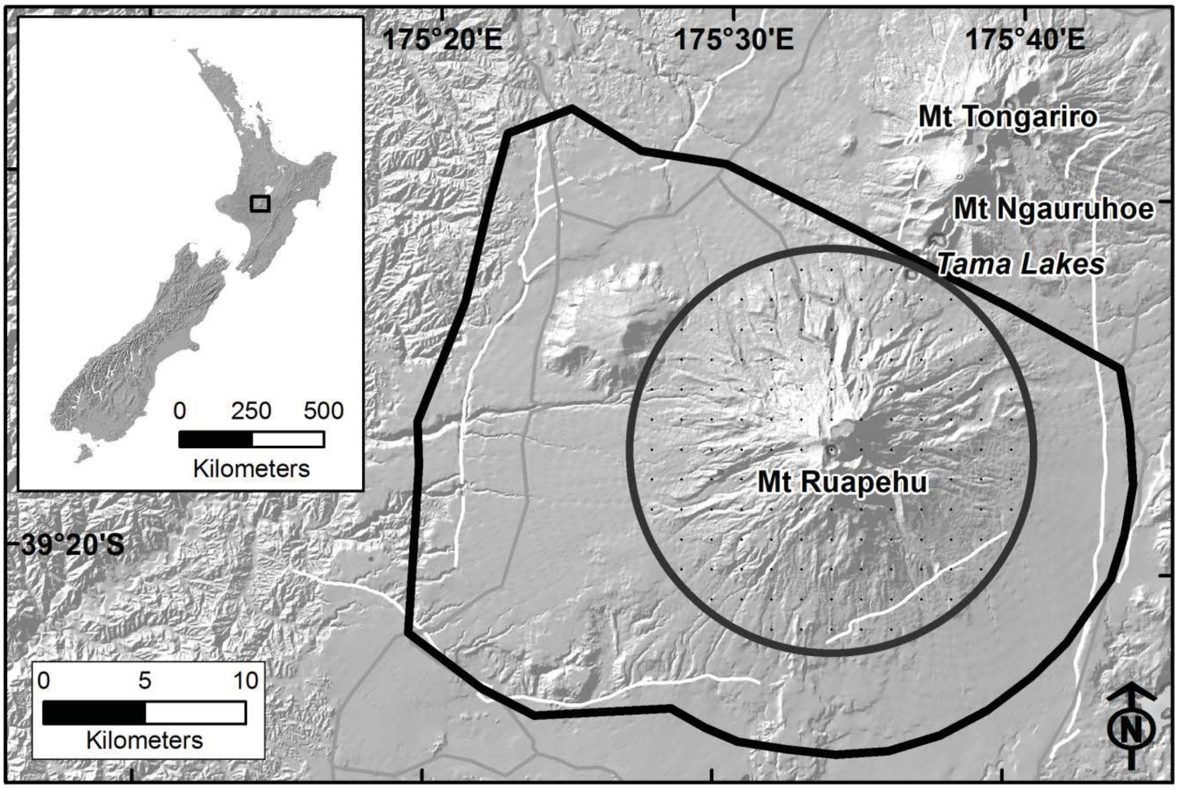


Figure 5.2. The geographic area used when estimating the VUI for Mt Ruapehu, New Zealand, is indicated by the outer irregular polygon. This area contains locations of unrest thought to be potentially relevant to Mt Ruapehu, and excludes nearby tectonically active zones and neighbouring volcanoes. The inner circle with a 10 km radius and stippled area defines the "close to vent" locations of seismicity as used in the VUI framework for this volcano (Table 5.1). Major faults are depicted as white lines and main roads are grey lines.

The VUI is estimated for the episode starting on 1 November 1994 and continuing to the first eruption on 18 September 1995 (Table 5.2). Table 5.2 demonstrates that Mt Ruapehu's unrest episode prior to its phreatomagmatic eruptions in 1995–96 was of moderate intensity, with a VUI of 4. Another example of VUI estimation is given for the TVC, in Chapter 6. The VUI has also been estimated retrospectively for a number of volcanic unrest episodes in a variety of tectonic settings, volcano types, and range of monitoring capabilities (Figure 5.3, Table 5.3). These are based on information in the published and accessible literature, and are for illustration only. A more robust VUI determination could be made by volcanologists at local observatories, who will have many more data records available, including access to data for episodes which were not intense enough to be reported in the literature, and a better understanding of what thresholds the parameter ranges should have.

Table 5.2. Parameters used to estimate the VUI for Mt Ruapehu's unrest episode from November 1994 to the first magmatic eruption on 18 September 1995. VT = Volcano Tectonic earthquakes. All VAB references in this table are available from the GeoNet website[28].

Unrest parameter	**Summarised Mt Ruapehu data**	**Individual row score**	
Local earthquakes			
Duration of earthquake swarm (all frequencies)	Nov. 1994 to May 1995 VT swarm 15<22 km west of Crater Lake (Hurst & McGinty, 1999)	5	
Location of earthquakes (all frequencies)	Very shallow tremor under vent (Sherburn et al., 1999).	5	
Maximum rate of high frequency earthquakes	Up to approx. 25 events per day (Hurst & McGinty, 1999)	(4)	(only the highest score out of these two rows is used)
Tremor, low-frequency and hybrid earthquakes	Tremor described as very intense with dramatic increases immediately prior to eruptions (VAB RUA-1995/06; VAB RUA-1995/07)	5	
Local deformation			
Max. rate of local deformation	No deformation seen until after 20 Sept eruption (VAB RUA-1995/01:10)	1	
Location of deformation source (e.g., through modelling)	No deformation seen until after 20 Sept eruption (VAB RUA-1995/01:10)	1	
Groundwater levels and spring flows	No data	--	
Geothermal systems and degassing			
Surface temperature, heatflow, and manifestations	Multiple phreatic eruptions occurred (e.g., Jan., Feb., June 1995), as well as geysers in the Crater Lake (VAB RUA-1995/01:10)	5	
Gas flux	No data	--	
Gas and fluid composition	Strong magmatic signature (e.g., VAB RUA-1995/07)	5	
Total		27	
Number of parameters used		7	
VUI for this episode		**4**	

[28] http://info.geonet.org.nz/blog/volc, accessed on 23 June 2014. Use the search function on this website, entering the code provided in Table 5.2.

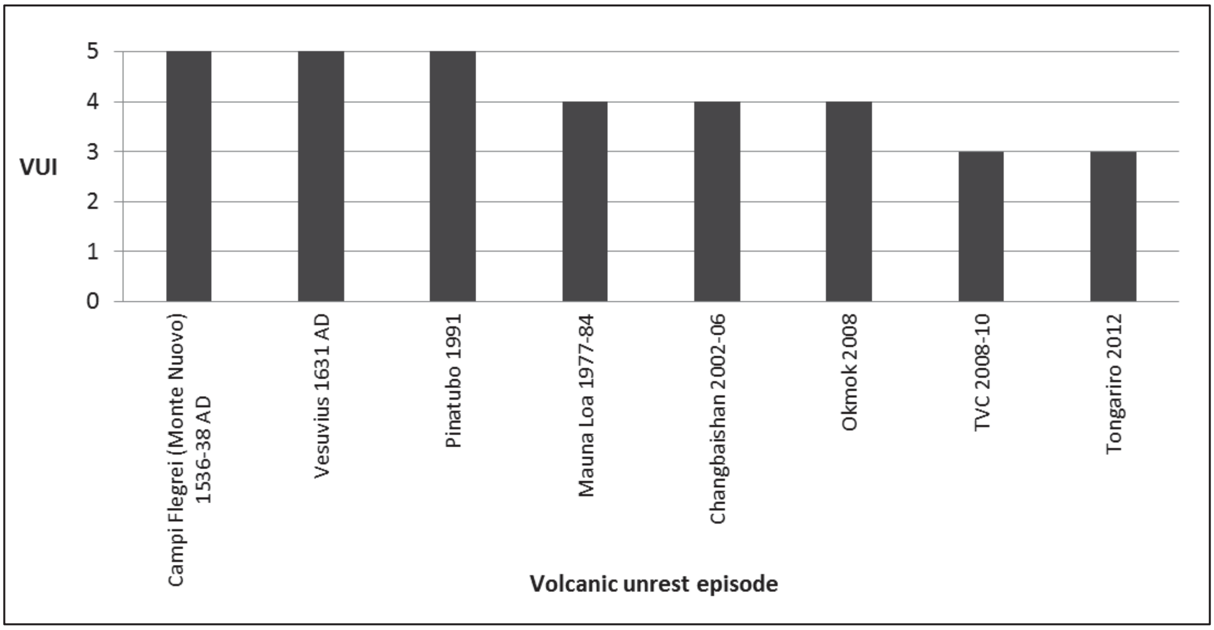


Figure 5.3. VUI estimations for volcanoes in a variety of settings.

As can be seen in Figure 5.3 and Table 5.3, the VUI for the selected episodes of unrest can be compared. The episode of minor unrest at TVC in 2008–10 can be labelled as the same intensity as the unrest observed at Tongariro in 2012, relative to the known past (and potential future) activity at each volcano. However, the 'absolute' intensity of the unrest at TVC was higher than that observed at Tongariro. This is due to the differences in assigned thresholds, and reflects the different baselines of activity between the two volcanoes.

Table 5.3. Example estimations of the VUI for volcanoes in a variety of settings. Thresholds used in the VUI framework are available from the author on request.

Volcano	Date	Local Earthquakes				Local Deformation			Geothermal Systems and Degassing			VUI (total/ no. of columns)	Resulted in magmatic eruption?
		Duration of earthquake swarm	Location of earthquakes	Using only the highest of these two scores: Max rate of HF seismicity	Using only the highest of these two scores: Tremor, low-frequency and hybrid earthquakes	Max rate of local deformation	Location of deformation source	Groundwater levels and spring flows	Surface temperature, heatflow and manifestations	Gas flux	Gas and fluid composition		
Campi Flegrei (Monte Nuovo)	Aug. 1536 to Sep. 1538 AD	5[29]		5[29]		5[29]		5[29]	3[30]	5[29]		**5**	Yes
Vesuvius	Aug.–16 Dec. 1631	4[31]		5[31]		5[31]	4[31]		5[31]	4[31]		**5**	Yes
Pinatubo	15 Mar.–8 Jun. 1991[32]	4	5	(5)	5	5	5		5	5	5	**5**	Yes
Mauna Loa	1977–84[33]	4	3	(5)	5	3	5		5	4		**4**	Yes
Changbaishan	2002–06[34]	5	4	3	(3)	3	4		2		5	**4**	No
Okmok	2008	2[35]	4[35]	5[35]	(3)[35]	4[36]	5[36]					**4**	Yes
TVC	2008–10[37]	3	4	2		3	5		3			**3**	No
Tongariro	13 Jul. to 7 Aug. 2012[37]	4	4	4	(4)	1	1		5		5	**3**	No

[29] Guidoboni and Ciuccarelli (2011);

[30] Gruppo Nazionale per la Vulcanologia C.N.R. Italia, 1986; cited in Newhall and Dzurisin (1988)

[31] Sandri et al. (2009)

[32] Newhall and Punongbayan (1996a), and references therein for all parameters. This episode begins at the first felt earthquakes, and ends with the first confirmed magmatic eruption (a lava dome)

[33] Lockwood et al. (1987), for all parameters

[34] Xu et al. (2012), for all parameters

[35] Johnson et al. (2010)

[36] Lu et al. (2010)

[37] Data from GeoNet, and Volcanic Alert Bulletins, available from http://info.geonet.org.nz/blog/volc, accessed on 22 December 2013. The Tongariro episode includes the 6 August 2012 phreatic eruption.

5.7 Discussion and summary

The VUI uses an integration of monitoring, observational, and modelling data, incorporating multiple volcanic unrest parameters. The VUI defines volcanic unrest as any episode of ≥VUI 3. This allows a robust, transferable, quantitative, and multi-parameter definition to be formed for individual volcanoes relative to their historical activity. While phenomena from any genesis (magmatic or not) are included in the VUI estimation, the framework is set up to provide a higher weighting to episodes that generate signals produced by magmatic processes. Therefore, episodes of ≥VUI 3 are more likely to indicate magmatic unrest than episodes of VUI 1 or 2. It is a standardised framework, and therefore cannot compete with expert interpretation of data regarding the location and movement of magma in a volcanic system. Thus, it is not an eruption forecasting system, but it provides an indication of the intensity of unrest. VUI 2 is defined as 'dynamic volcanic system, no unrest' rather than 'unrest' because some volcanoes constantly sit at this level (especially those with geothermal systems), without showing any signs considered to be above 'background activity'.

Comparisons with the frequency of eruptions to unrest episodes can be undertaken using the VUI, which in turn allows the application of probabilistic models (e.g., Newhall & Hoblitt, 2002; Garcia-Aristizabal et al., 2013). The VUI can be used in other ways, including but not limited to:

- comparing the intensity of unrest episodes over long durations of time;
- communicating the intensity and frequency of complex, multi-parameter volcanic unrest in a simple way to non-scientists. This can help put future episodes into perspective for the benefit of end-users, as well as scientists themselves;
- associating the intensity of unrest with VALs for assisting real-time decision-making (for example, raising the VAL at a restless caldera volcano to communicate the status of unrest). This depends on the approach to unrest used in the VAL system (discussed further in the next section);
- using the pre-determined parameters as a reminder of the potential long term variation in data, enhancing consistency over time.

While the VUI incorporates subjectivity in setting ranges of parameters, using the structured framework is more objective than the common heuristic method of determining the intensity of unrest. This is due to the minimisation of social group influences and biases, which are often prevalent in subjective decision-making (e.g., Asch, 1952; Stoner, 1961; Janis, 1982). It results in a consistent approach to defining unrest between volcanoes and over time, promotes discussion prior to unrest, and prompts the development of models.

5.7.1 The concept of unrest

Seismicity, deformation, degassing, and geothermal phenomena are commonly recorded at low levels at volcanoes, the observable products of a complex interacting environment. The social construct of assigning labels to the status of this continuous activity is helpful for the purposes of communication, but it also creates difficulties. The chief difficulty is integrating continuous, complex, and multiple sets of data into (perhaps ideally) one common understanding of subsurface conditions and processes, which changes over time, sometimes rapidly, and then carving this into two states representing ‘background’ activity, and ‘unrest’. The point at which ‘background’ activity becomes ‘unrest’ (and vice versa) depends on the definition of unrest used.

Volcanic unrest has been defined in the literature on several occasions; these definitions can be grouped into two approaches. The first approach positions the level of activity at a specific point in time relative to the level of activity commonly seen at an individual volcano. The second approach positions the level of activity relative to activity at ‘all’ volcanoes.

The first approach is typified by the definition that unrest reflects “changes from the normal state” at a volcano, as stated by Newhall and Dzurisin (1988, p. 4). Other terms in this group include “background”, “baseline”, or “typical” activity instead of “normal state”; and/or relate to “anomalous” activity or similar (e.g., Marzocchi et al., 2004; Gardner & Guffanti, 2006; MCDEM, 2006; Martí et al., 2009; Garcia-Aristizabal et al., 2013; Phillipson et al., 2013). This approach recognises the different baselines of activity between volcanoes due to variations in magma characteristics, systems, and processes. It has a relatively narrow view, by considering only the level of activity at a specific volcano, and analogous volcanoes. Therefore, it may be more useful in communicating detailed changes in the level of activity for a specific volcano, such as for eruption forecasting. The VUI uses this approach to defining unrest, as parameter ranges are determined for each volcano, with consideration of analogous volcanoes.

A key difficulty with this approach is the often long time period involved with volcanic activity, such as the slow ‘warming’ of a volcano prior to an eruption, or the ‘cooling’ of a volcano after an eruption. Inevitably, questions are raised over whether a new background level of activity needs to be considered. When determining the background level of activity, phenomena that occurred within a defined period of time are usually considered (e.g., Marzocchi et al., 2004). Should that time period be one year, ten years, the duration of the monitoring period, or the entire historical time period? Shorter time periods result in a baseline that moves over time. Longer time periods include pre-monitoring and early monitoring capabilities, and therefore require high minimum thresholds for comparison of parameters over time (e.g., minimum magnitudes of earthquakes in a rate of earthquakes comparison). Once a time period is determined, the proportion of activity that constitutes unrest needs to be identified (e.g., the highest 10% of the rate of high frequency earthquakes might be used to indicate unrest). By presupposing a proportion of activity, one assumes that unrest occurred at a normal, representative rate during that time period – a big assumption (refer to Chapter 6 for further discussion on this). Using this first approach to the concept of unrest, each volcano has a different baseline level of activity. That is, volcanoes with warm crater lakes, active geothermal systems, and high gas flux are lumped together with volcanoes showing no signs of activity whatsoever, in the level of 'background' activity. These aspects are not ideal for the communication of the status of volcanic activity with wider audiences, such as when using VAL systems.

The second approach takes a broader, more 'absolute' view, comparing observed phenomena at a particular volcano to the whole range of possible activity at any volcano. This enables a direct, high-level comparison of activity between all volcanoes, and is therefore more suited for standardised VALs that are used for multiple volcanoes, and for global alerting systems such as the ICAO aviation colour code. This approach involves one theoretical baseline level of activity for all volcanoes, and the thresholds between levels of activity (such as between 'background' and 'unrest') are constant between volcanoes. As VALs are used by the public (and pilots, and many other stakeholders) to gauge the comparative level of activity at multiple volcanoes in New Zealand, end-users stated in this research that this approach to defining unrest would be more useful for them. As such, volcanologists at GNS Science will allocate VALs using this approach with the new VAL system. It allows the recognition of volcanoes that constantly sit in a state of unrest (e.g., Ruapehu usually has a VAL of 1), and emphasises that they may exhibit a 'higher' level of unrest for only a short period of time (if at all) before erupting.

Differences between volcanic settings, such as wide scale tectonic settings, regional tectonic processes, and magma properties create difficulties in establishing common thresholds, if the intensity or magnitude of activity is used to define unrest. However, if the magmatic signature of activity and its potential (or likelihood) for eruption were used to define unrest instead, these difficulties might be overcome. This way, if a volcano has a magmatic signature, it is classified as being in a state of unrest, and if it has a geothermal or meteoric signature, it is classified as not being in unrest. This is a more interpretive approach to defining unrest than the previous two approaches, which are more descriptive of the intensity of activity. However, the interpretive approach is too long to effectively disseminate warnings (such as VALs), due to the length of time that it currently takes to interpret data and ascertain the magmatic signature of integrated phenomena. This is a reason why many researchers and observatories consider any phenomena at the volcano to potentially indicate unrest, regardless of the genesis (including Newhall & Dzurisin, 1988; and for VUI estimations). The VUI may provide support for rapid decision-making with regards to the potential for magma to be involved in unrest. However, as it defines unrest based on the 'usual' level of activity at a single volcano, there are difficulties with tying it to a standardised VAL system that uses a comparative definition of unrest. Further research is needed on developing the comparative approach to classifying unrest, which is particularly important for warning tools such as VAL systems.

5.8 Summary

The VUI framework is a flexible system, able to be applied to any type of volcano, regardless of magma type, tectonic setting, or dormancy period. It can be utilised on volcanoes with virtually no historical monitoring record if thresholds from analogous volcanoes are considered. The VUI framework provides a semi-quantitative structure in which the overall intensity of multi-parameter volcanic unrest can be estimated, from a range of monitoring capabilities. The resulting VUI defines unrest and indicates unrest intensity relative to a specific volcano's past and potential activity for the comparison of historical episodes, and the communication of complex unrest information to non-scientists.

5.9 Acknowledgements

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CHAPTER SIX

DEFINING CALDERA UNREST AT TAUPO VOLCANIC CENTRE, NEW ZEALAND, USING THE VOLCANIC UNREST INDEX (VUI)

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6 DEFINING CALDERA UNREST AT TAUPO VOLCANIC CENTRE, NEW ZEALAND, USING THE VOLCANIC UNREST INDEX (VUI)

6.1 Abstract

Caldera unrest occurs frequently at Taupo Volcanic Centre (TVC), New Zealand, occasionally resulting in deleterious socio-economic impacts. This large silicic volcano most recently erupted in 232 AD in an explosive, caldera-forming rhyolitic eruption, devastating the central North Island. Eruptions of all sizes are preceded by volcanic unrest, often consisting of seismicity, deformation, degassing, and/or geothermal system changes. These phenomena may also occur due to non-magmatic processes, complicating eruption forecasting. Volcanic unrest needs to be distinguished from 'typical background activity' in order to effectively warn about impending eruptions; this is best achieved by understanding past unrest. In this research, a catalogue of caldera unrest at TVC is developed using an historical chronology methodology. The Volcanic Unrest Index (VUI) is estimated for the episodes in the catalogue, which spans from 1872 to December 2011, demonstrating its use and enabling volcanic unrest to be defined at this volcano. 16 episodes of unrest are identified; four classified as moderate unrest (VUI 4), and 12 classified as minor unrest (VUI 3). There has been an average interval of approximately nine years between unrest episodes, and a median unrest episode duration of just under five months. This research provides a context for future caldera unrest crises, and contributes to the global caldera unrest dataset.

Keywords

Taupo Volcanic Zone, caldera unrest, VUI, earthquakes, deformation, hydrothermal, catalog

6.2 Introduction

The integration of phenomena interpreted to be a result of the presence, addition, or movement of magma and related subterranean fluids has the potential to enable warnings of an impending eruption (e.g., Sparks, 2003). However, it can be difficult to isolate these signals from phenomena generated by non-magmatic processes. The overlay of large-scale tectonic processes, regional deformation, local fault belts, and geothermal systems combine with volcanic systems to create a complex array of observed phenomena in the form of seismicity, deformation, degassing, and changes in geothermal systems. Extraneous events can also complicate interpretation, such as pressure changes at geothermal systems caused by processes like heavy rainfall (Bromley & Mongillo, 1994) and commercial exploitation of geothermal fields (Newhall & Dzurisin, 1988; Martí et al., 2009). This complexity can cause uncertainty about the source of unrest, and difficulty in identifying the appropriate societal response (Barberi & Carapezza, 1996). A detailed caldera unrest management sourcebook by Potter et al. (2012; Appendix 2) discusses physical and socio-economic hazards and mitigation options, as well as giving an overview of many caldera unrest episodes observed globally, and within New Zealand.

Worldwide, it is a common occurrence for long-dormant rhyolitic and dacitic caldera volcanoes to show signs of unrest, despite the relative infrequency of eruptions (e.g., Newhall & Dzurisin, 1988; Johnston et al., 2002; Martí et al., 2009). Many volcanoes, including Taupo Volcanic Centre (TVC), New Zealand, tend to exhibit a constant low-level of activity that sometimes rises above a certain threshold, indicating unrest. Defining that threshold requires consideration of multiple unrest phenomena, an understanding of underlying processes, and knowledge of 'typical' levels of activity at the volcano in question (refer to Chapter 5 for further discussion on the complexities of defining unrest). The decision of when to classify the status of volcanic activity as unrest impacts the opportunity for civil defence to respond to an impending volcanic eruption.

The Volcanic Unrest Index (VUI) framework presented in Chapter 5 (Figure 5.1) integrates the intensity of multiple volcanic unrest parameters attained through monitoring, observations, and modelling, into one number per episode. The VUI provides a method of defining unrest and aids the communication of complex unrest data to end-users. The use of the VUI is demonstrated in this chapter, to define unrest and quantify its intensity at TVC.

Heightened caldera unrest can be hazardous to nearby communities and range in duration from hours to decades. The physical hazards may include ground shaking, which occurred, for example, at Campi Flegrei Caldera (Italy) in 1983, causing buildings to collapse (Barberi et al., 1984); hydrothermal eruptions, which can be potentially dangerous within geothermal fields (Bromley & Mongillo, 1994); poisonous gas emissions, particularly those which pool in low-lying, confined spaces (Blong, 1984); and ground deformation, which may cause localised flooding, damage to buildings, and disruptions to underground infrastructure.

Societal impacts of unrest may include psychological distress, evacuations, media speculation, and misreporting (Johnston et al., 2002). National, regional, and local economies may be impacted, particularly in the tourism, property investment, insurance, and banking industries (e.g., Mader & Blair, 1987; Johnston et al., 2002). Mistrust between scientists, civil protection personnel, and the public and business community from the lack of timely information and high uncertainty can result from volcanic unrest, as happened at Mammoth Lakes, Long Valley Caldera (U.S.) in 1982–84 (Mader & Blair, 1987). Historical caldera unrest has resulted in various degrees of emergency response, from interagency meetings with the community at Mammoth Lakes in 1982 (Mader & Blair, 1987), to mass evacuations of 40,000 people at Campi Flegrei Caldera in 1983 (Barberi et al., 1984). Volcanic observatory scientists, who have the duty of understanding and communicating the science of caldera unrest and potential eruptions to civil defence personnel, media, and the public, utilise information on the history of the frequency and severity of unrest at each volcano, so that possible future scenarios can be identified and communicated to these end-users.

Episodes of caldera unrest were known to have occurred at TVC in 1895, 1922, 1964–65, and 1983, in addition to two periods of heightened activity in 1996–99 and 2008 (Morgan, 1923; Gibowicz, 1973; Grindley & Hull, 1986; Johnston et al., 2002; Jolly et al., 2008; Potter et al., 2012). The first four episodes were marked by intense seismicity and by deformation of up to 3.7 m over a period of months. The latter two were not officially recognised as unrest, due to uncertainty over whether the activity was at a high enough intensity to warrant this label (e.g., Jolly et al., 2008). Other episodes of historical unrest may have occurred at TVC but have not yet been identified, for the same reason. This chapter aims to investigate the frequency and intensity of historical caldera unrest at TVC, whilst demonstrating the use of the VUI.

6.3 Regional setting

6.3.1 Geological setting

The North Island of New Zealand is situated on the Australian Plate, above the subducting Pacific Plate. The rifting continental crust related to this subduction zone has created an area of relatively thin crust termed the Taupo Volcanic Zone (TVZ; Figure 6.1) (Wilson et al., 1995; Leonard et al., 2010). The TVZ contains eight of New Zealand's eleven calderas, in addition to several other less silicic volcanoes (e.g., Houghton et al., 1995a; Figure 2.2 in Chapter 2). TVC is the southern-most caldera in the TVZ.

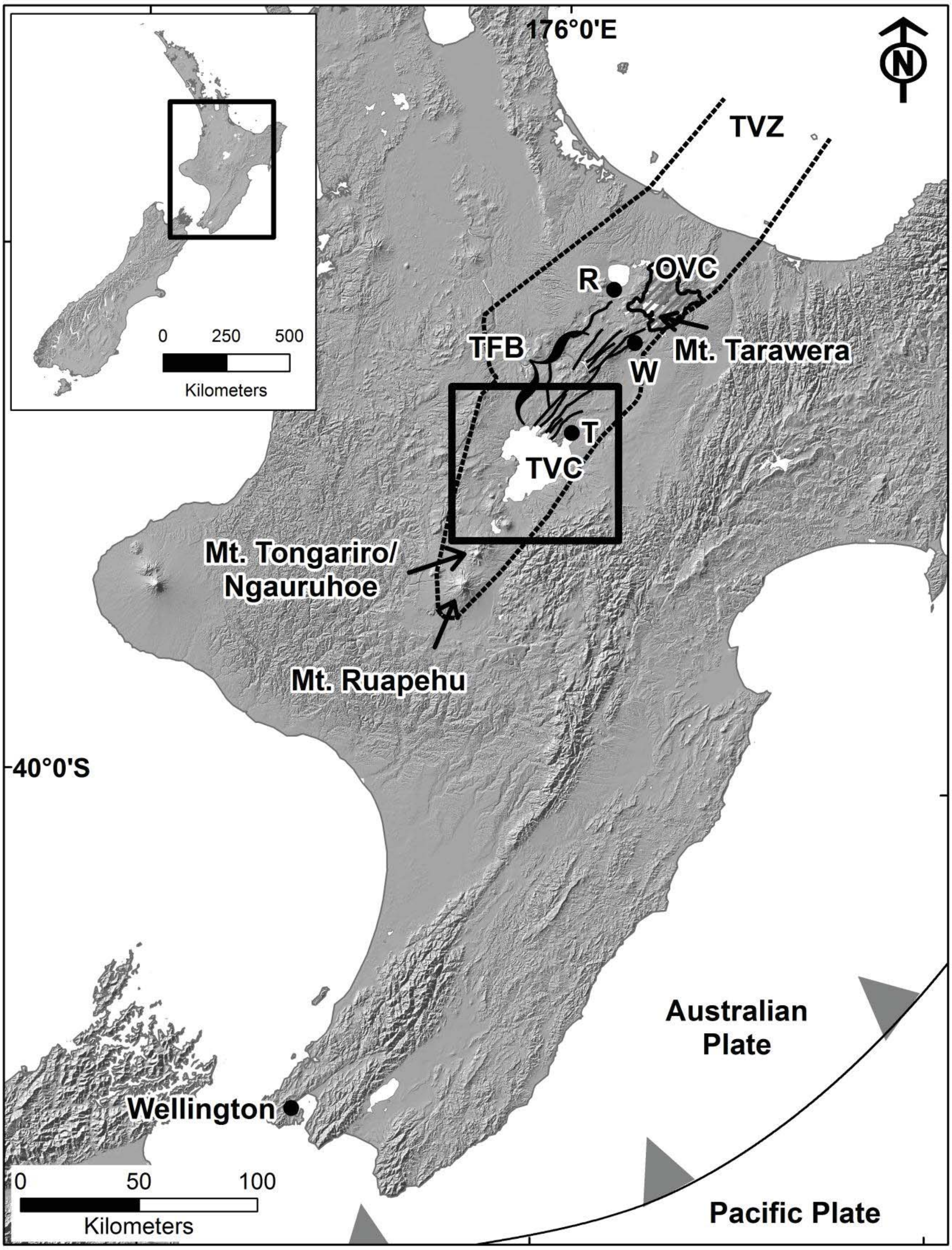

Figure 6.1. Map of the Taupo Volcanic Zone (TVZ, indicated by the dashed lines) in the North Island of New Zealand, and regional features; OVC = Okataina Volcanic Centre, R = Rotorua city, W = Waiotapu, TFB = Taupo Fault Belt, T = Taupo township, TVC = Taupo Volcanic Centre. The square box in the main map outlines the area shown in Figure 6.2. The inset map of New Zealand shows the extent of the main map.

Over the past 65,000 years TVC has had an average magma output rate of 0.2 m^3s^{-1}, and is therefore considered one of the most productive individual rhyolitic volcanoes in the world (Crisp, 1984; Wilson, 1993). The TVC has a complex history, with total magma equivalent erupted volumes ranging from 0.004 km^3 to 530 km^3 in the past 26,000 years (Wilson, 1985; Wilson & Walker, 1985; Wilson, 1993, 2001; Wilson et al., 2009). Periods of apparent quiescence have varied between approximately 20 years to 6000 years (Wilson, 1993). The most recent eruption from the TVC was in 232 ± 5 AD (Hogg et al., 2012), erupting a total magma equivalent volume of 35 km^3 (Wilson & Walker, 1985). It altered the shape of the caldera that had formed in the earlier Oruanui eruption (Figure 6.2), c. 25,400 cal. yr before present (B.P.), and devastated 20,000 km^2 of surrounding land due to widespread tephra falls and ignimbrite-forming pyroclastic flows (Wilson, 1993, 2001; Vandergoes et al., 2013).

Multiple active faults are recognised to the north and south of the caldera (e.g., Peltier et al., 2009). TVC also has high heat flow with five geothermal fields within a radius of 30 km, in addition to smaller areas with hot springs (Figure 6.2). Three of the geothermal fields are commercially exploited, which may have contributed to changes in the geodetic and hydrothermal (and likely seismic) phenomena recorded in the nearby areas, particularly during and since the 1950s (Thompson, 1960).

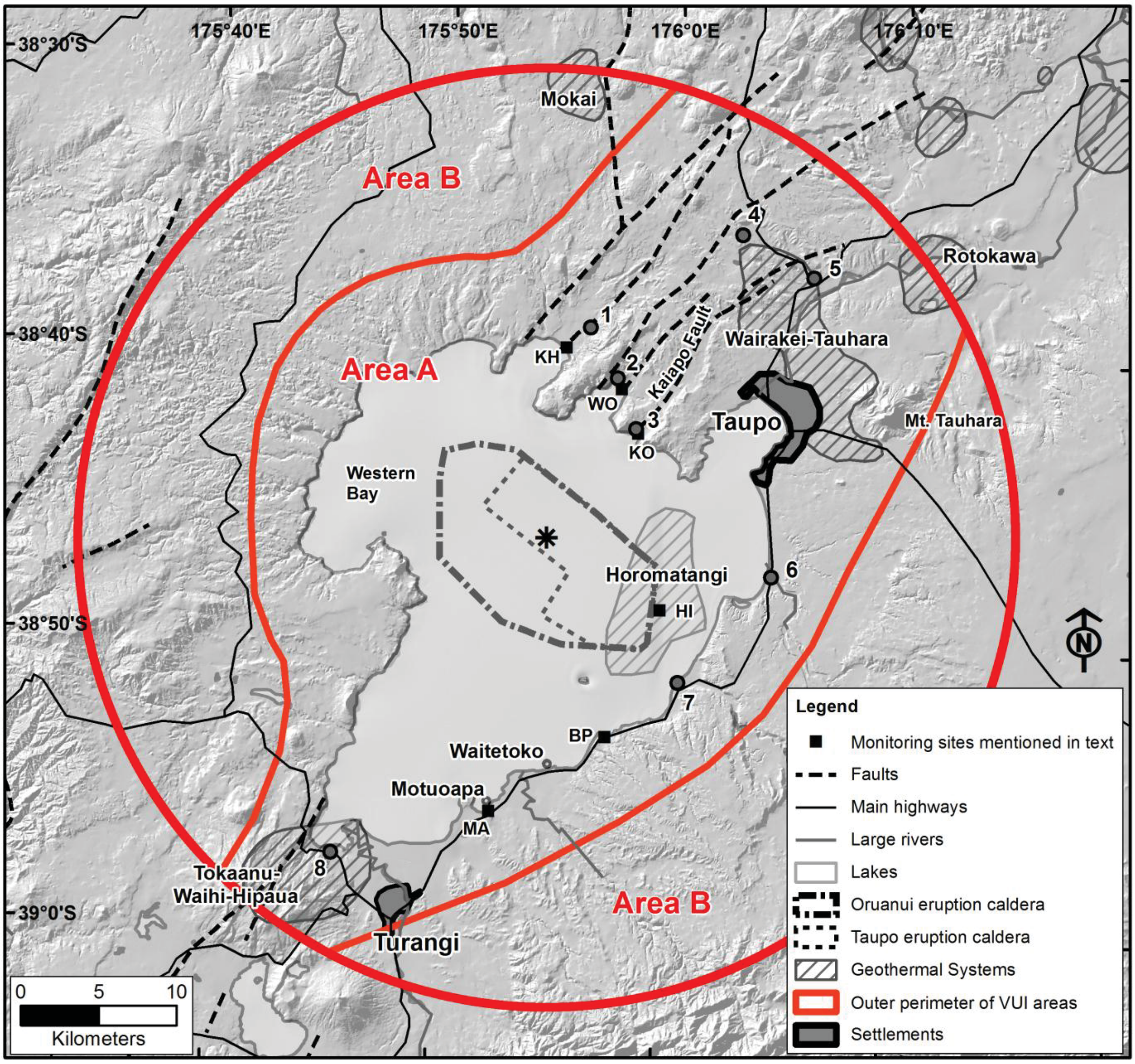

Figure 6.2. Taupo Volcanic Centre, with labelled settlements and natural features mentioned in the text. Lake Taupo fills both the Oruanui (25.4 ka) and Taupo (232 AD) eruption calderas. The area from which phenomena are included in this catalogue is defined by a red circle with a radius of 30 km centred on a virtual source at 2763000, 6266000 (New Zealand Map Grid; equivalent to 38 46 23 S, 175 54 40 E World Geodetic System 1984), indicated by the asterisk. Areas A (close to vent) and B (distant from likely vent) refer to the 'location of earthquakes' row on the VUI framework. Numbered settlements are 1= Kinloch; 2 = Whakaipo Bay; 3 = Kaiapo Bay; 4 = Oruanui; 5 = Wairakei; 6 = Waitahanui; 7 = Hatepe; 8 = Tokaanu. Monitoring sites mentioned in the text are indicated by small black squares, and are KH = Kinloch; WO = Whakaipo Bay; KO = Kaiapo Bay; HI = Horomatangi Reef; BP = Bulli Point; and MA = Motuoapa.

6.3.2 Social setting of Taupo District

Maori settlement began in the Taupo area in approximately 1200 AD, for which there are no written records (Cooper, 1989). Sealers and whalers arrived in coastal New Zealand from the early 1790s (Downes, 2004), however, very few Europeans visited the Taupo area until settlement began there in 1855 AD (Cooper, 1989). The first recorded earthquake with a likely epicentre near TVC was on 31 May 1850 (Eiby, 1973), with further isolated and undamaging earthquakes on 12 November 1862 (Hawke's Bay Herald, 9 December 1862) and 25 July 1871 (Transactions and Proceedings of the New Zealand Institute, 1871).

Written records became extensive enough for regular earthquake descriptions to be made from 1872 as Armed Constabulary troops moved to the future site of Taupo township. Settlers continued to arrive, and in the late 19th Century, postmasters were obligated to report earthquakes to the Seismological Office (Kearns et al., 1985; Cooper, 1989), which later became part of the Department of Scientific and Industrial Research (DSIR). The population continued to grow, with an increased rate in the 1950s due to geothermal development. The current population of the Taupo District is approximately 32,000 people, of which c. 22,000 are in Taupo township, with many more during large sporting events and holidays; and 3,250 in the second largest settlement, Turangi (refer to Figures 6.1 and 6.2 for locations mentioned in the text).

6.4 Methods

A catalogue of unrest at TVC is presented based on a range of information sources, many of which have not been analysed by previous researchers. The method used to create this catalogue involved two major steps. The first was gathering data to ascertain all of the activity potentially relating to caldera unrest at TVC. The socio-historical methodology employed is similar to that utilised in previous volcanic unrest and earthquake research (e.g., Eiby, 1988; Dvorak & Gasparini, 1991; Downes, 1995, 1996, 2004; Guidoboni & Ciuccarelli, 2011). From the resulting dataset, which spans from 1 January 1872 to 31 December 2011, a catalogue of activity was created, grouping the data into episodes. The second step involved estimating the VUI for these episodes to determine the relative intensities of unrest.

In their catalogue of worldwide caldera unrest Newhall and Dzurisin (1988) included all phenomena that were potentially related temporally and spatially, acknowledging that others may consider these phenomena unrelated to the calderas. The same approach was used to create a catalogue of unrest at TVC. As all phenomena were included in the dataset, some of the events reported in this catalogue are likely to have resulted from a source not related to magmatic processes. The interpretation of the dataset with regards to genesis of the phenomena was outside the aims of this research. However this has been done for some of the previously recognised episodes by other researchers (e.g., Grindley & Hull, 1986; Webb et al., 1986; Peltier et al., 2009).

6.4.1 Historical chronology

All earthquakes that have been located by GNS Science and its predecessors are included in the National Earthquake Information Database (NEID[38]). The rate of seismicity in the NEID appears to increase over time due to the growth in the monitoring network density and technological developments advancing the capabilities of monitoring equipment. Many seismic events prior to the development of monitoring are not included in the NEID. Therefore, the pre-monitoring time period required particularly detailed investigation.

The earliest sources of information for the Taupo area were predominantly reports by travellers and missionaries published in national newspapers. Additional sources included earthquake reports in the Transactions of the New Zealand Institute, earthquake-felt reports collected by the national Seismological Observatory (archived at GNS Science), local literature, and correspondence. The newspaper articles were accessed through the electronically searchable National Library Papers Past website[39], microfilm archives at Auckland City Library, GNS Science newspaper articles and correspondence archive, and the public Taupo Library.

It is acknowledged that using newspapers as a data source creates potential issues with information validity and reliability due to, for example:

- the selective nature of the reporting of news (Franzosi, 1987);
- overdramatic reporting and publishing of opinions and rumours rather than facts. The dramatized versions of events were generally easy to identify, enabling filtering of the misinformation;
- information gaps due to the unscientific nature of news reporting, such as uncertainty regarding hypocentre locations, and the number of seismic events felt;
- no magnitude or intensity scales existed in earlier times;

[38] http://magma.geonet.org.nz/quakesearch/, accessed on 27 November 2013
[39] http://paperspast.natlib.govt.nz, accessed on 27 November 2013

- inaccurate and imprecise dating due to the copying of reports from one newspaper to another. Musson (1986) also found this during his investigation of early British earthquakes;
- inconsistent place name spellings were used, causing difficulties in electronic searching. To minimise this potential error, multiple searches using different spellings were conducted;
- during more intensive seismic periods there was a likely heightened awareness of all environmental phenomena that were potentially perceived as linked;
- authorities, particularly the Government and local mayors, on occasion downplayed the effects of multiple earthquakes if it was thought that the events were affecting the economy of the town (also identified by Downes, 2004). Based on conflicting media reports, it is likely that this occurred during the 1922 episode in Taupo. Therefore media reports of unrest episodes and their effects may not be an accurate reflection of events.

To increase the reliability of information sourced from media and literature reports, information was cross-referenced between sources, and the severity of earthquake impacts were compared between towns to help identify epicentres likely to be outside of the study area (which is defined in section 6.4.2.1).

Scientific literature, reconnaissance reports, circulars, correspondence, and workshop material were included in the analysis for this catalogue. Findings from past earthquake catalogues were incorporated, including those by Bastings (1935) and Hayes (1953), who based their information on the Seismological Observatory records. The development of geothermal exploitation in the Taupo District in the 1950s contributed to an increased level of observations, particularly at Wairakei Geothermal Field, 10 km northeast of Taupo township.

The New Zealand Seismological Reports were published from 1921, forming an annual source of earthquake locations, magnitudes, and felt effects from larger events (Downes, 2004). The National Seismograph Network was developed from the 1930s. Prior to 1940, the only monitoring equipment to record unrest phenomena in the Taupo area were the rudimentary and temporary seismographs set up by the Government seismologist from the New Zealand Geological Survey during the 1922 episode (Evening Post, 14 July 1922).

Hydrothermal eruptions and other changes to surface features have been analysed from scientific literature, reports, and media. Geochemical data from the Taupo commercial geothermal fields are not generally analysed with a volcanological perspective, nor have repeated gas flux observations been recorded, therefore these data have not been included in this catalogue.

Lake levelling monitoring to measure deformation using Lake Taupo as a tilt meter began in 1979 (Otway et al., 2002). This record, in addition to more recent GPS monitoring, indicates that the caldera-wide deformation history is complex, with rates of uplift and subsidence varying over time as well as spatially. A long-term subsidence rate of 3 to 7 mm per year has been identified in the northern part of the lake (Peltier et al., 2009). Information sources from the period prior to the establishment of the monitoring network were searched for mention of deformation. A number of seiches in Lake Taupo and rapid lake and river level changes were noted in historical media articles. However, no accounts directly related to ground deformation were found, apart from what was already known to have occurred in the published literature.

Comprehensive monitoring of New Zealand's volcanoes advanced in 2001 AD with the creation of the GeoNet project, an Earthquake Commission-funded initiative run by GNS Science (Scott & Travers, 2009). This significantly increased the pool of data in the NEID used in the seismic analysis for this catalogue. The deformation monitoring network also increased in capability at this time, with telemetered GPS stations and additional campaign sites created.

The resulting dataset contains a mixture of qualitative and quantitative information referring to three separate but related categories of unrest through time.

6.4.2 Estimating the VUI

The procedure used to estimate the VUI is outlined in Chapter 5. This procedure is followed in the present chapter to estimate the VUI for TVC's catalogue of unrest by:

1) determining the geographical area to consider
2) determining ranges for each parameter
3) identifying criteria to determine start and end dates for episodes
4) applying the data to the VUI framework (which is Figure 5.1)
5) calculating the VUI for each episode.

6.4.2.1 Area of inclusion

To enable consistency over time, activity was considered within a circle with a radius of 30 km (roughly twice the maximum topographical caldera boundary radius), centred at 2763000, 6266000 (New Zealand Map Grid; equivalent to 38 46 23 S, 175 54 40 E World Geodetic System 1984; Figure 6.2). The centre point used is the approximate geometric centre of the Oruanui caldera (Davy & Caldwell, 1998), and is the virtual source of the Oruanui eruption used by Wilson (2001). This area was subjectively selected to include features such as nearby active geothermal fields, fault lines (including the active Taupo Fault Belt), the Oruanui and Taupo eruption caldera ring structures, the syn-collapse structure of the southern and western lake areas, Lake Taupo and its surrounding population centres, and all known vents associated with TVC (Wilson, 1993; Davy & Caldwell, 1998; Wilson, 2001). The use of the boundary minimises the inclusion of phenomena that may have been caused by nearby tectonic fault belts and neighbouring volcanoes (and therefore are likely to be unrelated to TVC magmatic unrest). Geothermal systems included within the study area are Tokaanu-Waihi-Hipaua, Motuoapa (small), Waitetoko (small), Horomatangi, Wairakei-Tauhara, Rotokawa, and Mokai (Kissling & Weir, 2005).

The area designated as 'close to vent' for the 'location of earthquakes' row in the VUI framework is labelled as Area A in Figure 6.2. There is uncertainty of where the next vent location will be at this large caldera, therefore the 'close to vent' area is correspondingly large, and incorporates the vast majority of the active geological features and past eruption vents within the study area. Area B incorporates all other areas within the 30 km radius that are excluded from Area A, and represents the locations 'distant from likely vent' as stated in the VUI framework. These areas were determined by GNS Science's monitoring scientists through a consultation and consensus process.

6.4.2.2 Parameter ranges

The ranges of unrest parameters in the VUI framework were determined for TVC based on the monitoring record and historical data, with consideration of activity at analogous volcanoes. Time-series plots were created from the results of the historical chronology, and were referenced to ascertain relative levels of activity. These initial parameters were then subjected to multiple iterations with monitoring volcanologists at GNS Science. The parameter ranges for TVC are presented in Table 6.1.

Table 6.1. Ranges of parameters used in the VUI framework for TVC.

Local Earthquakes		
Duration of earthquake swarm	Short	≤ 10 days
	Short to moderate	10 ≤ 90 days
	Moderate to long	90 days ≤ 6 months
	Long	> 6 months
Location of earthquakes	Deep	> 8 km
	Moderate depth	4 ≤ 8 km
	Shallow depth	≤ 4 km
	Distant from likely vent	Within area B (and not A)
	Close to likely vent	Within area A
Maximum rate of high frequency earthquakes	Low rate	0 ≤ 5 events per month[a]
	Low to moderate rate	5 ≤ 50 events per month[a]
	Moderate to high rate	50 ≤ 100 events per month[a]
	High rate	> 100 events per month[a]
Tremor, low-frequency and hybrid earthquakes	Weak tremor	No data[b]
	Moderate tremor	No data[b]
	Strong tremor	No data[b]
	Low rate	1 ≤ 20 per month
	High rate	> 20 per month

Local Deformation		
Max. rate of local deformation	Low rate	1 ≤ 10 mm/year
	Moderate rate	10 ≤ 100 mm/year
	High rate	> 100 mm/year
Location of deformation source	Deep source depth	> 8 km
	Moderate depth	4 ≤ 8 km
	Shallow depth	≤ 4 km

Geothermal Systems and Degassing		
Gas flux (for CO_2 and acid gases)	Low levels	No data[c]
	Moderate levels	No data[c]
	High levels	No data[c]

[a]This is the threshold used for the pre-1940 time period, prior to monitoring and refers to the number of 'felt' events. See Table 6.2 for the parameters used for different time periods.
[b]Tremor data has not been published for TVC.
[c]Gas flux measurements are not repeatedly measured at TVC. In the future, indicative levels from analogous volcanoes may be used for this parameter.

The parameters used for the seismicity hypocentre and deformation locations are based on the current state of knowledge relating to the position of the brittle-ductile transition beneath TVC, and the hypothesised depth of the magma body (e.g., Davy & Caldwell, 1998; Smith et al., 2007). The threshold of 20 events between the low and high rates of low-frequency and hybrid earthquakes (in Table 6.1) strikes a balance between the rarity of these events at TVC, and the high rate observed at other calderas. Regional seismicity and regional deformation are not seen as indicators of unrest as they are not caused by magmatic processes relating to the volcano in question, and therefore are not included in the VUI framework (see Chapter 5 for further information). The rate of deformation relates only to local deformation. If the regional deformation coincided with or resulted in local deformation over and above the regional rate, this ‘excess’ would be included in the VUI calculation using the parameters given in Table 6.1. The very little gas flux information available for TVC indicates a significant variation throughout the study area, and no repeated measurements have been made (A. Mazot, pers. com., February 2013). In future unrest events, analogous volcanoes would be considered for this parameter.

In order to identify episodes of unrest as consistently as possible, the rate of high-frequency earthquakes has been considered in three different time periods reflecting the level of monitoring capabilities. These time periods are pre-1940, when there was virtually no monitoring in the study area and a reliance on observations by non-experts; 1940 to 1989 (inclusive) reflecting low levels of monitoring, often with a large margin of error, combined with observations by the population of mixed levels of expertise; and from 1990 onwards, with a higher level and quality of monitoring and less reliance on qualitative information from the public. The thresholds for the rate of high frequency earthquakes for these periods are described in Table 6.2. The threshold between moderate and high rate of seismicity was based on events at other similar volcanoes that have experienced more intense episodes of unrest than observed at TVC. For example, a threshold of >5000 events per month was selected for the post-1990 ‘high rate’ based on unrest at Rabaul Caldera in 1984, which had up to 14,000 events per month (Davies, 1995b). No episodes at TVC have attained this intensity of seismicity yet. It may transpire that this ‘high rate’ threshold should be increased in the future, however it is not known whether TVC is capable of producing as many earthquakes per month as have been observed at Rabaul. The thresholds were estimated to be approximately equivalent across the three time periods in relation to monitoring capabilities, achieving consistency and allowing a comparison between episodes of overall unrest intensity over time.

Other unrest parameters in the VUI framework are not as dependent on monitoring capabilities, as they were either completely unobservable prior to monitoring (e.g., location of deformation source) and are therefore omitted from the overall VUI calculation and do not affect the overall score, or they have equivalent qualitative descriptions in the framework (e.g., groundwater level descriptions). The parameter ranges used may be refined in the future as knowledge and monitoring techniques develop, and as further episodes occur both at TVC and worldwide. The changes will need to be applied to the entire record to retain consistency over time and allow a robust comparison of the VUI. Episodes of unrest are categorised by time, irrespective of their location within the geographical boundary.

Table 6.2. Parameter ranges for the rate of high frequency earthquakes per calendar month, to be used in the VUI framework for TVC. Time periods relate to monitoring capabilities. Pre-1940 ranges are included in Table 6.1.

Rate of high frequency earthquakes	1940–1989	Post-1990
Low rate	0 ≤ 30 recognised events per month	0 ≤ 100 recognised events per month
Low to moderate rate	30 ≤ 100 recognised events per month	100 ≤ 1000 recognised events per month
Moderate to high rate	100 ≤ 200 recognised events per month	1000 ≤ 5000 recognised events per month
High rate	> 200 recognised events per month	> 5000 recognised events per month

6.4.2.3 Determine a time window

A source of uncertainty when defining unrest is the determination of when an episode starts and ends (e.g., Newhall & Dzurisin, 1988). In this research, an episode was defined to have started when low-level thresholds of individual phenomena were met (as described further in Appendix 15). Episodes were separated by a minimum of six months of quiescence based on the wider dataset; episodes separated by less than six months were joined together. The decision to use six months as a minimum period of quiescence separating episodes was fairly subjective, and based on the undefined and heuristic-based method used by GNS Science for separating episodes of unrest at New Zealand's volcanoes. The VUI was estimated for each of these episodes; the results are presented in this chapter.

6.4.2.4 Applying TVC data to the VUI framework

Each episode was allocated one number (from columns 1 to 5) for each row on the framework, according to how the data related to the previously determined parameter ranges. If no data were available for a parameter (for example all local deformation, geothermal and degassing parameters in 1872), that row was not included in the final calculation.

6.4.2.5 Calculating the VUI

As described in Chapter 5, only the highest of the two scores between the 'maximum rate of high frequency earthquakes' parameter, and the 'tremor, low frequency and hybrid earthquakes' parameter was included in the final calculation. The resulting numbers were summed and divided by the number of columns used (disregarding columns with no data), providing a mean score. The scores are rounded to the nearest integer, resulting in a VUI for each episode. For example, an unrest episode at TVC in 1897 has a summed total of 14, using four columns (Table 6.3). 14 divided by 4 is 3.5, which is rounded to a result of VUI 4 (moderate unrest).

6.4.3 Potential Sources of Error

As this catalogue is based on qualitative reports of earthquakes and noticeable changes in deformation and hydrothermal systems for the period prior to monitoring, in addition to the potential sources of error related to media articles mentioned above, it is restricted by factors including:

- the magnitude of the events, requiring them to be large enough to be noticeable by the public and/or postmaster;
- the small population size in the study area during early European settlement, limiting the likelihood of events being reported;
- limited interregional communication, causing a reliance on noticeable events to be reported by the local postmaster in order to be included in the written record.

In order to plot seismicity over time and estimate the VUI using the pre-determined thresholds, qualitatively reported events from the pre-monitoring time period were quantified. A minimum number of earthquakes was assigned to each qualitative phrase (for example, "several" was assigned '3', and "many shakes" was assigned '5'), and used consistently (see Appendix 14 for more details). The rate of seismicity during the 1922 episode is estimated from unpublished work by G. Downes. There is a high level of uncertainty regarding this conversion, so data in the plots should be used with caution.

The classification of unrest requires decisions to be made on what constitutes abnormal levels of intensity, flux, depth, duration, and rate, for multiple characteristics of each unrest parameter, in a context of uncertainty. The determination of parameter ranges for the rate of earthquakes and deformation remains fairly subjective in this research, with a group consensus approach employed based on the range of historical activity, knowledge, and prior experience. A statistical approach could also be used where appropriate to determine individual parameter range thresholds, provided unrest at analogous volcanoes is also considered. However, the statistical technique also involves the subjective decision of what proportion of past activity constitutes unrest. For example, it could be decided that the threshold for the rate of high frequency earthquakes will be at a level where ten per cent of the activity observed in the past 20 years constitutes unrest. This involves a major assumption that activity in the past 20 years has been typical, and given the long time periods associated with geological processes, this is often not the case. If the time period considered is increased, a more representative range of activity may be included, however, difficulties in retaining consistency are often exacerbated due to changes in monitoring capabilities. Furthermore, the pre-determination of a fraction of activity that constitutes one of the parameters of unrest prohibits the recognition of changes in the frequency of unrest over time. For these reasons, a firm statistical threshold based on a proportion of activity was not used in this research, and a more flexible group consultation and consensus approach was chosen. The use of low, moderate, and high categories for some of the parameters in the VUI framework allows more detailed classification, and in addition to the integration with other unrest parameters, enables consideration of the bigger picture rather than defining unrest based on just one threshold for one parameter. Nevertheless, it seems inescapable that there is a degree of subjectivity in the determination of parameter ranges due to the preconceived notion of the proportion of past activity which ‘should’ constitute unrest. As more monitoring data are recorded and understanding of the volcanic processes and systems develop, thresholds should be reviewed and potentially adjusted.

Determining the start and end dates of unrest, and minimum periods of quiescence separating episodes also introduces uncertainty. In particular, these parameters affect the results for the duration of unrest, and may also affect the classification of the intensity of unrest using the VUI. To minimise this potential bias, thresholds were chosen and used consistently (discussed further in Appendix 15).

Aleatoric (stochastic) uncertainties relate to the intrinsic unpredictability and complexity of volcanic systems, and are irreducible (e.g., Marzocchi et al., 2004; Marzocchi et al., 2006). This impacts the VUI by imposing the possibility of an eruption directly from even minor unrest. Epistemic (data- or knowledge-limited) uncertainties, on the other hand, have been reduced over the duration of the 140 year unrest catalogue for TVC as scientific knowledge and the amount of data have increased. For example, the accuracy and precision of measurements have improved over time (e.g., Sherburn, 1992; Otway et al., 2002). The VUI framework incorporates qualitative descriptions to include pre-monitoring observations, and allows parameter ranges to be determined for individual volcanoes. This can take into consideration the precision of monitoring and measurements. The TVC catalogue is divided into three time periods according to seismic monitoring capabilities to minimise the impact of this potential bias on the results.

Finally, as TVC contains a large lake, there are uncertainties because monitoring capabilities are restricted almost completely to outside the perimeter of the caldera. Ellis et al. (2007) demonstrated than an inflation source at 15 km depth under the lake with a volume of 10 km^3 could almost go entirely unnoticed by monitoring equipment at the surface. Past unrest events beneath the lake may well have been missed. Improvements to the monitoring network at TVC in the future depend on a number of factors, including funding and technology advancements.

6.5 Results

The historical chronology methodology resulted in a dataset containing over 9,300 earthquakes, 37 hydrothermal events, and continuously fluctuating deformation rates at TVC. The dataset is held by GNS Science, New Zealand. The dataset is summarised in Tables 6.2, 6.3, and 6.4 for the three time periods used of pre-1940, 1940 to 1989, and 1990 to December 2011. These tables provide a qualitative summary of the unrest, based on the original data sources wherever possible, and lists the VUI scores for each parameter to demonstrate the determination of the VUI for each episode. For references used to develop this catalogue, see Appendix 16.

A large number of earthquakes are in the wider dataset, many of which were isolated events. A number of these did not reach the rate of earthquake thresholds used (detailed in Appendix 15) and so were not included in this catalogue. If observed phenomena did not meet these criteria, the VUI was guaranteed to be 1 or 2. Therefore, due to time constraints, these events were not included in the catalogue. Thus, many more episodes of VUI 1 and 2 have occurred than are included in this catalogue; VUI 1–2 represents the 'background' level of activity.

6.5.1 Pre-1940 unrest

For the unmonitored period prior to 1940, three episodes of minor unrest (VUI 3) have been identified since 1872 (Table 6.3). These occurred in 1877–78, 1880, and 1895. Additionally, two episodes of moderate unrest (VUI 4) occurred in 1897 and 1922–23. This corresponds to an average recurrence interval of 13.6 years for the two categories combined. The number of earthquakes in each episode is provided in Table 6.3 whenever this information is provided by the source or can be estimated. The multivariate dataset for this time period is shown in Figure 6.3A.

Table 6.3. Estimation of the VUI for TVC for the pre-1940 time period. Descriptions summarise the historical data. Beneath each description, scores are allocated to individual parameters (listed as column headers) from the VUI framework. HF = high frequency earthquakes, and LF = low frequency earthquakes. Parameters with no scores indicate no data are available. References are listed in Appendix 16. The VUI is calculated by dividing the 'total' for each episode by the 'number of columns used'.

Date	Local Seismicity				Local Deformation			Geothermal and Degassing			Total	Number of columns used	VUI	References
	Duration of earthquake swarm	Location of earthquakes	Max rate of HF earthquakes	Tremor, LF, and hybrid earthquakes	Max rate of local deformation	Location of deformation source	Groundwater levels and spring flows	Surface temperature, heatflow and manifestations	Gas flux	Gas and fluid composition				
5–6 Jun. 1872	Two moderate earthquakes felt in Taupo between 5–6 June. No damage reported.													
	2		1								3	2	**2**	1
20–28 Sep. 1875	Two "severe" earthquakes felt in Taupo. No damage reported.													
	2		1								3	2	**2**	2, 3
8 Apr. 1877–23 Apr. 1878	Two "smart shocks" felt in Taupo on 8 April 1877, and "several" were felt on 23 July 1877, described as severe. Further earthquakes were felt in Taupo on 9 (1 felt) and possibly 15 December (1 felt), 12 (2 felt) and 20 (3 felt) February 1878, 21 March (1 felt), in addition to an "unprecedented number of slight shocks" in March/April 1878. No damage was reported to have been caused by any of the earthquakes. A change in the activity of the springs after the 12 February earthquakes was reported.													
	3		2				4				9	3	**3**	4–14
27 Jun.–24 Sep. 1880	Many earthquakes felt in Taupo, including at least 13 in 24 hours on 27–28 June 1880 which caused slight damage to chimneys and alarm within the Taupo population. Further earthquakes are reported to have occurred on 18 July (1 felt), 29 July (1 felt) and "many" on 15 August. At least 25 earthquakes were recounted for the fortnight of 10–24 September 1880.													
	3		2								5	2	**3**	15–23
6 Jun. 1881–27 Feb. 1882	Eleven earthquakes were felt overnight in Taupo from 6–7 June 1881. Two earthquakes were felt on 27 July 1881, the second "very severe". Two earthquakes were felt in Taupo on 10 November 1881, and the geysers were reported as more active than usual. Two further earthquakes were felt on 27 February 1882.													
	2		2					3			7	3	**2**	24–27
24 Feb.–4 May 1883	Felt earthquakes were reported in Taupo on 24–25 February (a "succession" over several hours), 9–14 March ("several") and 4 May 1883 (1 felt). The hot springs were reportedly "very active" after the 4 May earthquake.													
	2		2					3			7	3	**2**	28–33
7 Jan.–23 Mar. 1884	Earthquakes felt in Taupo on 7 January 1884 (1 felt "violent", but may have been centred southwest of Taupo as it was also felt elsewhere), 18 (13–15 felt, small) and 20–23 March (one "very severe" followed by 40–50 smaller). (The March earthquakes are presumed here to be a foreshock – mainshock – aftershock sequence due to the "very severe" nature of one of the earthquakes.) Some of the region's hot springs were reportedly more active than usual following the 7 January earthquake.													
	1		3					3			7	3	**2**	34–40

Date	Local Seismicity				Local Deformation			Geothermal and Degassing			Total	Number of columns used	VUI	References
	Duration of earthquake swarm	Location of earthquakes	Max rate of HF earthquakes	Tremor, LF, and hybrid earthquakes	Max rate of local deformation	Location of deformation source	Groundwater levels and spring flows	Surface temperature, heatflow and manifestations	Gas flux	Gas and fluid composition				
4–5 Jan. 1885	Approximately 40 earthquakes were reported as felt on 4–5 January 1885, including one reported as "very severe" (presumed to be a mainshock – aftershock sequence).													
	1		2								3	2	**2**	41–43
9 Jun.–29 Oct. 1886	Earthquakes coinciding with the Tarawera eruption (in neighbouring Okataina Volcanic Centre) were felt at Taupo from 9–15 June 1886. Taupo lake water rose quickly the morning of 13 June (local time) as well as on the 14 June, receding again after both, described as a “great wave”. The earthquakes were strong in Oruanui on 19 June, and they were felt again in Taupo on 30 June 1886. There was unusual steam activity reported around Taupo at this time. Earthquakes were felt in Taupo (2 felt) on 29 October, and "volcanic fire" was seen in the direction of Rotomahana (near Tarawera).													
	2		2					3			7	3	**2**	44–54
24 Aug. 1890	An earthquake coincided with unusual hot spring activity around Taupo.													
	1		1					3			5	3	**2**	55
9–10 Feb. 1892	Earthquakes felt (1 or possibly 2) through the central North Island on 9–10 February. Hypocentres may not have been local.													
	2		1								3	2	**2**	56–58
10 Aug. 1892	25 earthquakes reported as felt over 6 hours at Tokaanu, "some of them were very severe". Springs and geysers at Taupo were “unusually active”.													
	2		2					3			7	3	**2**	59, 60
May–2 Sep. 1895	A large earthquake struck Taupo on 17 August 1895 at 6.27 pm (NZLT; 0657 UTC), estimated to have a local magnitude of 6–7.5 (MM8). The earthquake was felt as far south as Wellington (300 km to the south). Aftershocks continued frequently throughout the night, with at least 38 felt by 7 am (NZLT) the next morning. 36 earthquakes were felt in Tokaanu on the 23 August (no damage was caused), of which at least 3 were felt in Taupo. Effects included: • crockery and bottles smashed, and all chimneys in Taupo destroyed except for five; • minor injuries, including burns, however no severe injuries or loss of life were reported; • “hundreds” of landslides blocked roads around the lake, cutting off access to Tokaanu, including a very large slip near Hatepe; • a 2 ft (0.6 m) wave was seen on Lake Taupo; • springs in the Hatepe area emitted quantities of fine pumice, • fissures were reported in the Wairakei area, and possible faulting towards the east of Lake Taupo; • self-evacuations; • effects on tourism; • psychosocial impacts on residents, e.g.,loss of sleep; • rumours. Preceding the 17 August earthquake, an area of hot water “bubbling up from the depths below” was observed “about half way across the Western Bay” of Lake Taupo, in about May 1895, but could not be found again after this. The last report found regarding aftershocks was on 2 September 1895, with no further mention of earthquakes at Taupo until January 1896.													
	1		3				4	3			11	4	**3**	61–73, NEID

Date	Local Seismicity				Local Deformation			Geothermal and Degassing			Total	Number of columns used	VUI	References
	Duration of earthquake swarm	Location of earthquakes	Max rate of HF earthquakes	Tremor, LF, and hybrid earthquakes	Max rate of local deformation	Location of deformation source	Groundwater levels and spring flows	Surface temperature, heatflow and manifestations	Gas flux	Gas and fluid composition				
28 Aug. 1896	4–5 small earthquakes felt in Taupo and/or Tokaanu overnight.													
	2		1								3	2	**2**	74
20 Mar.–17 Oct. 1897	2–3 earthquakes were felt in Taupo on 20–21 March. Further earthquakes were felt in Taupo on September 8–9, 16–18 ("almost continuous"), 18–19 ("rather severe" in Taupo), 20–21 ("numerous"), and 22 ("frequent") 1897. There was a "heavy shock" on the 25 September with subsequent frequent tremors. At least 89 earthquakes were felt over two hours on 30 September; no damage was reported. Many earthquakes were felt on the 6 October, causing slight damage, and continued until the 8th. An earthquake on 17 October dislodged boulders in the Western Bay and caused at least 30 felt aftershocks. (Estimated maximum reported rate of 134 earthquakes felt during the month of September 1897.) The number and size of earthquakes decreased by the end of October, however the geysers and hot water features were notably active, with higher flow but a similar temperature to usual. The water in the Western Bay of Lake Taupo was reported as "warm and sulphurous".													
	3		4				4	3			14	4	**4**	75–104
4 Sep. 1899	Numerous earthquakes felt in Tokaanu on 4 September. Residents camped outside for the remainder of the night, and the Tokaanu Hotel chimney was destroyed.													
	1		2								3	2	**2**	105
27 Oct. 1902	17 earthquakes felt in Taupo.													
	2		2								4	2	**2**	106
4 Dec. 1903	A new fumarole developed at Spa Park, Taupo, following earthquakes at Waiotapu and Waimangu (outside the study area). (No earthquakes within the study area were reported, however this does not preclude a micro-earthquake swarm from having occurred.)													
		1	1					3			5	3	**2**	107
25 Feb. 1918	An earthquake caused a crack in the road, subsidence, and many landslips between Hatepe and Waitahanui. The subsidence resulted in a car accident and made the Taupo to Tokaanu road impassable. It is unclear whether the subsidence was due to a landslide as a secondary result of the earthquake.													
	1		1		3						5	3	**2**	108, 109
10 May 1922–Jan. 1923	Earthquakes began at Waiotapu (outside the study area) in April 1922 and migrated south through Taupo to Tokaanu by September causing damage, public alarm and evacuations. The earthquakes were felt from 10 May in Taupo, with an increase in rate throughout the month. Often 20 earthquakes were felt in one hour, and they averaged about 100 felt per day. The earthquakes estimated to have had the highest magnitude occurred on 9 (ML 6) and 19 June (MM7), 4, 8, 12, 14, and 17 July, and 5 September. Intense swarms of earthquakes were also felt on 25 June at Taupo (57 felt in 8 hours), and 3 September at Tokaanu (140 felt). This episode had a maximum monthly rate of seismicity of approximately 590 felt earthquakes, in June. An apparent fall in lake level of 1.1 m along the eastern side of Lake Taupo is interpreted to be potentially caused by pre-seismic uplift (Grindley & Hull, 1986). At Whakaipo Bay, subsidence caused a sunken shoreline (totalling 3.7 m by January 1923), fissuring of up to 1 m deep, displacement of approx. 0.5 m on Kaiapo Fault, large waves and seiching on Lake Taupo and hundreds of water fountains. There were conflicting reports about minor changes to activity at hot springs and geysers throughout the region. Effects included: • the collapse of several chimneys in urban areas; • bottles, crockery, books and other items were thrown on the floor, and the Taupo town clock stopped;													

Date	Local Seismicity				Local Deformation			Geothermal and Degassing			Total	Number of columns used	VUI	References
	Duration of earthquake swarm	Location of earthquakes	Max rate of HF earthquakes	Tremor, LF, and hybrid earthquakes	Max rate of local deformation	Location of deformation source	Groundwater levels and spring flows	Surface temperature, heatflow and manifestations	Gas flux	Gas and fluid composition				
	• many landslips blocked roads; • psychosocial effects; • impact on tourism locally, regionally and nationally; • self-evacuations; • official Government suggestion to evacuate. The Government Seismologist, Dr. Adams and Victoria College Professor Marsden suggested a source progressively shallowing close to Oruanui and Wairakei, with a depth of 3 miles (approx. 5 km). Professor Marsden stated on the 19 June 1922 “in view of the danger it was not right to keep the people in the district”, and it was suggested that “the chances of a blow-up were one in six”.													
	5	4	4		4		5	3			25	6	**4**	61, 110–118, NEID
4–8 Jun. 1934	Earthquakes felt at Taupo and near Mt Ruapehu.													
	2		2								4	2	**2**	119
15–16 Jul. 1935	An earthquake (MM6) centred to the north-east of Taupo on 15 July causing surface waves on the lake. There was damage to ornaments and a chimney at Wairakei. A landslide blocked the main road at Hatepe, and subsidence was reported at Wairakei (it is unclear whether this was due to a landslide). 26 lighter earthquakes were felt throughout the next day. The earthquakes caused the Taupo residents to become “seriously alarmed”. The geyser activity was reported as not unusual.													
	1		2		3			3			9	4	**2**	120–122

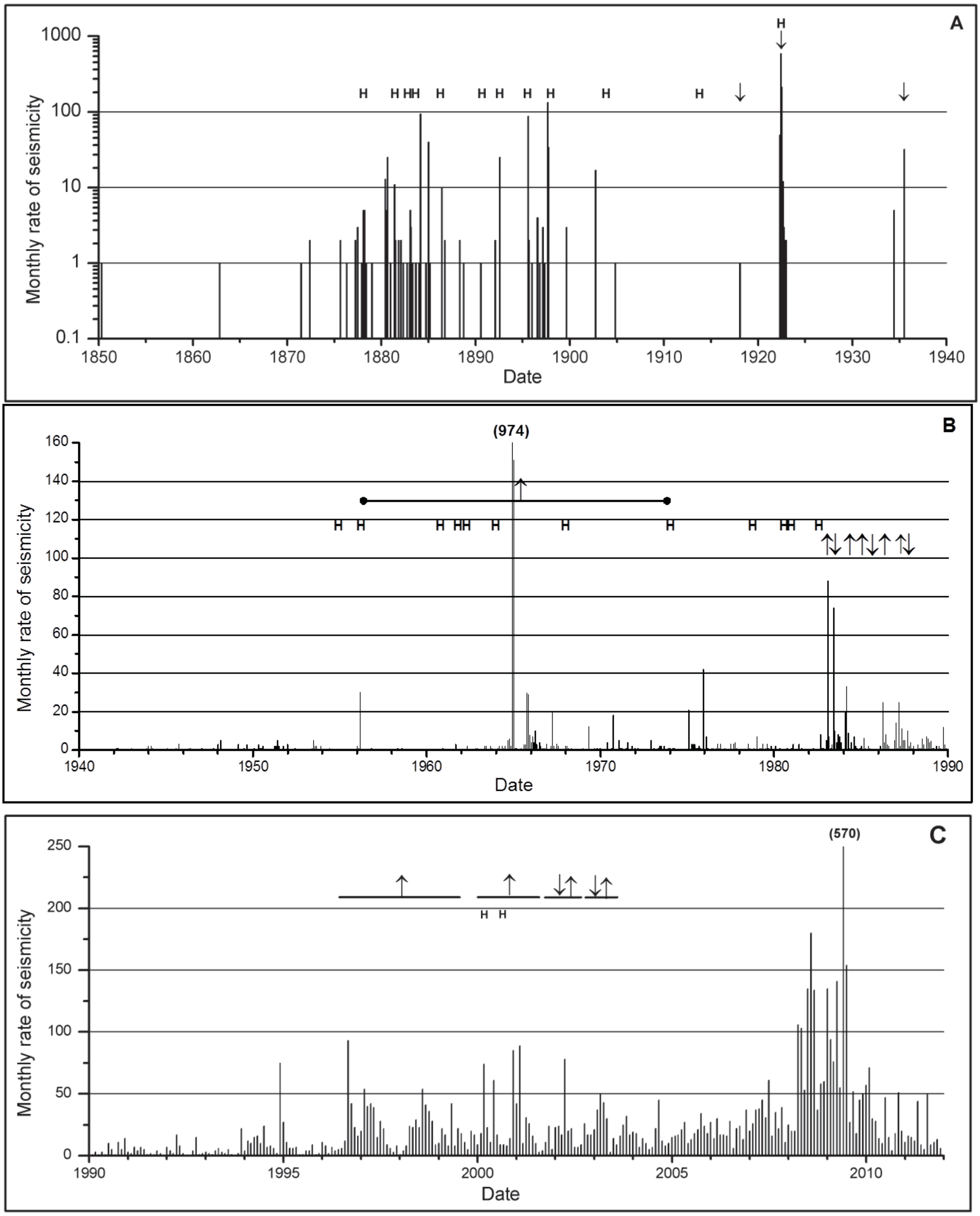

Figure 6.3. Earthquake, deformation, and hydrothermal activity at Taupo Volcanic Centre, New Zealand. Hydrothermal events are labelled 'H', and periods of deformation are depicted with arrows (downwards pointing arrow for subsidence and upwards pointing for uplift). The monthly rate of seismicity includes both reported and recorded magnitudes. A) Activity prior to 1940. Note the logarithmic scale used for the calendar monthly rate of seismicity, whereas B) and C) use linear scales.

Quantitative rates of earthquake events are predominantly estimated from qualitative descriptions in this period. B) Activity from 1940 to 1989 (inclusive). C) Activity from 1990 until 31 December 2011.

Of these episodes of unrest, only two had previously been recognised, in 1895 and 1922. The earliest episode of unrest recognised in this research occurred from April 1877 to April 1878. In this episode, felt seismicity was sporadic but reportedly more frequent that usual, culminating in a swarm in March and April 1878. Another minor unrest episode three months in duration began in June 1880, causing alarm amongst the local population, and involving three pulses of felt earthquakes. Using the VUI, the 1895 episode is classified as minor unrest. It has been interpreted in previous literature to be a tectonic mainshock/aftershock sequence (Eiby, 1968; Grindley & Hull, 1986; Johnston et al., 2002); reports found in this research of the intensity of the first magnitude 6–7.5 earthquake on 17 August at 6:27 pm (New Zealand local time) compared to the reported intensity of the aftershocks supports this. Unlike Grindley and Hull (1986) and Johnston et al. (2002), Bastings (1935) incorrectly reports this earthquake to have occurred on 18 August 1895. This is despite his referenced source, the N.Z. Times (19 August 1895), stating the earthquakes began on a Saturday, which was 17 August. Eiby (1968) and the NEID also state the earthquake occurred on 18 August; these dates may be based on the research by Bastings. The hot water “bubbling up from the depths below” in Lake Taupo about three months prior to this earthquake (as published in local literature by Kearns et al., 1985) has not previously been reported in the scientific literature. This information may be innocuous given the multiple hot spring locations in Lake Taupo, and the uncertainty over the location of the spring.

The first episode of unrest observed during the historical time period that is classified as a VUI 4 occurred in 1897 and was not previously recognised in the literature. After a scattering of felt earthquakes from January to May, 1897, the rate abruptly increased on 8 September. From 16 September, there was "nearly forty-eight hours of almost continuous quivering and shaking of terra firma", but no reported damage (e.g., Feilding Star, 18 September 1897; N.Z. Herald, 18 and 20 September 1897; Transactions of the New Zealand Institute, 1897; see Appendix 16 for information source details). Frequent localised earthquakes continued through until 30 September, when at least 89 earthquakes were felt within two hours (Evening Post, 7 October 1897). After a period of a few days with no felt earthquakes, they continued from 3 until 18 October. It was reported that on about 7 October “the water is warm and sulphurous in the small bay” of Western Bay, Lake Taupo (Evening Post, 9 October 1897). Rockfalls occurred in the Western Bay area following intense earthquakes on 17 October. It is unknown whether this activity could be connected to coinciding eruptions at Mt Tongariro (e.g., N.Z. Herald, 20 October 1897; Scott & Potter, 2014), approximately 40 km south-southwest of Western Bay (Figures 6.1 and 6.2).

The next unrest episode occurred in 1922–23, and has been well described in the literature (e.g., Morgan, 1923; Eiby, 1968; Grindley & Hull, 1986; Smith & Webb, 1986; Johnston et al., 2002). Seismicity began 50 km northeast of Taupo in April 1922, migrating south through the Taupo district from May to September, include many damaging earthquakes (Table 6.3). Uplift of the northeastern shores of Lake Taupo may have occurred by June, based on reports of an unusually low lake level (Grindley & Hull, 1986). Following intense seismicity and rupture of the Kaiapo Fault at this time, hundreds of water spouts 1 m tall were observed for a period of hours, and a total of 3.7 m of subsidence occurred on the western side of this fault over a period of months. Ground fractures and on-going seismicity contributed to increased anxiety in the area and evacuations. It has not previously been recognised that earthquakes continued to be felt until at least January 1923, according to a presentation given by a scientist at the time (Evening Post, 16 January 1923).

6.5.2 1940–1989 unrest

Eight episodes of unrest occurred during the 50 year time period between 1940 and 1989 (inclusive; Table 6.4). Six episodes of minor unrest (VUI 3) occurred in 1961, 1964, 1974, February 1975, December 1975, and 1984–85. Two episodes of moderate unrest (VUI 4) occurred in 1964–65 and 1983–84. This equates to an average combined recurrence interval of 6.3 years. The multivariate dataset for this time period is shown in Figure 6.3B.

Minor unrest in 1961 and March 1964 included hydrothermal eruptions coinciding with earthquake swarms. An episode of moderate unrest two months in duration occurred from December 1964 to January 1965, including a high rate of high frequency earthquakes and potential volcanic tremor. Uplift of up to 160 mm was also recorded and potentially attributed to this episode (the activity is described further in Table 6.4, and by Eiby, 1966; Gibowicz, 1973; Smith & Webb, 1986; and Johnston et al., 2002). Low frequency earthquakes were also recorded during minor unrest in 1974, coinciding with hydrothermal eruptions, as well as in February 1975. Unrest in December 1975 consisted of a shallow seismic swarm.

The most recent episode of moderate unrest (VUI 4) to have been observed at TVC occurred from February 1983 to March 1984 (as previously described by Otway, 1983a; Otway, 1983b;

Hull & Grindley, 1984; Otway et al., 1984; Grindley & Hull, 1986; Otway, 1986; Smith & Webb, 1986; Webb et al., 1986; Johnston et al., 2002; Otway et al., 2002; and Peltier et al., 2009, among others). Seismicity was centred 6 km west-northwest of Kinloch in February 1983, followed by uplift of 53 mm in the northern caldera area. The rupture of Kaiapo Fault in June was preceded and followed by further earthquakes, and the western side of Kaiapo Fault subsided an equivalent amount that it had been uplifted. A ‘volcanic earthquake’ and a hydrothermal eruption were observed (Allis, 1984; Webb et al., 1986), in addition to uplift of 11 mm at eastern Lake Taupo by October 1983 (Otway et al., 1984). Further small seismic swarms were recorded until March 1984. Nine months later, in December 1984, minor unrest occurred lasting until February 1985. This episode consisted of up to 15 mm of uplift and an earthquake swarm in eastern Lake Taupo.

Table 6.4. Estimation of the VUI for TVC between 1940 and 1989 (inclusive). Descriptions summarise the historical data. Beneath each description, scores are allocated to individual parameters (listed as column headers) from the VUI framework. HF = high frequency earthquakes, and LF = low frequency earthquakes. Parameters with no scores indicate no data are available. References are listed in Appendix 16. The VUI is calculated by dividing the 'total' for each episode by the 'number of columns used'.

Date	Local Seismicity				Local Deformation			Geothermal and Degassing			Total	Number of columns used	VUI	References
	Duration of earthquake swarm	Location of earthquakes	Max rate of HF earthquakes	Tremor, LF, and hybrid earthquakes	Max rate of local deformation	Location of deformation source	Groundwater levels and spring flows	Surface temperature, heatflow and manifestations	Gas flux	Gas and fluid composition				
Oct. 1954	The activity at Wairakei Geothermal Field increased in the month of October (exact date not specified), with the formation of a new fumarole, tree kill from newly steaming ground, and mud pools more active than usual. No seismicity was recorded or reported.													
		1	1					4			6	3	**2**	123
1–6 Mar. 1956	Earthquakes were felt at Tokaanu from 1 March, followed by a M5.3 (< MM7) earthquake on 3 March. Minor damage was caused, including broken windows, crockery and glassware, and cracked walls. Eight chimneys collapsed, all were of "poor design". A 1 m high wave was reported at both southern and northern ends of Lake Taupo. Areas of the lake bed were witnessed to be "boiling", attributed by visiting scientists to the release of methane gas from lake sediments. Aftershocks were felt until 6 March in Tokaanu (total of 30 events in March).													
	1	3	1								5	3	**2**	61, 124–127, NEID
3 May–15 Jul. 1960	There was a hydrothermal eruption at Wairakei Geothermal Field on 3 May 120 ft [~40 m] north of a new bore, and continuing until at least the end of June. It erupted mud and steam up to 800 ft [~245 m] high and depositing finer particles at least half a mile (~800 m) away. Steaming at cracks in the ground nearby increased a few weeks later. On 15 July there was a hydrothermal eruption at a drillhole near Wairakei, which destroyed a road, and covered an area of 3 acres in debris. Increased activity alongside the road had been noted previously. The July eruption was attributed by Allis (1979) to pressure building up in the drillhole, which had been cemented closed. Other changes in activity included an increase in the steam flow (a "ten-fold increase"), some hydrothermal features showed no changes, and a couple decreased in activity. Thompson (1960) suggested the changes were due to a large-scale process rather than a localised source due to the widespread area affected, and stated that the "effect of increased draw-off from the production bores [since geothermal exploitation began in 1952] cannot be overlooked". No seismicity was recorded or reported.													
		1	1					4			6	3	**2**	128–132
Apr.–Sep. 1961	In April, a hydrothermal eruption occurred from a fumarole at Wairakei Geothermal Field, forming a steaming crater, and ejecting mud and pumice material. A feature at Wairakei Geothermal Field also erupted in September, forming a 60 m x 20 m crater. Ejected material uprooted and snapped nearby pine trees. (Exact dates of the hydrothermal eruptions are unknown; only months were stated.) Three earthquakes of M 3.8 ≤ 4.2 were recorded within 10 minutes on 15 September, located within Area A at an unknown depth.													
	2	3	1					4			10	4	**3**	129, NEID

Date	Local Seismicity				Local Deformation			Geothermal and Degassing			Total	Number of columns used	VUI	References
	Duration of earthquake swarm	Location of earthquakes	Max rate of HF earthquakes	Tremor, LF, and hybrid earthquakes	Max rate of local deformation	Location of deformation source	Groundwater levels and spring flows	Surface temperature, heatflow and manifestations	Gas flux	Gas and fluid composition				
3–4 Mar. 1964	There was a hydrothermal eruption on 3 March at Wairakei Geothermal Field. Five craters formed with an area of 1250 m^2, and trees were uprooted. Ejecta were deposited >100 m from the source. <5 earthquakes occurred within Area A at an unknown depth during 3 to 4 March.													
	2	3	1					4			10	4	**3**	128, 129
7 Dec. 1964–29 Jan. 1965	An earthquake swarm occurred with 974 earthquakes ≥M2.6 recorded during December 1964 and 151 in January 1965 near Taupo. 33 earthquakes were recorded ≥M4.0. The epicentres migrated from Western Bay, Lake Taupo in early December 1964 to northern Lake Taupo by 21 December (within Area A at an unknown depth). Earthquakes on 21 December caused cracks to appear in buildings, chimneys moved, and crockery broke. Epicentres then moved south to Horomatangi Reef and the Waihaha area by January 1965, when the rate of earthquakes decreased. The earthquake swarm was seen as a possible magmatic intrusion by DSIR[40] seismologist Mr. Eiby, with potential (but unconfirmed) volcanic tremor observed on the Kinloch seismic record (Daily Post, 14 December 1964). Social impacts included: • rumours; • concerns over "exaggerated" reporting effecting tourism; • potential tourism impacts: it was stated that "hotel owners and tourist agents have reported no cancellations of bookings" by mid-December (before the increase in seismicity on the 21st) (17 December 1964, N.Z. Herald). However retrospective research by Johnston et al. (2002) found there were in fact a minority of holiday accommodation bookings cancelled; • psychosocial effect on residents but it was reported that they became used to the tremors; • a small number of residents moved out of the district. No fault displacement observations or deformation measurements were taken during this time period, however uplift of 90 mm on average (<160 mm) was recorded during road surveying east of Horomatangi Reef between two measurements in 1956 and 1977. Due to the intensity of this episode, it is possible the deformation occurred during the 1964–65 episode, however no robust rate can be calculated, or location modelled.													
	3	4	4	(3)							11	3	**4**	133–141, NEID
10 Oct.–8 Dec. 1965	An earthquake swarm occurred, with 30 events recorded >M2.6 in October, and 29 in November. Epicentres were within Area A, at an unknown depth.													
	3	3	1								7	3	**2**	NEID
20 Apr. 1967	An earthquake swarm at Turangi lasted for several hours. No damage was reported. Epicentres were within Area A, at an unknown depth.													
	2	3	1								6	3	**2**	142, NEID
Dec. 1967–30 Jan. 1968	A new powerful fumarole broke out at Wairakei Geothermal Field in December (exact date unknown). A magnitude 5.3 earthquake (<MM6) occurred on 30 January 1968, within Area A (near Turangi), at an unknown depth.													
	1	3	1					4			9	4	**2**	128, NEID

[40] Department of Scientific and Industrial Research, the government science organisation in place prior to GNS Science.

Date	Local Seismicity				Local Deformation			Geothermal and Degassing			Total	Number of columns used	VUI	References
	Duration of earthquake swarm	Location of earthquakes	Max rate of HF earthquakes	Tremor, LF, and hybrid earthquakes	Max rate of local deformation	Location of deformation source	Groundwater levels and spring flows	Surface temperature, heatflow and manifestations	Gas flux	Gas and fluid composition				
Mar.–14 Apr. 1974	Hydrothermal eruptions occurred in March in the Tauhara Geothermal Field at Spa Park (a small, shallow eruption from an existing crater, exact date unknown) and the Pony Club (28 March, enlarging an existing crater). Surface heat flow increased throughout the 1960s and 1970s in this area. Shallow, low frequency earthquakes, thought to have been of "volcanic origin" occurred between Oruanui and Wairakei on 14 March, and in the Wairakei area on 14 April.													
	1	5	(1)	3				4			13	4	**3**	143–149
14–23 Feb. 1975	In mid-February there was a "conspicuous increase in the number of earthquakes taking place near Taupo" Latter (1975). Both high- and low-frequency earthquakes were recorded (max. rate of 21 events per month, within Area A, at an unknown depth). Latter (1975) describes a "large number of small events of volcanic appearance" to have been recorded between 18 and 21 February, with hypocentres located near Wairakei (no exact number of low frequency events was stated, assumed less than 20 per month).													
	2	3	(1)	3							8	3	**3**	147, NEID
30 Dec. 1975	41 shallow earthquakes were centred near Wairakei (in Area A) over three hours; many were felt. Minor contents damage was reported. No low frequency signatures were observed.													
	2	5	2	(1)							9	3	**3**	150
Jun. or Aug. 1978	A hydrothermal eruption occurred at Wairakei Geothermal Field, forming a 600 m^2 crater. Deposits of material were over 10 m deep and reached more than 100 m from the vent. Allis (1984) states that this eruption occurred in August 1978, while Allis (1979) states it occurred in June.													
	1	1	1					4			7	4	**2**	128, 151
Dec. 1980	A hydrothermal eruption occurred at Wairakei Geothermal Field (no exact date given).													
	1	1	1					4			7	4	**2**	151
20–27 Jun. 1981	A hydrothermal eruption occurred on 20 June in the Tauhara Geothermal Field, near the Pony Club. Mud and rocks were deposited as far as 800 m from the vent towards the northeast, with an area covered of 1640 m^2, and a volume of ejected material of about 6800 m^3. It knocked over and buried trees, grass, and a fence, and ballistics >20 cm in diameter were found >100 m from the source. The area was only slightly active a few days later. A second hydrothermal eruption occurred one week later at Wairakei Geothermal Field, enlarging an existing crater.													
	1	1	1					4			7	4	**2**	145, 151
1 Feb. 1983– 6 Mar. 1984	A seismic swarm occurred for 10 days in February 1983, centred 6 km west-northwest of Kinloch (in Area A) at a depth of 4–8 km, with further earthquakes at a lower rate for another 50 days (max. rate of 88 events per month recorded in February). Up to six seismic events ≥M2.8 were recorded per day in February, with only one felt in Taupo. The block of land west of Kaiapo Fault, which had previously been subsiding, uplifted by a total of 53 mm between March and mid-June 1983 at a rate of up to 60 mm/yr. This was modelled to be caused by an inflating source at a depth of 4 km beneath the northern end of Lake Taupo (Peltier et al., 2009). To the east of Kaiapo Fault uplift continued from March 1983 until January 1984, totalling 55 mm (relative to a site on the SE side of Lake Taupo). Slight subsidence (20 mm/yr) was seen in south-eastern Lake Taupo. A hydrothermal eruption occurred on 9 April 1983 at Wairakei Geothermal Field, throwing recycled pumice < 60 m into the air for three hours. Fine deposits were found < 120 m from the crater. The eruption had a volume of 1000–2000 m^3, with further small pulses ejecting													

Date	Local Seismicity				Local Deformation			Geothermal and Degassing			Total	Number of columns used	VUI	References
	Duration of earthquake swarm	Location of earthquakes	Max rate of HF earthquakes	Tremor, LF, and hybrid earthquakes	Max rate of local deformation	Location of deformation source	Groundwater levels and spring flows	Surface temperature, heatflow and manifestations	Gas flux	Gas and fluid composition				
	material over the next two weeks. Earthquakes, barometric pressure, and self-sealing mechanisms were discounted as triggers. An earthquake swarm was centred near Kaiapo Bay (in Area A) and peaked in intensity on 20–21 June with over 30 earthquakes per day (max. monthly rate of 74 events recorded in June), declining through to late July. Magnitudes of <4.3 were recorded, and tension cracks formed. Kaiapo Fault ruptured on 23 June, causing a 1.2 km displacement and subsidence of 43 mm to the west of Kaiapo Fault, which increased to 55 mm by 19 July. One possible volcanic earthquake was recorded on all nine portable seismograph stations on 2 July, and resulted from a source process, not from attenuation whilst travelling from source to stations (Webb et al., 1986). Felt reports from the June and July earthquakes included descriptions of fallen ornaments and mirrors, cracked chimneys, and other structural damage. Further small, localised swarms occurred on 4 August, 20 September, and 4 October 1983, and in February and March 1984. Uplift was observed on 6 October 1983 with "a possible 5 mm rise at Motuoapa and a more certain 11 mm rise at Bulli Point".													
	3	4	(2)	3	3	5		4			22	6	**4**	139, 151–156, NEID
Dec. 1984–Feb. 1985	A swarm of "several" small felt earthquakes occurred beneath the north-eastern shoreline of Lake Taupo (near Waitahanui, in Area A), preceded by 3 to 4 months (exact dates unknown) of 10–15 mm of uplift in the same area, and followed by a reversal. This swarm was not recorded on monitoring equipment, therefore the magnitude, depth, and total number of earthquakes is unknown. Subsidence with a rate of up to 20 mm/yr was recorded for the Kinloch/Whakaipo Bay area during 1984 and 1985.													
	2	3			3						10	4	**3**	155, 157
Dec. 1985–Apr. 1986	Uplift of 17 ± 5 mm was centred near the middle of Lake Taupo over this 4 month period (relative to a monitoring station on the north-western shoreline). Subsidence in the Kinloch/Whakaipo Bay area slowed to < 5 mm per year throughout 1985–1986. A micro-earthquake swarm occurred at Tokaanu (within Area A) on 20–21 April 1986 (max. rate 25 events in April, depth unknown).													
	2	3	1		3						9	4	**2**	158

6.5.3 1990–2011 Unrest

In the 22 years from 1990 to 2011 (inclusive), three episodes of minor unrest (VUI 3) have been identified at TVC, occurring in 1996–99, 1999–2001, and 2008–10 (Table 6.5). No episodes of moderate or heightened unrest have occurred. This equates to an average recurrence interval of 7.3 years. The multivariate dataset for this time period is shown in Figure 6.3C.

Forty mm of uplift was observed between March 1996 and March 1999 at Horomatangi Reef, above the site of the most recent eruption from TVC, and the most likely location of the next eruption (Wilson, 1993). This was inferred by Peltier et al. (2009) to be caused by an inflating source located 1 km beneath this site. The unrest included earthquake swarms and a hydrothermal eruption. From December 1999 to June 2001, uplift of 20 mm per year was recorded in the north-eastern caldera, and further earthquake swarms. At least three hydrothermal eruptions occurred at Wairakei Geothermal Field during this episode.

The most recent episode of unrest in the catalogue occurred from March 2008 until February 2010 (Table 6.5). Between 40 and 50 mm of uplift was observed at Horomatangi Reef, and the rate of seismicity increased (Jolly et al., 2008). This unrest is thought to have been triggered by a tectonic slow slip event, resulting in fluid-driven inflation (Fournier et al., 2013).

Table 6.5. Estimation of the VUI for TVC between 1990 and 31 December 2011. Descriptions summarise the historical data. Beneath each description, scores are allocated to individual parameters (listed as column headers) from the VUI framework. HF = high frequency earthquakes, and LF = low frequency earthquakes. Parameters with no scores indicate no data are available. References are listed in Appendix 16. The VUI is calculated by dividing the 'total' for each episode by the 'number of columns used'.

<table>
<tr><th rowspan="2">Date</th><th colspan="4">Local Seismicity</th><th colspan="3">Local Deformation</th><th colspan="3">Geothermal and Degassing</th><th rowspan="2">Total</th><th rowspan="2">Number of columns used</th><th rowspan="2">VUI</th><th rowspan="2">References</th></tr>
<tr><th>Duration of earthquake swarm</th><th>Location of earthquakes</th><th>Max rate of HF earthquakes</th><th>Tremor, LF, and hybrid earthquakes</th><th>Max rate of local deformation</th><th>Location of deformation source</th><th>Groundwater levels and spring flows</th><th>Surface temperature, heatflow and manifestations</th><th>Gas flux</th><th>Gas and fluid composition</th></tr>
<tr><td rowspan="2">11 Dec. 1994</td><td colspan="10">A magnitude 4.5 earthquake occurred within Area A at a moderate depth on 11 December and was followed by 54 smaller earthquakes.</td><td rowspan="2">5</td><td rowspan="2">3</td><td rowspan="2">2</td><td rowspan="2">NEID</td></tr>
<tr><td>1</td><td>3</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Mar. 1996 – Mar. 1999</td><td colspan="10">From March 1996 until March 1999 the Horomatangi Reef monitoring site recorded a total uplift of 40 mm, at a maximum rate of 11 mm/yr. Other nearby sites also recorded a small amount of uplift in an apparent east to west lineation. The northern side of the lake continued to slowly subside. The deformation source was modelled and inferred as an inflation source 1 km under Horomatangi Reef (Peltier et al., 2009). A hydrothermal eruption ejected mud to treetop height at Wairakei Geothermal Field in July 1997. Earthquake swarms had durations of 1 to 2 months, located within Area A at a moderate depth. The highest monthly rate of recorded earthquakes occurred in:
• September 1996 (93 events);
• February 1997 (54 events);
• August 1998 (54 events).
Scientists considered increasing the Volcanic Alert Level (VAL) to one, however it remained at zero. Response meetings were held with local and regional councils.</td><td rowspan="2">19</td><td rowspan="2">6</td><td rowspan="2">3</td><td rowspan="2">152, 154, 159–163, NEID</td></tr>
<tr><td>3</td><td>3</td><td>1</td><td></td><td>3</td><td>5</td><td></td><td>4</td><td></td><td></td></tr>
<tr><td rowspan="2">Dec. 1999 – Jun. 2001</td><td colspan="10">Uplift of a north-eastern section of Taupo Caldera relative to the south-western area occurred at a rate of 20 mm/yr, causing a tilt towards the west south-west between December 1999 and June 2001. This was interpreted by Peltier et al. (2009) to be caused by inflation in the north-eastern caldera area at 11 km depth.
Earthquakes were generally within Area A, at a moderate depth. The months with the highest rate of earthquakes were:
• March 2000 (74 events, max. swarm duration 2 days);
• June 2000 (61, max. swarm duration 1 day);
• December 2000 (85, max. swarm duration 14 days);
• February 2001 (89, max. swarm duration 2 days);
Hydrothermal eruptions reportedly occurred at Wairakei Geothermal Field (WGF) in February 2000 and 22–23 March 2001. The latter eruption destroyed 1 hectare of pine trees and formed a 20 x 30 m crater. Another hydrothermal eruption occurred at WGF between 29 March and 4 April 2001, flattening vegetation.</td><td rowspan="2">17</td><td rowspan="2">6</td><td rowspan="2">3</td><td rowspan="2">152, 163, 164, NEID</td></tr>
<tr><td>3</td><td>3</td><td>1</td><td></td><td>3</td><td>3</td><td></td><td>4</td><td></td><td></td></tr>
</table>

Date	Local Seismicity				Local Deformation			Geothermal and Degassing			Total	Number of columns used	VUI	References
	Duration of earthquake swarm	Location of earthquakes	Max rate of HF earthquakes	Tremor, LF, and hybrid earthquakes	Max rate of local deformation	Location of deformation source	Groundwater levels and spring flows	Surface temperature, heatflow and manifestations	Gas flux	Gas and fluid composition				
16 Apr. 2002–Jun. 2003	78 earthquakes were recorded in April 2002, mainly on 16–17 April, located in Area A around 5 < 10 km. At this time, there was subsidence of up to 20 mm/yr observed on the western side of Kaiapo Fault (typical of the long-term trend) and uplift of 5 mm/yr on the eastern side of the fault, interpreted to be a deep deflating source and/or fault movement (Peltier et al., 2009). From June 2002–June 2003 uplift west of Kaiapo fault relative to the north-eastern side of the caldera was observed, with a small amount of subsidence east of the fault. No rate of deformation was stated by Peltier et al. (2009), who interpret this deformation to reflect slow-slip fault movement following the 1999–2001 inflation. 50 earthquakes were recorded in the month of March 2003, during short swarms.													
	2	2	1		3	2					10	5	**2**	152, NEID
Jul. 2007	61 earthquakes were recorded in July. These mainly occurred on the 14 and 25–27 July, within Area A at a depth of 5 < 7 km. Subsidence at a rate of 10–22 mm/yr was observed, typical of the long-term trend.													
	2	3	1		3	2					11	5	**2**	152, NEID
30 Mar. 2008 – 9 Feb. 2010	High rates of earthquakes were recorded over nearly 2 years, with up to 150 recorded per day (with < 14 reported as felt per day), and up to 570 earthquakes recorded per month (>50 events per month were recorded in 19 months of this episode, with multiple short duration swarms, which had a max. duration of 13 days). There were four earthquakes ≥M4.0. The earthquakes were located at a range of depths (predominantly 5 < 10 km, but also shallower) and mainly within Area A. No low frequency seismicity was observed. A maximum rate of uplift of 40–50 mm/yr was recorded at Horomatangi Reef, thought to be the result of a shallow inflating source in this area (Jolly et al., 2008; Fournier et al., 2013). No changes to the hydrothermal systems were reported.													
	3	4	2	(1)	3	5		3			20	6	**3**	165, 166, NEID
25 Nov. 2010	51 earthquakes were recorded in the month of November, predominantly on the 25th. They were located near Turangi (within Area A), at a depth of 5 < 8 km. 10 earthquakes >M2.0 were recorded within 8 hours. No published synthesis of deformation data is available, and no changes to the hydrothermal systems were reported.													
	2	3	1	(1)				3			9	4	**2**	NEID
28–29 Aug. 2011	50 earthquakes were recorded during the month of August, predominantly on the 28th–29th. This was a mainshock-aftershock sequence (max. M3.0) on the edges of Area A, at a moderate depth (5 < 10 km). No published synthesis of deformation data is available, and no changes to the hydrothermal systems were reported.													
	1	3	1	(1)				3			8	4	**2**	NEID

6.5.4 Frequency, duration, and intensity of unrest at TVC

This research has identified 16 episodes of unrest (≥VUI 3) that have occurred at TVC during recorded history; four were moderate unrest (25% of the identified unrest episodes), and 12 were minor unrest (75%). No episodes of heightened unrest (VUI 5) have been observed. The frequency and intensity of unrest observed at TVC during this time period is summarised in Figure 6.4, utilising the VUI.

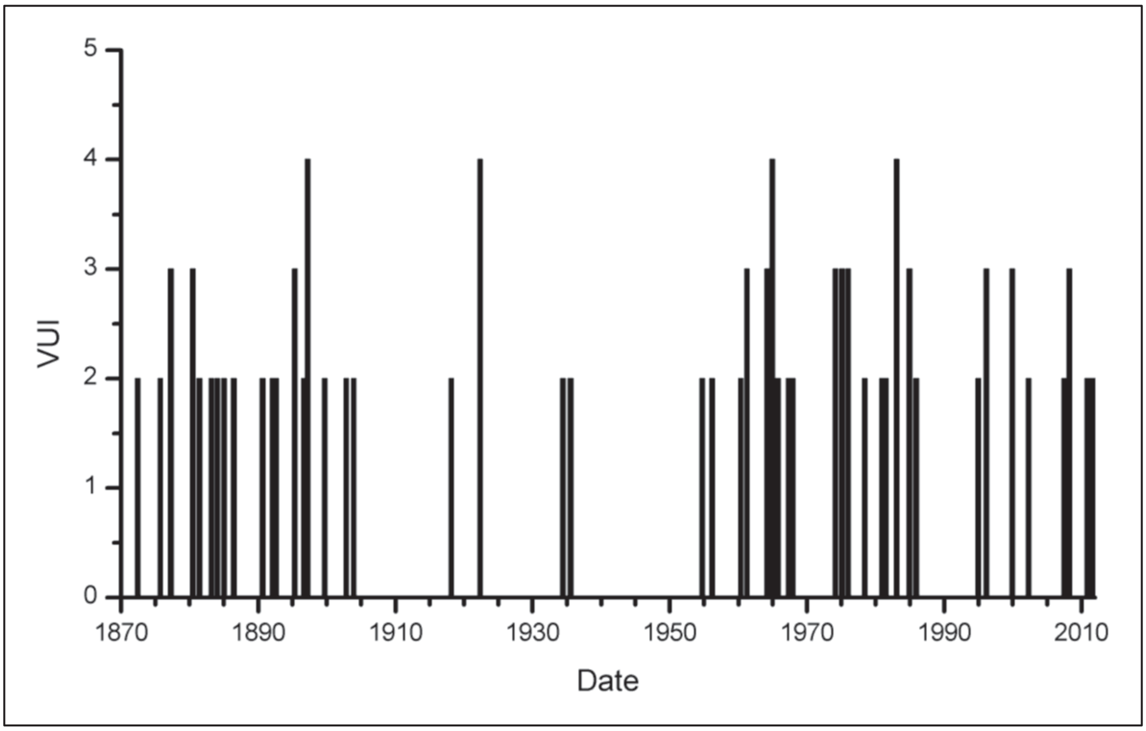

Figure 6.4. Plot of the relative intensity and frequency of historical volcanic unrest at TVC, utilising the Volcanic Unrest Index (VUI).

In the 140 year time span included in this catalogue, there has been an average of one unrest episode every 8.8 years. The average recurrence interval of moderate unrest is 35.0 years, and the average recurrence interval of minor unrest is 11.7 years. There has been a wide range in the duration of quiescence between unrest episodes, from just over eight months to approx. 40 years.

The duration of unrest episodes identified in this research is described in Table 6.6. There is a wide range in duration of unrest episodes, with a minimum of one day, and a maximum of 1126 days (approx. three years). The median duration of all unrest episodes at TVC is 147 days, or just under five months. The median duration of episodes of moderate unrest is approximately twice as long as the median duration of episodes of minor unrest.

Table 6.6. Duration of unrest episodes at TVC.

Date of Episode	Duration (days)
Minor unrest (VUI 3)	
1877–78	381
1880	90
1895	125
1961	168
1964	2
1974	45
1975, Feb.	10
1975, Dec.	1
1984–85	90
1996–99	1126
1999–2001	549
2008–10	682
Mean	272
Median	108
Moderate unrest (VUI 4)	
1897	212
1922–23	251
1964–65	54
1983–84	400
Mean	229
Median	232
All historical unrest (≥ VUI 3)	
Mean	262
Median	147
Minimum	1
Maximum	1126

The purpose of using minimum thresholds of activity (Appendix 15) in this research was to exclude very small events from the catalogue. Therefore, the number of VUI 2 episodes that have been recognised is a minimum, and it is possible that VUI 1 episodes have also occurred. Episodes of activity classified as VUI 2 in Tables 6.3 to 6.5 are considered to be part of the normal state or 'background' activity at TVC. For example, an earthquake swarm occurred in April 1967 near Turangi (Table 6.4). The rate of high frequency earthquakes and the short duration of the swarm influenced the VUI classification for this episode as 2 (dynamic volcanic system, no unrest). Earthquake swarms such as this are common at TVC (also occurring in 2007 and 2010, among others), and are considered to be part of the 'background activity'. The estimation of the VUI for the continuous record of activity at TVC (that is, retrospectively use a six month sliding time window to capture every small event) is beyond the scope of this research, although it would be beneficial to investigate this in the future. This would ascertain whether episodes of VUI 1 are possible at TVC or if the 'background' level is always VUI 2 given the numerous active geothermal fields, local deformation, and occasional seismicity.

6.6 Discussion and conclusion

Using the VUI and a detailed historical chronology methodology, this research has identified 16 episodes of unrest at TVC, a substantial increase from the number of previously recognised episodes. Moderate intensity unrest has been identified to have occurred in 1897, in addition to previously recognised unrest in 1922–23, 1964–65, and 1983–84. The most recent episode of unrest occurred in 2008–10; it has been classified as minor. Other recent episodes of minor unrest occurred in 1996–99 and 1999–2001. All three of these episodes within the past 20 years were characterised by inflating pressure sources within the caldera area (Peltier et al., 2009; Fournier et al., 2013). Many other episodes identified in this research are also potentially volcanologically significant and would benefit from further research. The apparent pattern of inflation, rupture of Kaiapo Fault, seismicity, and subsidence of the western side of the fault seems to be a recurrent theme. This occurred in at least 1922–23 and 1983–84, as identified by Grindley and Hull (1986), as well as at a less intense level in 1999–2003, as identified by Peltier et al. (2009). This may indicate a future course of events, should uplift be observed in the north-eastern caldera area.

6.6.1 Comparison of unrest to global datasets

In their statistical analysis of global volcanic unrest between January 2000 and July 2011, Phillipson et al. (2013) found the median duration of pre-eruptive unrest (12 volcanoes) at large calderas to be 66 days, and the median duration of non-eruptive unrest (11 volcanoes) to be 679 days (just under two years). The median duration of non-eruptive unrest at TVC is 147 days (approx. five months), only about one fifth of the duration that was found by Phillipson et al. (2013). The statistics for duration of unrest are influenced by the definition of time constraints on episodes, as well as on reporting characteristics (Newhall & Dzurisin, 1988).

The wide range in average recurrence interval between episodes of unrest highlights that it should not be used to determine that an unrest episode is ‘overdue’. The average recurrence interval between unrest episodes is longer in the pre-1940 time period (13.6 years) than in the two more recent time periods (6.3 and 7.3 years, respectively). This may be due to a lower population in the study area and low monitoring capabilities, reducing the possibility of unrest being reported. It is also a possibility that fewer unrest episodes occurred in this time period, or it could be a reflection of the thresholds used to identify the episodes.

TVC has had 16 episodes of unrest in 140 years without resulting in an eruption. If the average rate of recurrence of one episode every 8.8 years was assumed to be constant over time, and extrapolated back to the date of the last known eruption at TVC, in 232 ± 5 years B.P. (Hogg et al., 2012), there would have been over 200 episodes of non-eruptive unrest. This is vastly different to the findings of Newhall and Dzurisin (1988) that on average, one in six episodes of unrest at long-quiet silicic calderas result in an eruption. It is also different to their finding that 48% of unrest at any caldera results in an eruption, and to Phillipson et al.’s (2013) finding than 52% of reported unrest results in an eruption at caldera volcanoes within the studied timeframe.

Does this indicate that TVC has a much higher frequency of unrest without resulting in an eruption, and shorter unrest durations than most calderas in the world? This could lead to a false sense of security for both scientists and responding parties where pre-eruptive unrest is not recognised nor responded to effectively. Two likely explanations exist. The first is that the global analyses by Newhall and Dzurisin (1988) and Phillipson et al. (2013) include calderas with frequently active small stratocones within them, indicating that they may be too different to TVC for an adequate comparison. A second explanation for this discrepancy with global analyses is that very few episodes of unrest at calderas have been recognised and reported worldwide. The statistical analyses of global datasets only includes the most significant episodes of unrest (as identified by Phillipson et al., 2013) that have been reported at just a portion of the world’s volcanoes, producing what may well be a false indication that a higher proportion of unrest episodes will result in an eruption. By developing detailed unrest catalogues at volcanoes worldwide over historical time periods, integrating all data available (including qualitative reports; and seismic, deformation, geothermal, and degassing data), and using consistent definitions of unrest, then reporting the findings, a more accurate indication of the proportion of unrest to eruptions can be ascertained.

Another possible explanation for the difference in unrest duration and proportion of unrest to eruptions with the global dataset is that the definition of unrest used in this research is more inclusive of lower intensity activity than has been used in analyses of global unrest, resulting in the recognition of more frequent unrest. Analysis by Newhall and Dzurisin (1988) and Phillipson et al. (2013) incorporates all *reported* unrest, including phenomena likely to have been caused by non-magmatic processes. This leaves the determination of what constitutes unrest up to local scientists, who decide whether or not to report the activity. The catalogue of unrest presented in the present paper includes much more activity than that officially reported by scientists in the form of warning messages or information bulletins. This further highlights the role of scientific decision-making, particularly regarding the definition of unrest and the communication of scientific information. The VUI assists with defining unrest and recognises that this differs at each volcano, hence why the framework utilises flexible parameter ranges, which are determined on a case-by-case basis.

6.6.2 Socio-economic impacts of unrest at TVC

A large range in intensity of unrest has been found at TVC. Reported events include earthquake swarms, low frequency seismicity, subsidence of < 3.7 m over nine months, changes in hydrothermal activity including numerous hydrothermal eruptions, audible rumbling, rapid lake level changes and surface waves, and reportedly warm and sulphurous areas of lake water. Some of the episodes detailed in this catalogue were hardly noticeable by the residents in the study area, and it is likely that additional unrest phenomena went unnoticed, particularly prior to the development of the monitoring network.

Evacuations and perceived impacts on the economy, the tourism industry (locally, regionally, and internationally), infrastructure and building contents, and the psychological and physical health of nearby populations have resulted from unrest at TVC. The most recent episode of unrest classified as VUI 4 was in 1983, 30 years ago, and beyond the memory and experience of many of Taupo’s current residents. This may cause difficulties in persuading residents of the potential for volcanic unrest and its impacts at Taupo. The development of this catalogue of unrest and the VUI will contribute towards improving the effectiveness of this message.

6.6.3 Methodological aspects

The method of estimating the VUI to classify unrest for a historical record was developed in this research. It may be utilised for the development of multi-parameter historical unrest chronologies at other volcanoes. If significantly different monitoring capabilities exist between the start and end of a catalogue, the time period may be divided into sections with similar capabilities and a constant threshold used in each section.

The ranges of parameters used in the VUI framework for TVC might be revised in the future as more multi-parameter data become available. Once populated, the World Organisation of Volcano Observatories database of volcanic unrest (WOVOdat[41]) will provide additional data for defining unrest at calderas worldwide.

Downes (2004) identified four main factors influencing the completeness of the record of historical earthquakes in a catalogue. These are

- population distribution,
- written records being kept,
- availability of these records, and
- whether these records have been accessed and researched.

The same factors have affected the completeness of this multi-parameter volcanic unrest catalogue. As with most earthquake catalogues, those containing volcanic unrest are restricted to the time for which humans have settled in an area and kept written records. This is due to the lack of evidence left by most volcanic unrest in the geological record, unlike volcanic eruption deposits. These two factors have restricted this TVC catalogue of unrest to the past 140 years. Availability of the historical records continues to be improved as newspaper articles become searchable online and more easily shared. Previous research into unrest at TVC has been limited by restricted access to these resources. The present research is the most comprehensive compilation undertaken of volcanic unrest at and around TVC.

6.6.4 Implications and mitigation of caldera unrest in New Zealand

Johnston et al. (2002) indicate that a Volcanic Alert Level (VAL) of one ("initial signs of possible volcano unrest. No eruption threat", as stated in the current system for 'reawakening volcanoes' in New Zealand; MCDEM, 2006) could have been given to unrest in 1895, 1922,

[41] http://www.wovodat.org/, accessed on 23 January 2013

1964–5, 1983, and 1997–8. Using the current definition of VAL 1, and the current use of the term 'unrest' as a 'departure from typical background activity', this list has now grown to include all 16 episodes of unrest. Furthermore, had the VAL system been in place for the duration of this catalogue, the VAL may have been raised to 2 in each of the four episodes classified as VUI 4. This demonstrates the possibility of defining unrest using the VUI to assist with the determination of the VAL and/or the International Aviation Colour Code.

However, acknowledging unrest at TVC, from which the last eruption was one of the largest in worldwide recorded history, may result in significant social and economic consequences. This occurred at Long Valley Caldera, California in 1982, when the U.S. Geological Survey issued a Notice of Potential Volcanic Hazard for Mammoth Lakes (Mader & Blair, 1987; Hill, 1998). In New Zealand, a multi-agency strategic planning group with a core membership of regional and local councils, the Ministry of Civil Defence and Emergency Management, and GNS Science, called the Caldera Advisory Group, was formed in 2010 to address the risk of potential caldera unrest. The estimation of the VUI for the TVC unrest catalogue as described in this Chapter provides a simple method to communicate the intensity and frequency of caldera unrest. The VUI and Figure 6.4 has been used to explain the history of caldera unrest at TVC to the Caldera Advisory Group, with positive feedback.

6.7 Summary

In summary, a catalogue of volcanic unrest is presented for the period between 1872 and December 2011 for TVC, New Zealand, a large silicic caldera that last erupted in 232 ± 5 AD (Hogg et al., 2012). The use of the VUI to define, classify, and communicate unrest intensity and frequency is demonstrated. Sixteen episodes of unrest are identified, including ten episodes that had not previously been recognised in the literature. Four episodes of unrest were of 'moderate' intensity (VUI 4), occurring in 1897, 1922–23, 1964–65, and 1983–84; and 12 episodes were classified as minor (VUI 3), occurring in 1877–78, 1880, 1895, 1961, 1964, 1974, February 1975, December 1975, 1984–85, 1996–99, 1999–2001, and 2008–10. No episodes of heightened unrest (VUI 5) have occurred at TVC during the historical time period. There has been an average interval of approximately nine years between unrest episodes, and a median unrest episode duration of just under five months. As unrest at TVC is now known to occur more frequently than previously recognised, the perspectives of volcanologists and government officials may be altered in dealing with future crises. The integrated record presented in this compilation provides context to evaluate and plan for future unrest crises.

6.8 Acknowledgements

The authors would like to acknowledge GNS Science and the New Zealand Earthquake Commission for funding this research, the GeoNet project for access to much of the data, Dr. Steven Sherburn, Dr. Nicolas Fournier, and Gaye Downes for their contributions. Thank you to Chris Newhall and John Stix for their helpful, detailed, and constructive feedback when reviewing this paper.

CHAPTER SEVEN

CONCLUSION

7 CONCLUSION

7.1 Introduction

This chapter discusses the findings of this research in relation to the research aims, which are stated on page 14 of this thesis. It specifically answers the guiding research question, and identifies avenues of potential future research based on the findings presented in this thesis.

Chapters 1 and 2 of this thesis describe background information relating to this research. Chapter 3 describes the ethnographic methodology, and Chapter 4 presents and explores the results relating to the VAL system research, positioning them within the theoretical context from the literature. Chapters 5 and 6 investigate aspects relating to comparing and defining volcanic unrest, particularly at TVC, and include discussions of the findings. As Chapters 4 to 6 already discuss the findings and position them within the context of the literature, this chapter is kept brief, integrating those discussions and relating them to the research aims. It finishes with a summary of the research.

7.2 Addressing the research aims

This section summarises the findings of this research described in Chapters 4 to 6 in relation to the research aims described in Chapter 1.

7.2.1 Research aim 1

Research aim 1 is to *"Establish the context of New Zealand's Volcano Early Warning System"*. This aim was fulfilled by interpreting information gathered during a literature review, which is summarised in Chapter 2. This process was guided by the research question 'How is volcano-related information communicated between scientists, end-users, and the public in New Zealand?' Findings from theme 1 of the VAL research ("establishing the context of the VAL system") also contributed to establishing the context of the VEWS.

Based on the literature review, a model is presented in Figure 7.1 demonstrating the general flow of information in the context of New Zealand's VEWS. Data are received by the GeoNet monitoring project and interpreted by staff at GNS Science, with input from university scientists during a crisis. Volcanic phenomena may also be observed by the public/media and stakeholders. In the early stages of an eruption, the activity may be automatically detected and a rapid warning disseminated to relevant stakeholders, the public, and GNS Science (this capability is only available at Ruapehu and Tongariro at this stage). On receipt of monitoring data and automated warnings, GNS Science duty staff interpret the data, and if the interpretation is deemed significant, they disseminate information to the public/media, and directly to stakeholders. These warnings may be in the form of VALs and VABs, which are communicated to the public/media, stakeholders, and through the NWS. Other formats of information are also communicated, as described in Chapters 2 and 4. GNS Science staff may also directly talk to MCDEM staff, who manage the NWS. The NWS disseminates VABs (containing VALs) to a wider range of stakeholders, which are sent on to the public/media. Double-ended arrows between two groups in Figure 7.1 indicate the dissemination and receipt of information from both parties.

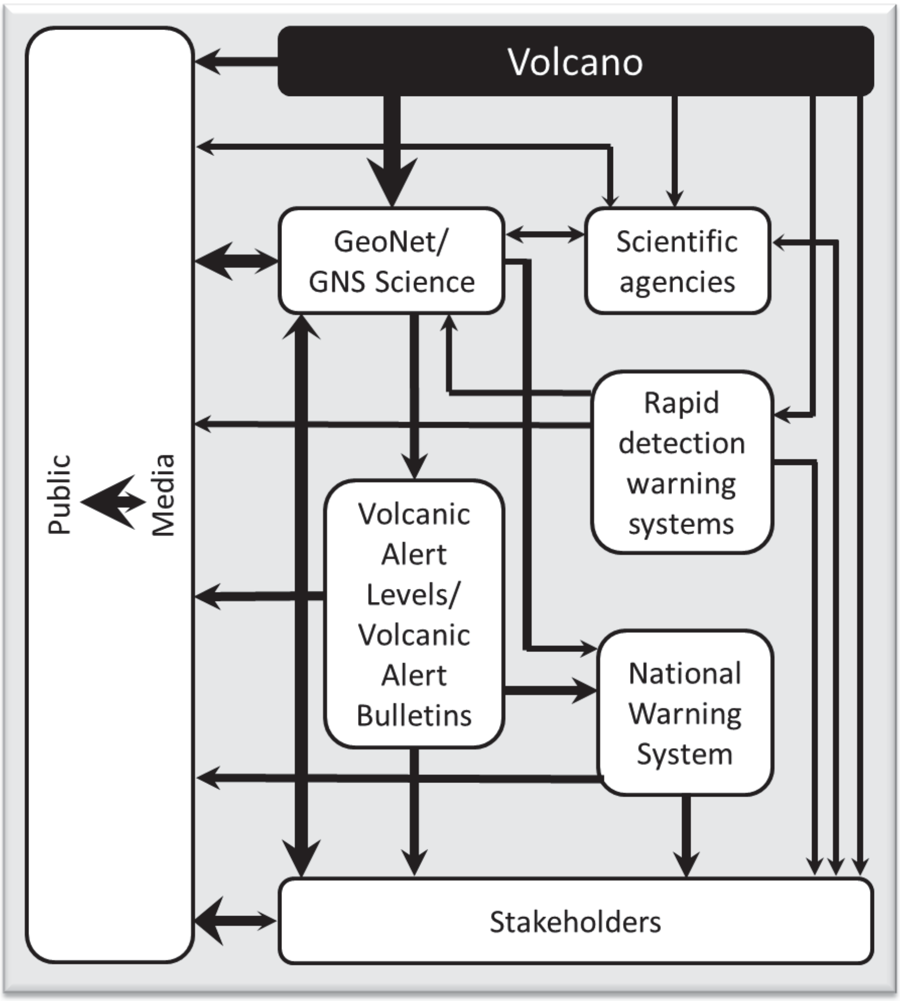

Figure 7.1. The flow of information within New Zealand's Volcano Early Warning System. The size of the lines and arrows gives an approximate indication of the relative amount of information communicated.

An integrated overview of New Zealand's VEWS, including emergency management aspects, the history of MCDEM, the CDEM structure, and the history of GNS Science relating to volcano monitoring, (i.e. New Zealand's VEWS) has not previously been published. Therefore Chapter 2 and Figure 7.1 provide this information in one place for future use as needed. Leonard et al.'s (2008) model (Figure 1.2 in Chapter 1) focuses on the development of a generic EWS largely from an emergency management point of view. As such, it does not distinguish between different organisations, and does not address the flow of information specifically for a volcano context, as is the focus of Figure 7.1.

7.2.2 Research aim 2

Research aim 2 is to *"Explore New Zealand's VAL system, and how it is used"*. The specific research questions guiding this aim are:

a) What are the opinions of the research participants of New Zealand's VAL system?
b) What is the purpose of the VAL system?
c) How is the VAL system in New Zealand currently used by scientists and end-users?
d) What are the decisions involved in a VEWS?
e) What are the influences on the decision to determine the VAL?

Using the methodology outlined in Chapter 3, Chapter 4 presents the results of research into New Zealand's VAL system, which relate directly to this second aim. Themes 1 to 4, as identified in Chapter 4, relate to this research aim. Various volcano-specific information sources that are available and used by end-users are identified, the relationship between end-users and the VAL system is explored, and the participants' beliefs relating to the content and structure of the current system are described. By examining each of these factors, the findings presented and discussed in Chapter 4 provide a detailed exploration of New Zealand's VAL system.

7.2.2.1 Exploring New Zealand's VAL system

Many aspects of the exploration of New Zealand's VAL system, including the identification of specific information sources that are available, and analysis of the content and structure of the VAL system, are specific to the New Zealand context. As such, the findings are limited in their potential for application to other countries, cultures, and systems. However, the methodology used to explore VAL systems in this research may be applicable to other countries. If utilised, the development of systems suitable for the requirements of those other settings will result.

The importance of considering the local context in VEWSs was also recognised by Fearnley (2011).

7.2.2.2 The purpose of the VAL system

The purpose of New Zealand's current VAL system was identified in Chapter 4 as 'a communication tool used by the scientists at GNS Science to enable end-users to quickly understand the current state of activity at the volcanoes, from which they can decide their response'. This has similarities to the goals of the USGS VAL system, which were described by Gardner and Guffanti (2006, p. 1) as to:

1) "communicate a volcano's status clearly to nonvolcanologists (sic)
2) help emergency-response organizations determine proper mitigation measures
3) prompt people and businesses at risk to seek additional information and take appropriate actions".

The "Volcano Traffic Light Alert System" (VTLAS) used at Popocatépetl volcano, Mexico, was described as needing to be capable of "distributing critical information among a large population in a short time, and contain enough clear information to mitigate as much as possible any potential loss, through the reduction of uncoordinated response and panic" (De la Cruz-Reyna & Tilling, 2008, p. 133). As can be seen from this phrasing, the VTLAS system is focussed on response and mitigation of risk, rather than the communication of volcanic activity, which is different to the wishes of the participants in this New Zealand-based research.

7.2.2.3 How is the VAL system used?

End-users placed reasonably low emphasis on New Zealand's VAL system and high importance on person-to-person communication with scientists. The importance of person-to-person communication, especially to discuss information with high levels of uncertainty, was also recognised by Fearnley (2011). Another finding of this research which supports that found by Fearnley (2011, 2013) is the recognition of the VAL system and international ACC as linear scales. This is despite the complex, uncertain context of warning systems. Some end-user participants stated that they wanted to include three levels of eruptions in the new VAL system. This apparently enables a linear interpretation of the system by the public, for example to position the relative level of minor eruptions compared to potential larger-scale eruptions. It was a somewhat surprising finding of my research that scientists in New Zealand constructed new meanings of ACC levels, which do not necessarily match the meanings of the words written in the table.

7.2.2.4 Decision-making in EWSs

There are similarities in the decisions made by many organisational roles involved in a volcanic crisis. For example, scientists, stakeholders, and the public need to interpret information received and determine the threat or risk before responding (e.g., Eiser et al., 2012; as indicated in Figure 7.2). Scientists generally integrate and interpret volcano monitoring data to understand the level of hazard, or in some cases, the risk (such as the likelihood of a hazardous eruption occurring). Monitoring networks may be enhanced if the level of hazard is perceived as high, in order to obtain more data. Scientists decide whether to alert stakeholders and the public, and in what format, and may ‘informally’ communicate information to stakeholders instead of, or as well as, disseminating official alerts. The informal communication link between roles in a warning system is important to tie together the community-based and official systems (Sorensen & Gersmehl, 1980). Stakeholders interpret the scientific information, as well as any natural warnings received directly from the volcano (such as felt earthquakes, or witnessing an eruption) to ascertain the risk to society. Their determination of protective actions, including whether to disseminate an official warning, is based on this information and may also be influenced by actions taken by other stakeholders (e.g., personnel with similar roles in neighbouring areas). The public must hear, understand, believe, and personalise the scientific, official (CDEM/MCDEM), and natural warnings (Mileti & Sorensen, 1990). They must then determine whether to undertake protective action, and in what form, and often actively seek confirmation (Mileti & Sorensen, 1990). These processes are summarised into ‘Public interpretation of risk’ and ‘Determination of protective action’ in Figure 7.2 for simplicity.

Figure 7.2 is a conceptual model that includes many of the findings of this thesis. It develops the model of organisational decision-making points in an EWS that was presented by Sorensen and Mileti (1987; Figure 1.3 of this thesis), in a New Zealand context. It does not represent actions taken, nor does it represent the flow of information during a crisis. The model contains only major decision-making points, and is based on a volcanic crisis. Many other influences on every one of the decisions in this model exist, which are not included here for sake of simplicity.

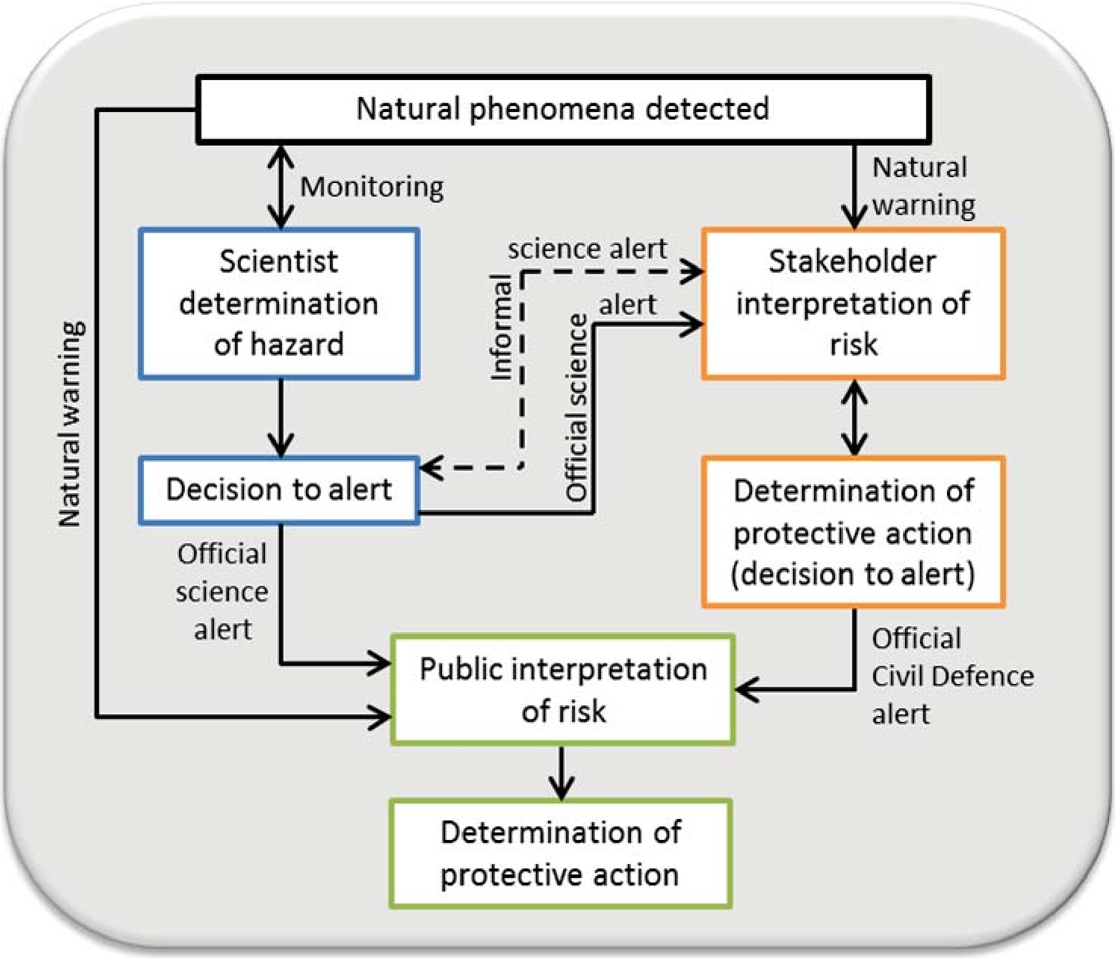

Figure 7.2. Decision-making points in an Early Warning System (EWS), reflecting the findings of this thesis. Adapted from Sorensen and Mileti (1987, p. 38), based on a volcanic crisis in New Zealand. The colour of the boxes reflects the different sectors of the EWS; blue = scientists, orange = stakeholders, and green = public.

As with Sorensen and Mileti's (1987) EWS decision-making model, Figure 7.2 indicates that the number and type of people or organisations involved in the system affects the time it takes to complete the process, as well as affecting the outcome. There are uncertainties at every decision-making point (for example, scientists distinguishing between 'background' activity and 'unrest'), and every process in between. There are also uncertainties associated with every decision-maker at an individual level (such as interpreting the meaning of the VALs), particularly as demands and stress increase during an emergency (e.g., Paton & Flin, 1999). Planning for a crisis can reduce some of the uncertainties (Sorensen & Mileti, 1987).

Clearly defined roles and responsibilities between scientists and stakeholders is an important issue (e.g., Hill, 1998; Marzocchi et al., 2012), as demonstrated by the L'Aquila trial (Cartlidge, 2011). This distinction is not discernible in most system-based EWS models, which combine scientists, stakeholders, and the public into integrated elements (e.g., the 'monitoring and warning' service subsystem of the UN/ISDR PPEW model (2006, p. 2; figure 1.1), the 'management subsystem' of Mileti and Sorensen's model (1990, p. 2.4), the 'formulation of warnings' and decision-based box in Twigg's model (2004, p. 31), and the 'volcanic crisis management' subsystem in Fearnley's model (2011, p. 252), among others). The distinction between roles could be made in EWS models, as has been done in Figure 7.2.

In some countries, such as Mexico, Japan, and Spain, science-based information relating to a volcano's activity is communicated to the Civil Protection agency, who interpret it and allocate a VAL for dissemination to the public (e.g., De la Cruz-Reyna & Tilling, 2008). The VAL, therefore, contains information relating to actions that should be taken by the public, i.e. evacuation, and is not directly based on levels of volcanic activity. This is different to the New Zealand and U.S. systems, where scientists communicate VALs directly to the public, as well as consulting with responding agencies that disseminate response advice. The pros and cons of each approach could be an avenue of future research, and are likely to vary according to the cultural context.

7.2.2.5 Influences on the VAL decision-making process

As part of the review of New Zealand's VAL system, influences on scientists during the determination of VALs were also identified in Chapter 4, and are summarised in section 4.7.4. Some of these influences have previously been identified in the literature. For example, the influence of monitoring data on the VAL decision was identified by Fearnley (2013), while Sorensen and Mileti (1987) recognised the ability to interpret an event as a source of uncertainty in their research on how organisations with a role in warning systems undertake decision-making. In particular, processes involved in interpreting the event include recognising the threat and the hazard (as identified in the previous section), and identifying the relevant information (e.g., spending adequate time on effective communication; Sorensen & Mileti, 1987). The experience and knowledge (or 'gut feeling') of the decision-making scientists was also identified as an influence by Fearnley (2013). Sorensen and Mileti (1987) found that the outcome of previous experiences by decision-makers can influence their decisions (e.g., whether past events turned out to be 'false alarms' or resulted in many deaths). This is an interesting finding, and one that could be an avenue of future research within the volcanic context.

The desire to maintain credibility was found to be an important influence on VAL determination by Fearnley (2013). If a decision turns out to be 'wrong', there can also be a perceived threat to personal credibility (Sorensen & Mileti, 1987). Fearnley (2011, 2013) found that risk has been implicitly incorporated into the VAL decision in the U.S., and calls for the consideration of a more formal acknowledgement of the role of risk in the system.

The identification of the potential impacts of a change in VAL as an influence on the VAL decision supports the finding by Fearnley (2013), who places the impacts as being in a local societal, political, and environmental context. In a more general EWS decision-making context, Sorensen and Mileti (1987) also found the perceived impacts of the warning (including misconstrued perceptions that people will panic; homes will be looted; and if it is a false alarm, people will not follow warnings in the future) are points of uncertainty in warning systems. Additionally, fear of liability as a result of the impacts of the warning (or consequences if no warning is issued) may influence decisions (Sorensen & Mileti, 1987).

Fearnley's (2013) research identified the influences of economic drivers (internal to USGS and external agencies/industries), which may be similar to the internal and external organisational pressure found in my New Zealand-based VAL research. Sorensen and Mileti (1987) also found outside expectations were a source of decision-making uncertainty. Fearnley (2013) identified institutional dynamics (protocols and procedures), and the association between 'type of volcanic activity occurring' and associated strategies for VAL movement, as influences.

Factors relating to VAL decision-making that were identified in my research which were not evident in Fearnley's (2011, 2013) research are peer influence and potential social psychology biases on group decisions, specific factors contributing towards the desire to maintain credibility, the interpretation of the VAL system by voting scientists as a guideline or as a prescription, specific factors relating to interpretation of the content of the system, the perceived purpose of the system, and fieldwork intentions. There are many other influences on decision-making that have been identified in the literature, including those relating to hazards, risk, and emergency response situations (e.g., Janis, 1982; Flin, 1996; Paton et al., 1999; Huber et al., 2009; Hastie & Dawes, 2010; Eiser et al., 2012; Lindell & Perry, 2012), that could be explored in the New Zealand volcano-context in future research. A specific example is the influence on decision-making in EWSs of the duration of time between the detection of a hazard and when the effects occur, as this can rush or delay decisions, as identified by Sorensen and Mileti (1987). This was not specifically identified as an influence by the participants in my research, except as an influencing factor on the desire to maintain credibility. However, it seems likely that this is also a relevant influence on New Zealand's VAL decision-making process.

7.2.3 Research aim 3

Research aim 3 is *"Identify ways to make New Zealand's VAL system more effective"*, guided by the research questions:

a) Which aspects (if any) of New Zealand's VAL system can be improved, and how?
b) What are possible foundations of VAL systems?

These aims are addressed in Chapter 4, particularly relating to 'Theme 5' of the VAL research. Recommendations for changes have been detailed and summarised in section 4.7, so are not repeated here. Many are specific to New Zealand's VAL system (particularly the recommendations relating to the review of the current VAL system), in accordance with the requirements of the end-users and scientists. Aspects that are able to be compared and contrasted to existing global literature, and potentially transferred to other countries are, however, addressed below.

7.2.3.1 Recommended changes to New Zealand's VAL system

Transferable recommendations described in section 4.7 are related to the literature and discussed further in this section.

- Increased person-to-person communication: as mentioned under research aim 2, an emphasis on person-to-person communication and the use of other informal channels is supported by others in the literature, including Fearnley (2011), and Sorensen and Gersmehl (1980).
- Regular dissemination of information, regardless of the uncertainty: this recommendation supports the findings of previous authors (e.g., Mileti & Sorensen, 1990; Paton et al., 1999; Ronan et al., 2000; Fearnley, 2011).
- The meanings of levels in the Aviation Colour Code (ACC) based on the wording in the table: in order for this international standardised system to be consistently used (and

therefore effectively responded to), future research is recommended investigating constructed meanings, and the use of this system globally.

- Use of the ACC for determining aviation hazard zones: future research could look at how aviation hazard zones are created globally, and if there is a consistent approach at a national level. This will most likely need to be in collaboration with Civil Aviation Authorities.
- Removing the ACC from the public arena: consideration on whether the ACC should be made available to the public, or should just be communicated to the aviation industry could be made, to avoid confusion over multiple alert level systems. This is an open question for both New Zealand and other nations, and may require further research into global practices.
- Flexibility needed between end-user actions and VALs: this recommendation supports the findings from the Exercise Ruaumoko assessment report that an effective balance is needed between pre-event arrangements and event-specific plans (MCDEM, 2008).
- The new VAL system should be kept clear and unambiguous: this is supported by the general communication guidelines described by Mileti and Sorensen (1990), Newhall (2000), Sorensen (2000), and De la Cruz-Reyna and Tilling (2008). Fearnley's (2011, p. 256; Table 7.1) recommended three colour 'Awareness Level' is very simple, but may be too ambiguous as it requires supporting information.

Table 7.1. Example hazard awareness scale, as recommended by Fearnley (2011, p. 256).

Awareness Level	Meaning
Red	Urgent
Orange	Important
Green	Of Interest

- Recommendations relating to the VAL structure and content that may be transferrable to the development of other VAL systems are reordering the levels to go from the highest level at the top to the lowest level at the bottom (as is used in the Japanese VAL system[42]); using numbers or words to label the levels to avoid confusion with colour-based hazard maps; and avoiding technical jargon in VAL systems.

[42] http://www.seisvol.kishou.go.jp/tokyo/STOCK/kaisetsu/English/level.html, accessed 24 November 2013

- Undertake regular exercises and record experiences: these recommendations and success stories are commonly expressed in the literature (e.g., Blong & McKee, 1995; Sorensen, 2000; Leonard et al., 2008; Bird et al., 2010; Lindsay et al., 2010). The need for exercises is also described by the Hyogo Framework for Action (UN/ISDR, 2005); UN/ISDR PPEW (2006), specifically relating to the 'response capability' element of an EWS; and MCDEM (2009), which also contains guidelines on preparing exercises for the CDEM sector in New Zealand.
- Social psychology biases on individual and group decision-makers: little has been mentioned in the volcanological literature relating to psychological influences and biases on decision-making in this context, including the effects of question phrasing and voting styles; these would benefit from future research, drawing upon findings in related disciplines (e.g., Stoner, 1961; Tversky & Kahneman, 1974; Paton et al., 1999; Baddeley et al., 2004; Larrick, 2004).

The recommended and draft new VAL systems presented in Chapter 4 (Table 4.10 and Figure 4.11) integrate both current VAL systems (i.e. for frequently active volcanoes and reawakening volcanoes) used in New Zealand into one, which is intended to be applied to all volcanoes. This is despite the wide range in potential eruption magnitude, style, and frequency; magma chemistry; tectonic setting; risk setting; and period of quiescence existing at volcanoes in New Zealand. Standardisation of VAL systems into one common system was investigated by Fearnley et al. (2012), who used the USGS system as a case study. They emphasised the role of the local context in VAL systems, particularly for variances in hazards, institutional practices, and social settings. They stated that a standardised VAL system can successfully operate if the communication product is effectively developed and utilised. This supports the integration of New Zealand's current two VAL systems into one for all volcanoes (in addition to the ACC). New Zealand's social and geographical setting is different to the US, where Fearnley et al.'s (2012) study was based. For example, the people involved in a volcanic crisis in New Zealand will often be the same, regardless of which volcano is exhibiting signs of activity, unlike in the U.S. The integrated, complex, and dynamic nature of hazards and effected communities (as described by Eiser et al., 2012) further supports having one standard VAL system. Additionally, there is only one 'volcano observatory', at Wairakei Research Centre (GNS Science), and therefore the same scientists are involved in the VAL decision. These factors allow a consistent use of the system, even if the volcanoes that are active change. This is opposed to the different groups of scientists and end-users involved in volcanic responses across the much larger U.S.

The recommendation to include hazard information into the new VAL system for New Zealand allows the potential impacts of the volcanic phenomena observed to be more easily understood by end-users – i.e., 'what does it mean for them?' It is a step closer to providing information specific to the consequences of an event, without confusing the roles and responsibilities of the various agencies. A number of VAL systems internationally include hazard information. For example, the VAL system for Popocatépetl, Mexico, includes 'expected scenarios' which are focussed on hazards (De la Cruz-Reyna & Tilling, 2008). The Japanese VAL system includes information relating to threat to life and response advice (Japan Meteorological Agency website[43]), as does the VAL system used by the Montserrat Volcano Observatory (as stated on their website[44]). The Philippines has different VAL systems for each volcano, some of which have more specific hazard information than others (PHIVOLCS website[45]). These examples demonstrate the inclusion of hazard information in a VAL system is not a new practice, globally.

It is recommended in Chapter 4 that forecasts of volcanic activity be made explicit and easy to understand in VABs and in other methods of communication. They could incorporate analogies, context, and comparative language, with careful consideration of risk language used, to ensure consistent interpretation. This supports the findings and recommendations given by Siegrist (1997), Newhall and Hoblitt (2002), Doyle et al. (2011), and others.

7.2.3.2 Foundations of VAL systems

This research identified a number of potential foundations on which to develop a VAL system. These are:

- Phenomena-based
- Hazard-based
- Process-based
- Risk-based
- Multi-foundation.

The recognition of these various foundations is not evident in the previously published literature. One of the implications of recognising these foundations is the ability to consciously

[43] http://www.seisvol.kishou.go.jp/tokyo/STOCK/kaisetsu/English/level.html, accessed 24 November 2013
[44] http://www.mvo.ms/about-volcanoes/safety/hazard-level-system, accessed 24 November 2013
[45] http://www.phivolcs.dost.gov.ph, accessed 24 November 2013

determine what the foundation of future VAL systems should be. Each type of foundation has advantages and disadvantages, as explored in section 4.6.1. As scientific knowledge, risk communication, and the understanding of relative risk amongst end-users develop, there may be a shift in preference towards risk-based foundations of VAL systems. However, physical scientists may not wish to stray outside their area of training by considering societal elements of risk (e.g., Marzocchi et al., 2012).

Some countries have alternative foundations of their VAL systems, which were not suggested by participants in the New Zealand context. For example, the Japanese VAL system[46] may be considered to have a response action-foundation. This system has five levels, labelled 1 = Normal, 2 = Do not approach the crater, 3 = Do not approach the volcano, 4 = Prepare to evacuate, and 5 = Evacuate. Other columns provide information relating to areas impacted, etc., but the levels in the system seem to be divided by recommended response actions. Further foundations of VAL systems not identified by the participants in the present research may be recognised in the future.

As described in section 4.6.3, the inclusion of forecasting language in VAL systems needs to be carefully considered. Some systems, such as the recommended VAL system presented in this research, intentionally do not incorporate forecasting language. That is, some systems are designed to state only the level of current volcanic phenomena that is observed, not what activity may be observed within a specified timeframe. The reasons for this are described in section 4.6.3, the main one being to reduce the threat to the scientists' credibility, which enables trust from the public and end-users to be maintained without fear of 'false alarms'. Forecasting language can still be disseminated in supplementary information sources (e.g., VABs), tailored to specific situations.

It is important to regularly review components of EWSs, including VALs, particularly as scientific knowledge increases. It is hoped that research in the future will review the effectiveness of New Zealand's other volcanic communication tools (particularly the VAB), as well as the recommended new VAL system after it has been in use for a few years (or earlier if need be).

[46] http://www.seisvol.kishou.go.jp/tokyo/STOCK/kaisetsu/English/level.html, accessed 24 November 2013

7.2.4 Research aim 4

"Document the intensity and frequency of historical caldera unrest episodes at TVC" is aim four of this research, with a specific research question of 'how frequently and at what intensity has TVC exhibited caldera unrest during historical times?' This aim is addressed in Chapter 6, which summarises the detailed caldera unrest catalogue produced during this research, indicates the recurrence rate, and compares the frequency and intensity of unrest to calderas globally.

Based on its historical record, future episodes of unrest at TVC are very likely to occur. Impacts of unrest that may occur include threatening exploited geothermal fields and hydropower structures on the Waikato River (Lake Taupo's outlet), especially if faulting and/or subsidence were to occur near the head of the river, causing increased (or decreased) river flow. Society's increasing reliance on electricity and rapid telecommunication (especially the internet and social media) results in higher vulnerability and may reduce the control of rumours during future caldera unrest episodes. A continuing decrease in the costs relating to travel is likely to result in a higher transient population in tourist towns such as Taupo, who require their needs to be met in a volcanic crisis. There are no detailed emergency management plans yet created, there has been little progress in development of integrated contingency plans for limiting socio-economic impacts of unrest, and no scientific decision-making structures (e.g., BETs) have been set up to match the complexity of a caldera unrest event at TVC. Therefore, there is a significant need for development in these fields. This is especially the case given the high frequency of caldera unrest episodes identified in this research.

7.2.5 Research aim 5

Research aim 5 is to *"Ascertain the point at which the background level of multi-parameter activity at TVC becomes considered as volcanic unrest, using a method which can be applied to any volcano and tectonic setting"*. The specific questions guiding the research relating to this aim are:

a) What constitutes volcanic 'unrest'?
b) How can the intensity of complex, multi-parameter volcanic unrest episodes easily be compared and communicated to non-scientists as a basis for their decision-making?

The wide range in intensity of volcanic unrest was evident following the creation of the wider dataset of activity at TVC. Ascertaining the threshold at which background activity is considered as unrest was recognised as important for the decision to determine the VAL. The variable existing definitions of volcanic unrest in the literature were addressed in Chapter 5. A new definition of volcanic unrest was created in that chapter, through the development of the VUI. The framework of the VUI, and subsequently the definition of unrest, is transferrable to any volcano and tectonic setting, allowing a consistent, yet flexible comparison of unrest intensity to be made between volcanoes, and at a single volcano over time. It is an integrated system for standardisation between volcanoes, yet allows the inclusion of local context. This follows recommendations by Fearnley (2011) and Fearnley et al. (2012) on standardisation of systems, particularly relating to a volcanic context.

The VUI was estimated for the TVC historical unrest catalogue in Chapter 6, which demonstrated the process and function of the VUI. This allowed the point at which background activity is considered as unrest to be identified, i.e. any combination of volcanic phenomena which equate to VUI ≥ 3 using the VUI framework, fulfilling this research aim. By using the VUI in the future, multi-parameter activity can easily be compared to previous unrest episodes, and to those that occurred at analogous volcanoes in other settings. Moreover, the information can be communicated very easily to end-users, such as by using a simple time-series plot of the VUI at a particular volcano (see Figure 6.4 for an example at TVC). The VUI for TVC has been communicated to the end-users of the New Zealand Caldera Advisory Group in this way, as well as in a number of conferences over the duration of this research, with positive feedback.

During the discussion in Chapter 5 on the concept of unrest, it was identified that defining unrest for the purposes of warnings and communication to end-users may require a different approach to that commonly used in the scientific literature. For example, to enable individual levels within a VAL system to be comparable to each other across different volcanoes, unrest may need to be defined in a broader sense than a definition relative to the ‘typical’ activity at each volcano. Further research needs to address this, including whether consistent thresholds in the VUI framework need to be developed in order to provide a definition of unrest for the purposes of warnings and comparable VALs, and repeatable VAL decisions. As identified in this research, the repeatability of VAL decisions relates to the desire for scientists to maintain credibility, and is an influence on VAL decision-making (see section 4.5.4).

7.3 Addressing the guiding research question

The guiding research question stated at the beginning of this thesis is addressed in this section, integrating the findings of the research aims addressed above. That is, *When a caldera volcano starts showing signs of unrest, at what point should the Volcanic Alert Level be raised?*

The first step in addressing this research question was exploring New Zealand's VAL system. Its role in communicating volcano information has been recognised, and recommendations given about how the system can be improved. The intended point at which the VAL for reawakening volcanoes is raised from 0 to 1 was identified to be when the activity passes through a threshold between 'background' activity to 'unrest', according to the current VAL system (Table 2.4). However, there is a high level of uncertainty over exactly what intensity of activity this threshold between background activity and unrest is. Moreover, the potential socio-economic impacts which are likely to occur as a result of unrest at a large caldera volcano, and the recognition of that unrest by changing the VAL, are thought to influence the decision which determines the VAL (as discussed in Chapter 4).

In order to define unrest, TVC was used as an example to determine relative intensities of activity. A historical catalogue of activity was produced for TVC during this research and is presented in Chapter 6. A new VUI framework was developed to integrate unrest parameters of seismicity, deformation, geothermal system changes, and degassing, and simplify the relative intensity of unrest activity into one number. The VUI was estimated for the entire historical catalogue of activity at TVC, enabling a threshold to be identified between background activity and unrest (i.e., VUI ≥3). This threshold provides a definition of unrest for TVC, which can contribute towards the decision to change the VAL, along with consideration of factors in the social, environmental, economic, and political contexts.

As an example, the VUI for the 2008 episode of activity at TVC was calculated in Chapter 6 to be 3. This indicates that it was an episode of minor unrest (i.e., above the level of background activity). According to the definition of the VAL system currently used, the VAL for reawakening volcanoes could have been raised for this volcano from 0 to 1.

However, the effects of potential socio-economic impacts resulting from raising the VAL remain. The most recent episode of unrest to be classified as VUI 4 (moderate unrest) occurred in 1983–84. The reported societal impact experienced by the local community during this episode was relatively minor, with only slight damage caused by the earthquakes. This indicates that future episodes of unrest with a moderate intensity may occur without large-scale socio-economic impacts. The extent of the socio-economic impact is likely to be dependent on the type of unrest phenomena that occur within an episode. If the unrest goes largely unnoticed by the public, or is not perceived to be linked to the volcano, the impact resulting from a change in the VAL may in fact be greater on the community than the impact caused by the physical unrest phenomena.

Societal influences and the consideration of risk may contribute towards a delay in raising the VAL (or of the communication of other types of volcano warnings) at caldera volcanoes such as TVC in the future. Scientists who make the decision to change the VAL may wait to raise the VAL until volcanic unrest is at a heightened level, and/or there is evidence of magmatic input at the volcano, which would decrease uncertainty over the future course of events. This delay would potentially decrease the likelihood of a 'false alarm', and therefore minimise the threat to the credibility of the scientists, and also reduce the threat of an unnecessary negative impact on society. However, it might also result in a community that is unprepared to respond to caldera unrest crises, and potentially has less time to prepare for an eruption. This complex situation highlights the inherently integrated nature of physical and social sciences, and the importance of transdisciplinary perspectives in decision-making and the development of policy and practice.

7.4 Future research directions

The findings of this research encourage a number of areas for future investigation, as mentioned throughout the thesis. These are briefly outlined and added to in this section.

- Further investigation of the international use and interpretation of the ACC would develop an understanding of the consistency of its use and effectiveness as a global system.
- The regular review of communication tools within VEWSs, with involvement of end-users, and including an evaluation of their effectiveness, would ensure confidence that the best system possible is being used, contributing towards an effective response.
- Exploring the social psychological aspects and biases on individual and group decision-making in a volcanology context would be interesting, with the aim of reducing negative or extraneous impacts on the decision-making processes. Other influences could also be investigated, for example, whether previous experiences of volcanologists impact their VAL decision-making (as identified by Sorensen & Mileti, 1987, in other contexts).

- Research the use of words (and potentially symbols) as labels in warning systems and scales, particularly preconceived interpretations of words, to find appropriate labels for future communication tools.
- Explore different volcanic crises management structures globally, comparing relationships between scientific and response (particularly government-based) agencies. This is particularly regarding the communication of scientific information and response advice, relating to roles and responsibilities, and taking into account the local context.
- Using the catalogue of unrest at TVC presented in this thesis, investigate unrest episodes identified in this research (and potentially episodes classified as VUI 2) in more detail. This might include searching historical data as it becomes available (e.g., added to searchable online databases), and interpreting the data to establish the involvement of magma where possible, and focusing on socio-economic impacts of caldera unrest in more depth.
- Investigate the history of unrest at all of New Zealand's volcanoes using an historical chronology methodology and the VUI to contribute toward risk assessments, and provide background knowledge for future unrest and eruption crises. This information should be communicated to end-users.
- Estimate the VUI for volcanoes globally to further test the framework and compare unrest intensities. Undertake analyses on relationships relating to unrest, for example between unrest intensity and characteristics of eruptions. Examine the effect of different time periods used when estimating the VUI, and the possibility of using comparable parameter thresholds.
- Investigate the potential for probabilities to be used in conjunction with the VUI.
- Explore aspects relating to the inclusion of forecasting using probabilities in VAL systems. This may reduce the threat to scientists credibility while allowing useful forecasting information to be disseminated.

The recommended VAL system presented in this thesis is in the process of being adopted for New Zealand. It will be incorporated into an updated version of the Guide to the National CDEM Plan (MCDEM, 2006) in July 2014, and integrated into New Zealand's society using a communication strategy.

7.5 Summary

The focus of this research has been on investigating aspects relating to changing the Volcanic Alert Level (VAL) at a caldera volcano when it shows signs of unrest. In this thesis, New Zealand's Volcano Early Warning System (VEWS) has been described; the existing VAL system was explored and a new system developed; a catalogue of historical caldera unrest at Taupo Volcanic Centre (TVC, New Zealand) has been compiled; and a new Volcanic Unrest Index (VUI) has been presented, which defines and quantifies the intensity of unrest at any volcano. These steps are summarised below.

A description of New Zealand's volcanoes and VEWS is presented in Chapter 2. Potential physical and socio-economic impacts of caldera unrest are outlined based on episodes experienced internationally. The flow of volcano information in New Zealand is summarised in Figure 7.1, and major decision-making points within a volcanic crisis are identified (Figure 7.2). This sets the context for exploring New Zealand's VAL system.

A VAL system is a tool used in many countries to communicate the status of volcanic activity to the public and other end-users. A qualitative ethnographic methodology was used to explore New Zealand's existing system, involving interviews with scientists and end-users of the system; observations of GNS Science volcanologists for three years, including while they were determining VALs during multiple unrest and eruption crises; and analysis of documents, such as communication products. The resulting data were analysed through coding and thematic analysis. These methods, which are described for the first time globally for the development of a new VAL system, may be applicable for use in other volcanic regions, and are described in Chapter 3.

Based on the findings (presented in Chapter 4), changes to the existing VAL system and its use have been recommended (e.g., Table 4.10). The purpose of New Zealand's VAL system was identified to be a communication tool used by the scientists at GNS Science to enable end-users to quickly understand the current state of activity at the volcanoes, from which they can decide their response. In addition to using the VAL system, high emphasis is placed on person-to-person communication by end-users.

Many factors were identified as influences on the determination of a VAL, including monitoring data and interpretation, experience and knowledge, group influences, the desire to maintain credibility, the use of the VAL table by scientists as a guideline or as a prescription, the interpretation of the VAL content, perceptions of end-user actions and societal impacts associated with VAL changes, incorporation of a hazard or risk perspective, use of the system with a sense of forecasting, internal and external organisational pressure, the perceived purpose of the VAL system, and scientists' fieldwork intentions. Some of these influences have previously been identified in the literature for VAL decision-making, while others were identified in the present research for the first time.

The foundation of a VAL system was identified as an important aspect when developing a new system. The foundation is essentially what category or theme is used to determine the divisions between the levels. Potential foundations of VAL systems were identified in this research for the first time, including phenomena-based, hazard-based, process-based, risk-based, and combinations of these ('multi-foundation'). Other foundations may also exist that are used internationally, such as those based on response actions. Built on feedback from research participants, the VAL system recommended for New Zealand is phenomena-based, and also includes hazard information (Table 4.10), and a new system has been developed for New Zealand (Figure 4.11).

The social construct of dividing continuous activity into separate categories representing 'background' activity and 'unrest' aids communication, but creates difficulties in practice. To assist with distinguishing 'unrest' from 'background' activity at volcanoes, the Volcanic Unrest Index (VUI) was developed in this research (described in Chapter 5). The VUI can be estimated for any type of volcano, using qualitative or quantitative data from a range of monitoring capabilities. The data are applied to a multi-parameter framework, which is presented in Figure 5.1. The VUI enables a comparison of the intensity of unrest over long periods of time, providing a simple means to communicate complex information to end-users.

The VUI is demonstrated using an example of unrest prior to the 1995–96 eruptions at Ruapehu (in Chapter 5), and the historical catalogue of unrest for TVC (presented in Chapter 6). The catalogue was created using a historical chronology methodology, spanning from 1872 to 31 December 2011, and included all intensities of activity. The VUI was then estimated for the entire catalogue and 16 episodes of unrest (≥VUI 3) were identified, including ten that had not previously been recognised in the literature. The unrest episodes occurred in 1877–78, 1880, 1895, 1897, 1922–23, 1961, 1964, 1964–65, 1974, February 1975, December 1975, 1983–84, 1984–85, 1996–99, 1999–2001, and 2008–10. The median recurrence rate is one episode of unrest every nine years, and the median duration of the unrest episodes is just under five months. Many of these episodes caused socio-economic impacts at a local and regional level.

Changing the VAL from zero (“usual dormant or quiescent state” using the existing VAL system in Table 2.4) to one (“initial signs of possible volcano unrest. No eruption threat”) at a reawakening volcano such as TVC involves many complex factors. As discussed earlier in the present chapter, the VAL for the most recent episode of unrest to date at TVC (in 2008–10) could have been raised to one. However, the potential socio-economic impacts of raising the VAL, the consideration of risk by scientists, and other influences on the determination of the VAL may contribute towards a delay in raising the VAL during future unrest crises. Further transdisciplinary research, including developing and implementing the findings presented in this thesis, will aid future developments in multi-directional communication of volcanic information. The findings of this research contribute towards effectively communicating the status of volcanic activity in New Zealand, particularly with regards to caldera unrest.

APPENDICES

APPENDIX 1: ACRONYMS AND ABBREVIATIONS

Airways	Airways Corporation of New Zealand Ltd
AVF	Auckland Volcanic Field
AVSAG	Auckland Volcanic Science Advisory Group
BET	Bayesian Event Tree
BET_EF	Bayesian Event Tree for Eruption Forecasting
CAA	Civil Aviation Authority
CAG	Caldera Advisory Group
CDEM	Civil Defence and Emergency Management
CIMS	Coordinated Incident Management System
CPVAG	Central Plateau Volcanic Advisory Group
CRI(s)	Crown Research Institute(s)
DoC	Department of Conservation
DSIR	Department of Scientific and Industrial Research
EDM	Electronic Distance Measurement
EDS	Eruption Detection System
EOC	Emergency Operation Centre
EQC	New Zealand Earthquake Commission
ERLAWS	Eastern Ruapehu Lahar Alarm & Warning System
EWS(s)	Early Warning System(s)
GNS Science	Institute of Geological and Nuclear Sciences Limited
GPS	Global Positioning Systems
HOD	Head of the Volcanology Department, GNS Science
IAVW	International Airways Volcano Watch system
ICAO	International Civil Aviation Organisation
IGNS	Institute of Geological and Nuclear Sciences Limited
MCDEM	Ministry of Civil Defence and Emergency Management
MetService	Meteorological Service of New Zealand Ltd
NEID	National Earthquake Information Database
NOTAM	Notice to Airmen
NWS	National Warning System

NZGS	New Zealand Geological Survey
NZV	Volcanic Hazard Zone (for New Zealand volcanoes)
OVC	Okataina Volcanic Centre
PPEW	Platform for the Promotion of Early Warnings
REMA	Regional Emergency Management Advisor
RSAM	Real-Time Seismic Amplitude
SA	Situation Awareness
SAL(s)	Scientific Alert Level(s)
TSVAG	Taranaki Seismic and Volcanic Advisory Group
TVC	Taupo Volcanic Centre
TVZ	Taupo Volcanic Zone
U.S.	The United States of America
UK	The United Kingdom
UN/ISDR	United Nations International Strategy for Disaster Reduction
USGS	U.S. Geological Survey
VAAC	Volcanic Ash Advisory Centre
VAAS	Volcanic Ash Advisory System
VAB(s)	Volcanic Alert Bulletin(s)
VAL(s)	Volcanic Alert Level(s)
VEI	Volcanic Explosivity Index
VEWS(s)	Volcano Early Warning System(s)
VONA	Volcano Observatory Notice for Aviation
VTLAS	Volcano Traffic Light Alert System
VUI	Volcanic Unrest Index

APPENDIX 2: CALDERA UNREST MANAGEMENT SOURCEBOOK

This appendix is published as a GNS Science Report:

Potter, S. H., Scott, B. J., Jolly, G. E. (2012). Caldera unrest management sourcebook. GNS Science Report 2012/12 (pp. 73): GNS Science.

It is also available from: http://www.gns.cri.nz/static/pubs/2012/SR%202012-012.pdf

Caldera Unrest Management Sourcebook

S H Potter
B J Scott
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KEYWORDS

Caldera unrest, volcano, Taupo, Okataina, Tarawera, Reporoa, Kapenga, Whakamaru, Mangakino, Rotorua, Ohakuri, Mayor Island, Raoul Island, Caldera Advisory Group.

EXECUTIVE SUMMARY

CALDERA UNREST MANAGEMENT IN NEW ZEALAND

The largest and most unpredictable of New Zealand's volcanoes are calderas, those which have erupted so explosively that the ground has collapsed to form large craters many kilometres across (such as Taupo and Rotorua volcanoes). These low frequency, high impact eruptions are preceded by geophysical and geochemical signals produced by the volcano as the magma forces its way through the ground, which can be interpreted by scientists to enable forecasting of the most likely future scenarios. The signals, collectively forming volcanic unrest episodes, occur far more frequently than there are eruptions. Volcanic unrest can be dangerous to nearby communities, even if there is no resulting eruption, as seen both in New Zealand and overseas. Caldera unrest can include damaging earthquakes, meters of ground deformation, hydrothermal explosions and poisonous gas emissions.

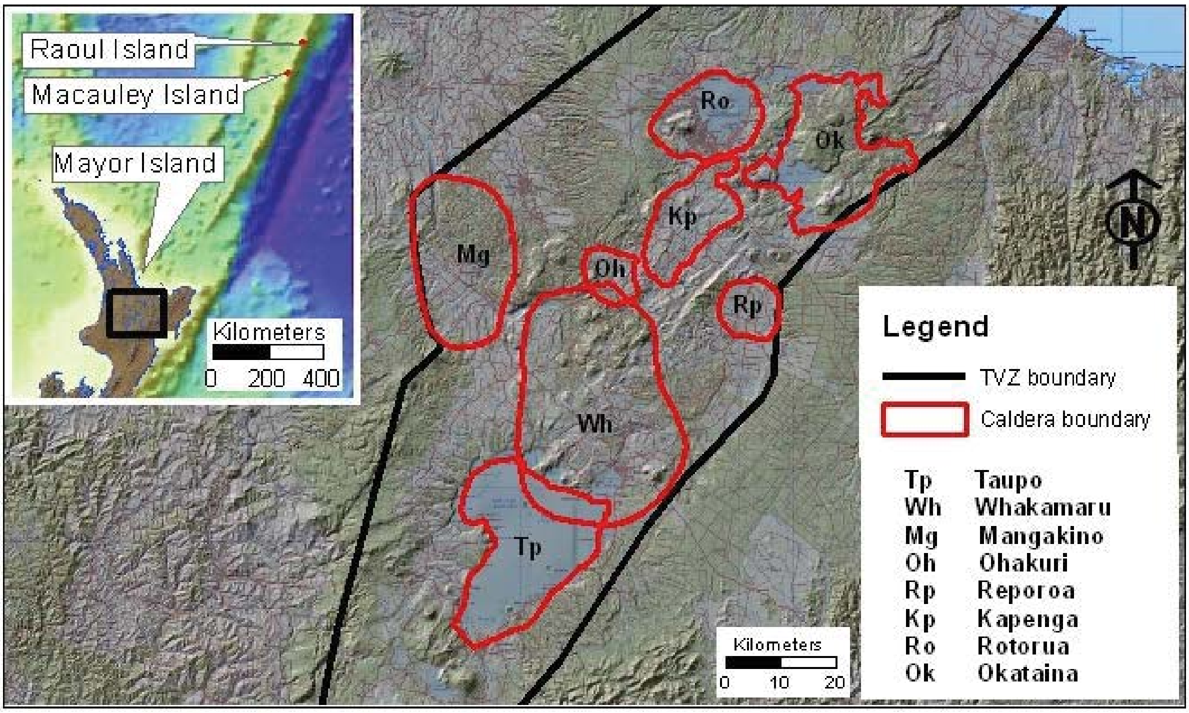

Figure ES1 Map of the eleven calderas in New Zealand.

New Zealand has eleven calderas (Figure ES1), many of which have shown frequent signs of unrest in the past 150 years. Two of these unrest episodes have resulted in eruptions (Tarawera (1886) and Raoul Island (2006)). Unrest has the potential to affect the local and national economies, the tourism industry, infrastructure of national importance, the psychological and physical health of the nearby residents and to undermine the trust between the community, media, emergency management officials and scientists. Caldera unrest episodes can last for days to decades, and must be carefully prepared for to avoid casualties and minimise the impact on society.

The calderas are monitored for signs of activity by GeoNet, an EQC-funded project run by GNS Science (Figure ES2).

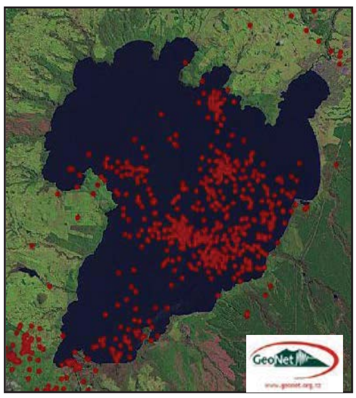

Figure ES2 An example of GeoNet monitoring data: earthquake epicentres at Taupo Caldera, April to September 2008.

Likely consequences of caldera unrest

Physical hazards

- *Ground shaking* from earthquakes (ranging from unnoticeable to damaging)
- *Ground deformation* (uplift and subsidence of millimetres to metres per day)
- *Gas poisoning* (potentially lethal in depressions)
- *Hydrothermal system changes* (including potentially large steam explosions)

Social effects

- *Psychosocial,* including public anxiety from months of earthquakes, and frustration and anger over economic impacts
- *Economic,* including likely impacts on tourism, local and national economies, insurance and investment industries

New Zealand caldera unrest episodes

During historical times New Zealand has experienced eruptions at calderas and numerous relatively small episodes of unrest[1]. We are yet to experience the magnitude of unrest seen internationally, in terms of episode duration and intensity of phenomena. Some examples are given in Table ES1.

Table ES1 Summary of caldera unrest episode examples in New Zealand and overseas.

Caldera name	Date of episode	Seismicity	Deformation	Hydrothermal/ other	Social impact & response	Eruption?
Okataina	1886	Felt seismicity started only about 1 hour before the eruption	No surface deformation is known	No unusual hydrothermal activity was noted. New features formed post eruption.	Unknown impact during unrest; 108 died in eruption	Yes (Tarawera)
Taupo	1895	M6 to 7.5 with 6 weeks of frequent aftershocks felt; liquefaction	Landslips; fissures; unknown if subsidence or uplift	0.6 m tsunami in lake; spring temperature changes	Chimneys collapsed; minor injuries; anxiety; self-evacuations	No
Taupo	1922	Thousands of earthquakes, max M6 over 10 months	Subsidence of 3.7 m at Whakaipo Bay; faulting; liquefaction	Changing hydrothermal activity at Mokai, Orakei Korako, Wairakei	Chimneys collapsed; tourism affected from misreporting; self-evacuations	No
Raoul Island	2006	5 days of earthquakes distant to volcano	No deformation recorded	No unusual hydrothermal changes	One fatality during eruption	Yes (hydro-thermal)
International examples of caldera unrest						
Campi Flegrei (Italy)	1982-1984	Hundreds of felt earthquakes, some large (<M4.2).	3.5 m uplift	Gas concentration increases	40,000 evacuated, damaged buildings	No
Long Valley (U.S.)	1979-1984	Swarms between 1982-4, 3 M6 quakes in 1 day	25 cm uplift in <6 months	No confirmed hydrothermal changes	Anger and frustration; economic & political impact	No

[1] Potter, S. H.; Scott, B. J.; Jolly, G. E. 2012. Caldera Unrest Management Sourcebook, *GNS Science Report* 2012/12. 74 p.

1.0 INTRODUCTION

Many of New Zealand's recently active volcanoes are situated near population centres, including our largest city, Auckland. There is a range in the type of volcanoes in New Zealand, including stratovolcanoes (see glossary at the back of this report for explanations of unfamiliar terms) such as Ruapehu, Tongariro/Ngauruhoe and Taranaki, volcanic fields such as Auckland, and calderas such as Okataina and Taupo (Wilson et al., 2004). Taupo Volcano is regarded as one of the most frequently active rhyolitic caldera systems in the world. The majority of the caldera volcanoes are in the Taupo Volcanic Zone (TVZ) which is located in the centre of the North Island of New Zealand (Figure 1).

The range of eruption styles between New Zealand's volcanoes and of the resulting landforms is largely due to the different chemistry of the magma. This also influences the frequency of eruptions, hazards and the extent of the area affected by an eruption. Rhyolitic magma has a high silica content compared to basaltic, andesitic or dacitic magma, it is viscous (doesn't flow easily) and can build up higher pressure before erupting. This is an influencing factor on why rhyolitic volcanoes don't erupt as often as less silicic (basaltic, andesitic, dacitic) volcanoes, but when they do erupt it can be in a very large, explosive way. Over the past 1.6 million years, at least 25 caldera-forming eruptions have occurred in the TVZ, most or all of which have caused widespread very dangerous pyroclastic (hot ash) flows (Wilson et al., 2009). New Zealand's calderas have erupted almost exclusively rhyolitic material (Wilson et al. 1984). Basaltic eruptions have also occurred in the TVZ, however they only make up <0.1% of the volume of deposits (Wilson et al., 1995). Andesitic and dacitic eruptions also occur in the TVZ, for example, Ruapehu, Tongariro and White Island erupt andesites, and Tauhara is formed from dacite, however dacite is rare. These eruptions tend to be smaller volume and impact a smaller area.

Part of the difficulty with understanding processes involved with rhyolitic eruptions is the very long gaps between eruptions (periods of quiescence), therefore very few rhyolitic eruptions have occurred worldwide during human existence. Of those that have, some have occurred in unpopulated areas. Therefore the precursors before rhyolitic eruptions have very rarely been witnessed, let alone recorded with modern monitoring equipment. Of the few witnessed eruptions at calderas which had previously been in quiescence, some erupted within only hours to days after the onset of noticeable unrest. However these volcanoes did not have monitoring networks such as in the TVZ, so it is likely a longer length of warning time will exist before eruptions here. Three of New Zealand's calderas have erupted post-settlement. At the Okataina Volcanic Centre, the Kaharoa eruption formed the summit domes of Mt Tarawera about 1314AD (Leonard et al., 2010) and Tarawera unusually erupted basalt in 1886. In the Kermadec Islands, five small eruptions have occurred at Raoul Island (1814, 1870, 1886, 1964 and 2006) as well as two potential eruptions at Macauley Island in 1825 and 1887. Over 110 fatalities have resulted from these eruptions, the vast majority from the 1886 Tarawera event.

This report summarises the current understanding of the eruption histories of New Zealand's 11 most recently active calderas – Raoul Island, Macauley Island, Mayor Island, Okataina, Rotorua, Kapenga, Reporoa, Ohakuri, Mangakino, Whakamaru and Taupo Calderas. Due to the large range of eruption sizes and styles from each of the calderas in the past, especially Taupo, it is extremely difficult to predict the size and style of the next eruption.

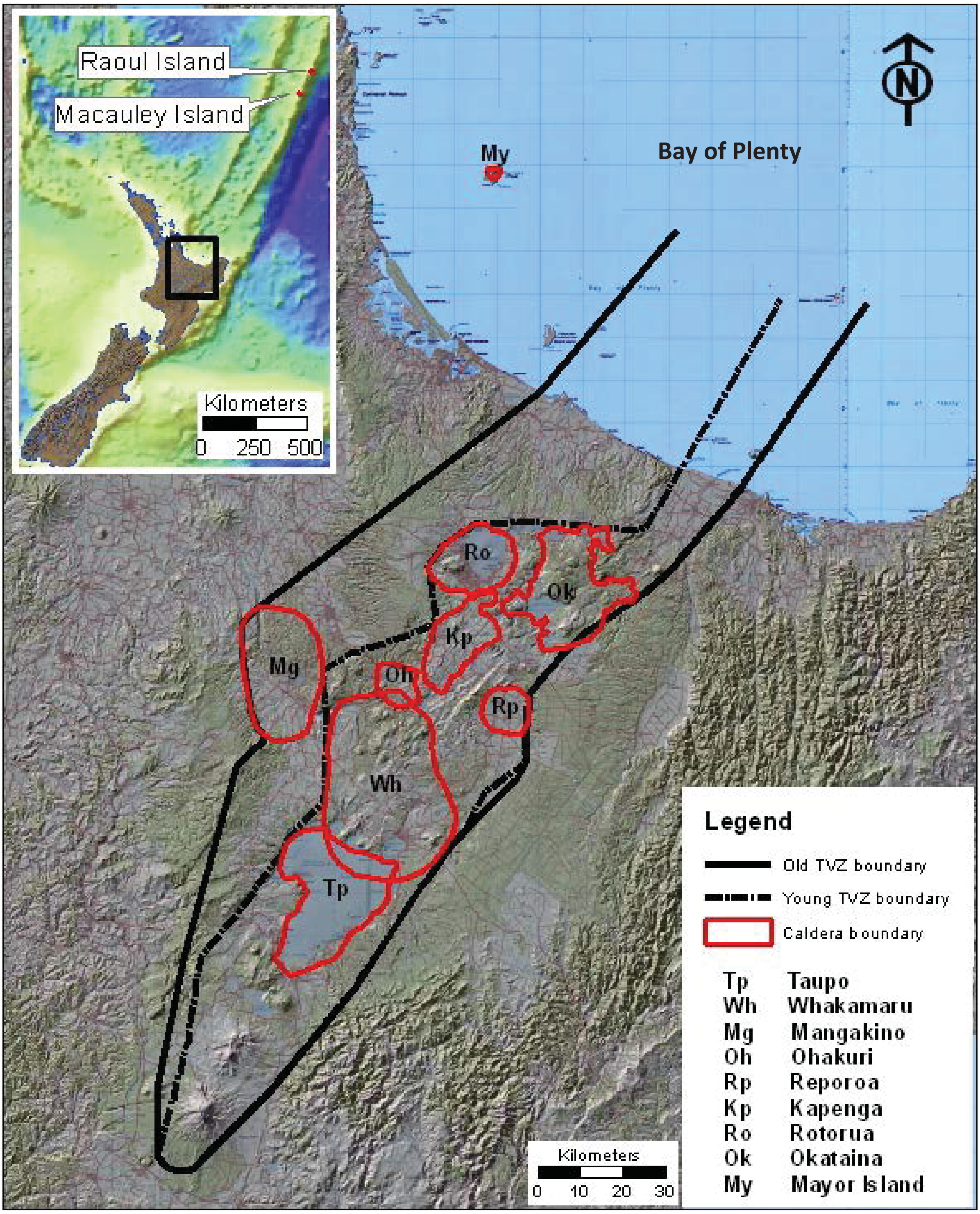

Figure 1 Map of the geomorphic boundaries of the eight calderas within the Taupo Volcanic Zone (TVZ). Three additional calderas lie outside the old TVZ boundary, Mayor Island in the Bay of Plenty and Raoul and Macauley Islands on the Kermadec Ridge, shown in the inset map. Based on Wilson et al. (2009) and Nairn (2002).

While eruptions at the calderas are relatively infrequent, volcanic unrest caused by magma and fluids moving underground and regional stress adjustment occurs more frequently. Most unrest episodes at calderas do not result in an eruption (Newhall & Dzurisin, 1988). Due to their frequency unrest episodes have been documented globally, including in New Zealand.

A summary of the known unrest episodes which have occurred in New Zealand is included in section 3 of this report for each caldera. Although unrest episodes are relatively frequent, they usually do not leave any trace in the geological record (except the occasional surface fault rupture, and large hydrothermal eruption deposits), so the knowledge is largely restricted to areas and times of human occupation. In New Zealand's case, this is reasonably limited, therefore to gain an understanding of what the unrest indicators may look like before future caldera eruptions in New Zealand, we must look overseas to countries with similar volcanoes and longer histories of settlement. This report provides descriptions of eruptions and unrest at rhyolitic calderas similar to New Zealand's including at Campi Flegrei (Italy), Long Valley (U.S.A.), Rabaul (Papua New Guinea), Chaitén (Chile), Aira (Japan), Taal (Indonesia), Novarupta (Alaska, U.S.A.) and Yellowstone Volcanic Centre (U.S.A.). Yellowstone is similar to the Taupo Volcanic Zone as both have had a similar discharge rate of magma in the past 2.2 million years and are a similar size, however the TVZ has had more frequent and smaller eruptions than Yellowstone (Houghton et al., 1995a).

Unrest phenomena may include seismicity, ground deformation and changes in the hydrothermal systems. These have the potential to be hazardous, damage buildings and infrastructure, and can result in psychosocial and economic impacts, all of which have occurred at Taupo Caldera in the past 160 years, as well as overseas (for example at Long Valley and Campi Flegrei Calderas). Unrest episodes can last for hours to decades. They need to be carefully managed by the CDEM sector, responding agencies, local and regional government, media, the public and scientists, even if there is no resulting eruption. Calderas with long periods of quiescence are particularly difficult to manage due to the public, media and public officials not fully recognising the hazards of the volcano, and the potential size and style range of any future eruption. There will be high levels of uncertainty for all groups, particularly as to the outcome of the unrest episode. This highlights the need for developing excellent pre-event interagency communication and cooperation as well as with the public and media.

In this report, we will discuss the physical, social and economic impacts of unrest and outline some of the implications for management of an unrest episode. We will not address in detail the eruption hazards from calderas. Volcanic eruption hazards, particularly for the Bay of Plenty region, have been outlined in Leonard et al., (2010).

1.1 What is a caldera?

A caldera is the depression in the ground formed by the withdrawal of underground magma (molten rock), causing the roof of the magma chamber to collapse. These depressions are usually formed during, but at a late stage in a coinciding large volcanic eruption from the caldera or a nearby vent. The natural bowl shape of these depressions can collect water, filling with lakes such as Lake Taupo and Lake Rotorua. Lakes within Okataina Caldera are broken up by lava domes formed in smaller eruption episodes well after the caldera-forming eruption itself.

Calderas can be created at a volcano with any type of magma, for example at basaltic volcanoes such as Kilauea (Hawaii) in 1750-1790; andesitic and dacitic stratocones such as Kuwae (Vanuatu) in ~1450 AD, Pinatubo (Philippines) in 1991 and Krakatau (Indonesia) in 1883; and rhyolitic volcanoes such as Taupo in 232AD (Lipman, 2000). The majority of New Zealand's calderas were formed during rhyolitic eruptions, which tend to form the largest calderas internationally.

The surface area of a caldera is many times larger than the individual vents that magma was erupted through. Small calderas (<5 km in diameter) can be formed during lava eruptions at andesitic and basaltic volcanoes, while calderas with a larger diameter (<75 km across) are usually formed during voluminous ignimbrite-forming (hot ash flow, called pyroclastic flow, deposits) eruptions (Lipman, 2000); generally ignimbrite-forming eruptions are rhyolitic. The size and geometry of calderas largely depends on the pre-existing host rock types, tectonic influences, magma chamber properties (such as size and shape) and the volume of material erupted (Lipman, 2000). Although calderas are usually formed from one or two very large eruptions, their magma system can also be the source of many smaller eruptions. This range in potential eruption size and style causes a large amount of uncertainty for decision makers during unrest.

The central TVZ can be viewed as one caldera complex akin to Yellowstone (e.g. Houghton et al., 1995 comparison). As such, unrest, hydrothermal eruptions, rhyolite magma eruptions and occasionally new calderas can occur outside of existing past caldera boundaries. This is very important to the interpretation of unrest, as the same uncertainties may exist as to the future outcome of unrest either inside or outside of known past calderas in the central TVZ.

1.2 What is caldera unrest?

Caldera unrest is simply volcanic unrest at a caldera volcano. Barberi and Carapezza (1996) define volcanic unrest as "the appearance on a dormant volcano of a multitude of anomalous phenomena indicative of possible eruptive reactivation (e.g. increased seismicity, ground uplift, physico-chemical changes in fumaroles and hot springs, increased heat flow, and changes in the gravimetric [and] magnetic…fields)". ‘Dormant’ generally means not-in-eruption, so in other words, volcanic unrest is signs that a sleeping volcano is starting to wake.

Volcanic unrest occurs when regional tectonic and/or volcanic processes cause magma (underground molten rock) and/or its fluids to interact with pre-existing rocks and sub-surface fluid. As the magma forces its way through the pre-existing rock, the rock can fracture causing earthquakes, and the ground surface may deform by millimetres to metres. Gas emitted by the magma (some of which can be hazardous) can be released at the ground surface, through the soil or at fumaroles (vents emitting gas and steam). Hydrothermal explosions, powered by steam, which can have been heated by the magma body, may occur at existing geothermal fields. Regional groundwater levels and spring temperatures can change due to alterations to the underground fluid systems, and the introduction of a new hot magma body.

If a monitoring or research programme exists, seismic, geodetic and other geophysical data like electromagnetic, magnetics and gravity may indicate the existence and size of an underground magma body.

1.3 Physical hazards during caldera unrest

Caldera unrest can be hazardous even if no eruption occurs. It is uncommon but possible that caldera unrest results in fatalities. A review of the literature indicates that gas poisoning has resulted in the most deaths at calderas during unrest (see section 1.3.3). Injuries can also occur from caldera unrest, such as from building failure if large earthquakes occur. However most episodes of caldera unrest do not result in any casualties, and many episodes show only one or two of the following unrest phenomenon, at varying levels of severity.

Volcanic hazards relating to eruptions are described in, for example, Johnston et al. (2011), Blong (1984) and the Yellow Book series (for example Nairn, 1991). Johnston and Nairn (1993) apply two eruption scenarios from Okataina Volcanic Centre and describe the potential impact on infrastructure and society. Becker et al., (2010) describe mitigation measures for volcanic hazards in New Zealand utilising land use planning. For social issues resulting from caldera unrest, refer to section 2.2.

1.3.1 Ground shaking

Earthquakes precede and accompany most, if not all volcanic eruptions. Volcanic processes generate a wide variety of seismic activity. These may be reflecting sub-surface processes like the movement of magma, signatures generated by eruptive activity or post-eruption readjustment (McNutt, 2000). Volcanogenic earthquakes are thought to rarely exceed magnitude 5 (Richter scale), but buildings within the volcano area may be subject to shaking damage (Johnston, 1997).

Earthquakes are the most common expression of volcanic unrest and eruptive activity (Newhall & Dzurisin, 1988). In some cases they are only detected if monitoring is adequate, while in other cases they will be felt locally and may cause some alarm. They can occur in swarms (many earthquakes occurring close together in time and space, usually of a similar size), or can be isolated events, affecting localised areas. Volcanic earthquakes largely have the same impacts as tectonic earthquakes. Ground shaking can cause building, structure and infrastructure damage or collapse, endangering lives. Earthquakes during eruptions have caused deaths at overseas volcanoes due to building collapse (or partial collapse) (Blong, 1984), however it is unusual for earthquakes during unrest to be large enough to cause fatalities. Collapsing brick chimneys can fall through building roofs; the rupturing of gas lines and electrical circuits may lead to a fire; and broken water pipes can cause flooding (Blong, 1984). Liquefaction (the upwelling of water and silt from ground shaking, as occurred in Christchurch during the 2010-12 earthquakes) can occur in areas with sand and gravel substrates, especially near low gradient waterways, if the earthquakes are of sufficient magnitude. Fault lines and cracks can be formed on the ground surface, potentially causing damage or destruction of buildings and underground services.

The GeoNet website (www.geonet.org.nz) contains a catalogue of historical earthquakes and a description of the seismic monitoring network in New Zealand. The main method of mitigation of earthquake damage is the enforcement of seismic building codes to protect structures against earthquake damage. Reinforcing chimneys, securing furniture, bracing structures and other seismic protection methods are recommended for areas surrounding volcanoes. Incorporating known fault lines into land use planning is also recommended (Kerr et al., 2003).

1.3.2 Ground deformation

Deformation (ground movement) at volcanic centres can occur as a result of magma moving beneath the ground surface, before, during and after eruptions. Movement of magma doesn’t necessarily result in an eruption, as it can often stall at depth and not reach the surface. As volcanoes lie in active tectonic environments they may also be influenced by regional deformation, such as rifting. Uplift or subsidence can cause damage to structures and infrastructure but is not directly life threatening. The deformation can range from millimetres to metres of uplift or subsidence, can affect a wide area, and may cause fissures (large cracks in the ground).

The most adverse effects of ground deformation are subsidence causing flooding (as seen in Taupo in 1922 and in Campi Flegrei over a number of centuries). Potential disruption to underground lifelines infrastructure in affected areas, such as gas, water, electricity and communication networks due to pipe or cable breakages can occur. Buildings, bridges, hydropower dams and geothermal power stations can be structurally damaged and roads cracked. Uplift and subsidence can cause flooding through altered water courses, subsidence below the water table or sea level or from hydropower dam and control gate failures.

There is very little which can be done to mitigate the effects of ground deformation. Depending on the form and location of ground deformation existing plans for flooding and landslides could be consulted, and areas deemed as dangerous could be evacuated and cordoned off as necessary. Gas, water and electricity pipelines in affected areas could be disconnected to minimise leakages and fires. Structures and infrastructure on areas of ground deformation should be regularly checked for safety.

1.3.3 Gas poisoning

Emissions of volcanic gases occur during eruptions, but are also common events between eruption episodes at many volcanoes and geothermal areas where they may be vented from the main crater, from fumaroles or diffusely through soil (Hansell et al., 2006). Volcanic gases include carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrochloric acid (HCl), hydrofluoric acid (HF), hydrogen sulphide (H_2S) and radon (Rn) (Parfitt & Wilson, 2008).

Documented health effects include discomfort and/or asphyxiation due to the accumulation of carbon dioxide (which is denser than air) in topographic lows (probably the most common life-safety hazard); deaths from hydrogen sulphide poisoning, primarily in geothermal areas; and respiratory effects (and occasionally deaths) from exposure to acidic sulphate aerosols formed from sulphur dioxide. High levels of volcanic gas in soil during unrest commonly causes areas of dying vegetation, as seen at Long Valley, Campi Flegrei and Rabaul during unrest episodes. During an eruption, the volcanic gas hazard is generally higher than during unrest. Wind tends to disperse gases to a point where they are at low concentrations and therefore are no longer hazardous, however they can still cause general discomfort. For a comprehensive review of health hazards from volcanic gases, refer to Hansell and Oppenheimer (2004) and the International Volcanic Health Hazard Network (www.ivhhn.org) (guidelines/gas pdf).

In Rotorua Caldera, about 14 people have been killed by gas poisoning in the past century. This is due to the geothermal nature of this region, and having buildings and hot pools sited over hot water bores and steaming areas. These deaths have mostly been attributed to asphyxiation by H_2S and CO_2 gases in low-lying, confined spaces such as geothermal spa pools, telecommunication trenches and workshop pits (Durand & Scott, 2005). This is in contrast to Rotorua's much less recent magmatic eruption history compared to the active (in terms of magmatic eruptions) Okataina and Taupo Calderas. In Cameroon in 1986, approximately 1700 people were killed by volcanic gas when a build-up of carbon dioxide was released suddenly from the waters of Lake Nyos (at the summit of a volcano) and flowed down the slopes to a nearby town (Baxter et al., 1989). At Rabaul in 1990 CO_2 gas killed six people who were collecting eggs in a small crater last active 50 years previously (as described by Rabaul Volcano Observatory bulletins, Global Volcanism Program website (www.volcano.si.edu)).

Mitigation of the volcanic gas hazard includes wearing face masks to provide protection for toxic gases, and ideally covering the eyes. During a volcanic gas hazard event, basements and other low lying, sealed areas may have to have restricted access or be entered with caution. Gas flux can be monitored from the active volcanic vent to provide an indication of the level of risk, and equipment can be installed in at-risk areas to monitor local gas concentrations if necessary.

1.3.4 Hydrothermal system changes

During caldera unrest, geothermal areas are susceptible to changes, including to the flow, temperature and chemistry of fumaroles and springs. A growing magma body can act as the catalyst providing additional heat to the overlying hydrothermal system, as well as releasing gas through it. As the temperature and/or pressure of the hydrothermal system changes, surface emissions can increase, and if large enough, can form small steam eruptions, called hydrothermal explosions (Browne & Lawless, 2001). Groundshaking (from tectonic or volcanic processes) can also change underground cracks and pressure systems, resulting in hydrothermal changes (Vandemeulebrouck et al., 2008). Most commonly no magma is erupted (Nairn, 2002; Nairn et al., 2005), however large hydrothermal eruptions at Rotomahana in an extension of the 1886 Tarawera eruption (Okataina Caldera) did include new magma (Nairn, 1979; Simmons et al., 1993).

As a complication, hydrothermal explosions can also occur without the influence of magma due to normal hydrothermal system processes, or to exploitation (drilling). For example, rainfall can influence the status of hydrothermal systems causing a hydrothermal explosion to occur. Another example of a cause of an increase in hydrothermal hazards not likely to be due to magma systems is inadequate borehole maintenance causing failure of the casing and hot fluids leaking at shallow depths, as occasionally occurs in Rotorua (Figure 2).

Hydrothermal systems are also located in the TVZ away from known calderas, e.g. at Kawerau, but unrest at these systems is likely to generate similar uncertainty with respect to possible future magmatic eruptions. This is because new rhyolite, and occasionally caldera eruptions occur outside of known past calderas from time to time.

Hydrothermal explosions occur fairly regularly in the Rotorua area (Scott et al., 2005). Recent significant events were at Kuirau Park in January 2001 and December 2006. Other significant hydrothermal eruptions have also occurred at Waimangu between the Okataina and Kapenga Calderas, with eruptions from Waimangu Geyser (1900-1904), Mud Rift (1906), Echo Crater (1915), Frying Pan Flat (1917), Frying Pan Lake (1924, 1973) and Raupo Pond Crater (1981) (Scott, 1994). Several of these resulted in fatalities. Geothermal fields near Taupo Caldera have also experienced several hydrothermal eruptions, such as in 2000 and 2001 (Bromley & Clotworthy, 2001). The eruption at Raoul Island in 2006, which caused one fatality, was a hydrothermal explosion. Hydrothermal eruption deposits have also been observed at Tahunaatara and Horohoro (near Kapenga), and at the Ongaroto, Ngatamariki, Rotokawa and Kawerau geothermal fields (Leonard et al., 2010).

Figure 2 St. Faith's church (Rotorua) hydrothermal explosion deposits in 2011, caused by the leakage of a bore, seen below the window on the right-hand side. Photo by A. Somerville.

Mitigating against hydrothermal explosions is difficult due to the unpredictability of the hazard. They tend to only occur in established geothermal fields, which generally already have restricted public access. Isolating dangerous fumaroles, springs and hydrothermal craters will minimise the risk. Restricting the development of land in geothermal fields is likely to minimise casualties and damage.

2.0 CALDERA UNREST MANAGEMENT

Caldera unrest management is a challenging and relatively underdeveloped field combining volcanology, local and regional government, lifelines, media, emergency management and the public. Bridging the gap between scientists and decision making officials for effective unrest management becomes a vital issue potentially affecting lives, property, infrastructure and economies. Future unrest episodes in New Zealand will occur, and scientists and emergency decision makers need to be as prepared for this as possible. Being aware of the past behaviour of the volcanoes will benefit these hazard management processes as an indication of possible future activity.

Eruptive and unrest histories from New Zealand and worldwide calderas are presented in sections 3 and 4 of this report and some scenarios are developed in Appendix 1. Data from these sections are used in the following discussions of caldera unrest and the management issues. It is also important to keep in mind that the central TVZ can be considered a single caldera complex, so semantics of whether unrest is within one known existing caldera or another, or inside or outside of a known caldera at all, should not necessarily or unduly colour the interpretation of what might happen in the future.

The level of risk encountered during caldera unrest is an interaction between the hazard and the exposure of people and structures. During some cases of caldera unrest, both of these factors have high levels of uncertainty and variability. To accurately estimate the level of hazard, any assessment has to examine the probability that unrest may result in a volcanic eruption. This needs to be defined in terms of magnitude, location, timing, style of potential eruption, and the probability of occurrence. To predict all of these factors with any accuracy is very difficult. The number of people exposed to the hazard can also vary according to the season in tourist locations. At the time of the Mammoth Lakes unrest episode in 1982-84, the population of the town was 5,500, while the surrounding area had almost 20,000 permanent residents. This number varied greatly during the winter season, as the number of skiers at Mammoth Mountain was estimated to be 1.2 million people per year, or approximately 15-20,000 people per day on weekends and holidays around the time of the unrest – a very significant increase in transient population to effectively manage (Mader & Blair, 1987). Taupo town's population of over 20,000 people can also multiply during large sporting events and the summer months. This variability in population as well as the future population size affects the level of risk and needs to be considered when planning for caldera unrest.

A high level of coordination between the scientists, response agencies and the public is needed to effectively manage an unrest crisis. Calderas with long periods of quiescence are particularly difficult to manage due to the public, officials and media not recognising the hazards of the nearby volcano, and the potential for eruptions.

GNS Science currently has the legal and contractual responsibility to monitor New Zealand's volcanoes through the Earthquake Commission (EQC) funded GeoNet project, and to communicate the levels of activity to the CDEM sector, media and public.

Natural and technological hazards in New Zealand are managed using the Resource Management Act 1991 (RMA), Building Act 2004 and Civil Defence and Emergency Management Act 2002 (CDEM Act). Local and regional government identify and rank the hazards and develop response plans around these. An indication of how volcanic hazards and caldera unrest are ranked at the various councils is summarised in Table 1. In parallel with this system, four volcano advisory groups have been established to improve management of volcano hazards in New Zealand. They are the Central Plateau Volcanic Advisory Group (CPVAG) for the Tongariro National Park volcanoes, Taranaki Seismic and Volcanic Advisory Group (TSVAG), Auckland Volcano Science Advisory Group (AVSAG) and the Caldera Advisory Group (CAG) with a focus on the central North Island calderas.

Table 1 A summary of how volcanic hazard is currently recognised by the six regional councils that list volcano hazards in their regional plans. Note there is a mix of 1st and 2nd generation plans represented here.

Council	Volcano threat	Likelihood	Consequence	Rating	Ranking
Northland	Local Volcano	Rare	3.4	Moderate/High	8/19
	Distal Volcano	Possible	2.2	Moderate	13/19
Auckland	Distal Volcano	Likely	Major	Very High	3/37
	Local Eruption	Rare	Catastrophic	High	8/37
Waikato	Caldera Unrest			Very High	2/20
	Ashfall source within region			High	5/20
	Ashfall source outside of region			Moderate	7/20
	Geothermal eruption			Low	18/20
Bay Of Plenty	Eruption Local Source			Very High	2/19
	Distal source			High	10/19
	Geothermal eruption			High	11/19
Taranaki	Local eruption	Certain	Major	Extreme	4/10
Horizons	Volcanic activity at Ruapehu				7/15
Hawke's Bay	Ashfall			High	15/38

2.1 Volcanic Alert Levels, Aviation Colour Code and Volcanic Alert Bulletins

The activity at volcanoes is communicated to the emergency management decision makers, media and public using Volcanic Alert Level (VAL) systems. In New Zealand, the VAL system describes the current state of activity and ranges from 0 (normal background activity) to 5 (major eruption in progress) (Table 2). All of the calderas in New Zealand are currently classified as *reawakening volcanoes,* and use the right-hand side of the VAL table, except for the recently active Raoul Island Caldera in the Kermadecs. The VAL system is defined in the Guide to the National Civil Defence Emergency Management Plan by the Ministry of Civil Defence and Emergency Management (2006) (found on the civildefence.govt.nz publications webpage, in section 19.4.2).

Table 2 Volcanic Alert Levels in New Zealand. All calderas in New Zealand, except for Raoul Island in the Kermadecs, currently use the 'reawakening volcanoes' side of the table. From the Guide to the National Civil Defence Emergency Management Plan (Ministry of Civil Defence and Emergency Management, 2006).

Frequently active cone volcanoes White Island, Tongariro-Ngauruhoe, Ruapehu, Kermadecs		**VOLCANIC ALERT LEVEL**	**Reawakening volcanoes** Northland, Auckland, Mayor Island, Rotorua, Okataina, Taupo, Egmont/Taranaki	
Volcano status	**Indicative phenomena**		**Indicative phenomena**	**Volcano status**
Usual dormant, or quiescent state	Typical background surface activity, seismicity, deformation and heat flow at low levels.	**0**	Typical background surface activity; deformation, seismicity, and heat flow at low levels.	Usual dormant, or quiescent state.
Signs of volcano unrest	Departure from typical background surface activity.	**1**	Apparent seismic, geodetic, thermal or other unrest indicators.	Initial signs of possible volcano unrest. No eruption threat.
Minor eruptive activity	Onset of eruptive activity, accompanied by changes to monitored indicators.	**2**	Increase in number or intensity of unrest indicators (seismicity, deformation, heat flow and so on).	Confirmation of volcano unrest. Eruption threat.
Significant local eruption in progress	Increased vigour of ongoing activity and monitored indicators. Significant effects on volcano, possible effects beyond.	**3**	Minor steam eruptions. High increasing trends of unrest indicators, significant effects on volcano, possible beyond.	Minor eruptions commenced. Real possibility of hazardous eruptions.
Hazardous local eruption in progress	Significant change to ongoing activity and monitoring indicators. Effects beyond volcano.	**4**	Eruption of new magma. Sustained high levels of unrest indicators, significant effects beyond volcano.	Hazardous local eruption in progress. Large-scale eruption now possible.
Large hazardous eruption in progress	Destruction with major damage beyond volcano. Significant risk over wider areas.	**5**	Destruction with major damage beyond active volcano. Significant risk over wider areas.	Large hazardous volcanic eruption in progress.

The Aviation Colour Code (Table 3) is defined in International Civil Aviation Organization (ICAO) documents, and is used by the Civil Aviation Authority in New Zealand to alert the aviation industry to changes in the status of volcanoes within the coverage of Wellington Volcanic Ash Advisory Centre (VAAC), which includes a large area of the southwest Pacific. Restrictions on the use of airspace during a volcanic eruption using the New Zealand Volcanic Ash Advisory System (VAAS) is outlined in Lechner (2009). The VAAS is the local enhancement of the International Airways Volcano Watch System. GNS Science, MetService and the Airways Corporation of New Zealand provide input into the VAAS (Scott & Travers, 2009).

Table 3 The ICAO Aviation Colour Code for volcanic activity.

ICAO Colour code		Status of activity of volcano
GREEN		Volcano is in normal, non-eruptive state. *or, after a change from a higher alert level*: Volcanic activity considered to have ceased, and volcano reverted to its normal, non-eruptive state.
YELLOW		Volcano is experiencing signs of elevated unrest above known background levels. *or, after a change from higher alert level*: Volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
ORANGE		Volcano is exhibiting heightened unrest with increased likelihood of eruption. *or*, Volcanic eruption is underway with no or minor ash emission *[specify ash-plume height if possible]*.
RED		Eruption is forecasted to be imminent with significant emission of ash into the atmosphere likely. *or*, Eruption is underway with significant emission of ash into the atmosphere *[specify ash-plume height if possible]*.

Volcanologists at GNS Science have the responsibility of setting the VAL and Aviation Colour Codes for New Zealand's active volcanoes. Responding agencies in New Zealand are notified of changes in volcanic activity, including changes to the VAL and Aviation Colour Code, by the dissemination of Volcanic Alert Bulletins which are issued by GNS Science. Volcanic Alert Bulletins are also issued without a change in VAL to provide additional information such as ashfall forecasts. This information can be used by the responding agencies to help determine decisions and responses. For up to date information on the current status and alert levels for the calderas, visit the GeoNet website (http://www.geonet.org.nz/volcano/).

2.2 Social consequences of caldera unrest

Social effects of caldera unrest include impacts on the national and local economies through the decline of tourism, investments and the real estate industry; media speculation and misreporting; temporary psychological distress, particularly from constant earthquakes; and self-evacuations (Johnston et al., 2002). Mistrust of the scientists and emergency management decision makers from the lack of timely information and high levels of uncertainty can arise during unrest episodes, such as occurred at the town of Mammoth Lakes at Long Valley caldera (California) during unrest in 1982-84 (Mader & Blair, 1987). The outcome of the local elections at Mono County (an area of which includes Long Valley caldera and Mammoth Lakes) in 1983 may have been affected by these factors.

2.2.1 Psychosocial

Initial reactions to the volcanic unrest episode are likely to include fear, confusion and denial, as seen at Mammoth Lakes, Long Valley Caldera in 1982 (Mader & Blair, 1987) and in Pozzuoli during Campi Flegrei (Italy) unrest in 1970 when an evacuation order for 3,000 people was issued (Barberi et al., 1984). Repeated earthquakes can have a detrimental effect on the community, leaving the people on edge and waiting for the seismic swarm to cease so they can respond to damage. Unrest causes a heightened feeling of uncertainty in the community as it is unknown whether the unrest will escalate and culminate in an eruption or die away. This stops life from being lived as it normally would for potentially long periods of time. Education systems may be closed, and some members of the community may leave to gain a sense of normalcy elsewhere. This decreases the workforce, potentially having a flow-on effect on business closure and the local economy.

Perceived effects of the unrest on the community and economy can tempt the public officials and politicians to put pressure on scientists to lower alert levels, or remove the label of volcanic unrest from the situation. Tensions between the two groups can heighten until mistrust occurs. This occurred at Mammoth Lakes, Long Valley Caldera in an attempt by a few of the officials and local business owners to lessen the impact on the tourism and local investment industries (Mader & Blair, 1987). Mistrust of the scientists by the officials and public can cause action delays in situations indicating an evacuation should take place. A high level of interagency communication and public information management is required during caldera unrest to minimise the risk of these issues from occurring.

There is a large demand for information from public officials and scientists by the public and media during unrest, as seen during the 1983-85 unrest episode in Rabaul. This resulted in special arrangements to be made, including establishing a regular newsletter and a Public Information Unit to fulfil this need (Lowenstein, 1988). Daily information meetings were well attended by the public during the 1983 seismic swarm at Long Valley (Mader & Blair, 1987).

2.2.2 Economic

The economic effects of a long period of caldera unrest are varied, and rely on factors such as the duration; magnitude of activity; types, strength and flexibility of businesses; and degree of uncertainty (Johnston et al., 2002). The increase in business uncertainty disrupts the local economy, which can last for weeks to decades. Preparing for a volcanic crisis event can reduce the overall impact on the local and national economies (Shearer Consulting Ltd. & Market Economics Ltd., 2008). The economic consequences of unrest at New Zealand's calderas are not yet well quantified.

The local and national tourism industry can by adversely affected, as experienced by Taupo during and immediately after the 1963-64 episode of unrest (Johnston et al., 2002), and in the ski-season of 1982-83 at Mammoth Lakes, Long Valley Caldera (Mader & Blair, 1987). In the latter example, the effect of unrest on the tourism industry, while easily blamed on the volcanic unrest, is hard to prove or measure due to contributing circumstances including the national recession, coincidental poor weather, and perceived overbuilding at Mammoth Lakes during the early 80's episode (Mader & Blair, 1987). Premature business closure and self-evacuations are likely to affect the image of the town and the confidence of tourists in visiting. Encouraging business owners to remain open during unrest can mitigate this, providing buildings have been deemed safe after earthquakes. The effect on tourism may be short lived if the unrest declines, as shown by the almost record ski season of 1983-84 at Mammoth Lakes, despite the unrest earlier in the year (Mader & Blair, 1987). A marketing campaign by the businesses of Mammoth Lakes in 1984 appeared to be a success in further boosting tourist numbers (Mader & Blair, 1987).

The investment market at Mammoth Lakes was seen to be hit harder by the caldera unrest than the tourism industry (Mader & Blair, 1987). This appeared to be due to the perceived risk on short-term visitors being less than the "constant threat" on long-term property investments. The decline in the real estate market was blamed on the volcanic hazard (Mader & Blair, 1987).

The insurance industry is likely to be affected during caldera unrest, largely due to the repeated and potentially damaging earthquakes. Changes by insurance agencies can include not reinsuring the previously insured once the standing annual contract expires.

Insurance companies may also cancel their cover giving 7-days notice, or they may change what the insurance includes, for example, not cover volcanic hazards. New Zealand's Earthquake Commission (EQC) (http://canterbury.eqc.govt.nz/faq) covers earthquake damage for a portion of the house and contents, provided the owner also has insurance with a private insurance company. After the 1983-85 Rabaul unrest episode, building insurance was restricted and had a high cost, resulting in a lack of finance from lending institutions (Lowenstein, 1988).

2.3 Mitigation measures for caldera unrest

In addition to the considerations mentioned in the above psychosocial and economic sections, a number of actions are recommended to take place during caldera unrest (especially if they haven't already occurred during quiescence). As previously mentioned, the difficulty with caldera unrest is the high uncertainty in the outcome, therefore the range of outcomes must be prepared for. This includes preparing for long periods of damaging unrest, anticipating the needs resulting from potential unrest phenomena (for example preparing to restrict access to hazardous locations, source engineers and equipment for building and infrastructure damage inspections and have cleanup crews ready to clear landslips), preparing for volcanic eruptions of various scales and associated recovery plans. In essence, the CDEM sector needs to be prepared, educated and activated at an appropriate time.

2.3.1 Planning

Emergency plans may need to be activated to prepare the surrounding areas. For example, hazard maps should be drawn and the most vulnerable areas from various unrest hazards (including liquefaction, faulting and flooding) identified, as well as for eruption hazards (for example, Scott & Nairn (1998), Figure 3 below). Evacuation plans should be created and streets and bridges assessed for potential obstacles. Alternative escape routes from isolated communities may need to be created, as occurred at Mammoth Lakes, California in 1983 (Mader & Blair, 1987). Exercises in the form of evacuation drills were carried out during Rabaul's 1983-84 unrest episode, and may have contributed to the successful evacuation of the town 10 years later during the eruption (Finnimore et al., 1995). Preparing for eruption hazards (including pyroclastic flows, tephra falls and lava flows) also needs to take place for a range of scenarios. For further information on preparing for a volcanic crisis, particularly in the Bay of Plenty, refer to Johnston et al., (1996).

2.3.2 Education and communication

Public education and communication is vital during unrest, particularly for events with a wide range of potential outcomes. Information sheets/flyers can be pre-prepared during quiescence and ready to be issued when required. A media plan should be created as the media can be a powerful tool or enemy in these situations. If problems are encountered involving inaccurate media releases, prepaid advertising can be utilised, or a private news-sheet published and distributed, as done in Rabaul (Lowenstein, 1988). Incorrect international reporting during the 1922 unrest episode at Taupo Caldera caused a perceived impact on the Rotorua tourism industry (Evening Post, 7 July 1922). In addition, during the same episode, a San Francisco source reported there had been 60 deaths due to the earthquakes in Taupo, when in fact there had been none, and it was greatly feared by the New Zealand Government and Tourism Department that this would have a detrimental effect on the number of visitors from this area (Evening Post, 10 August, 1922). A publicity officer was appointed for the Government, and in the future "such misrepresentations should be immediately corrected" (Evening Post, 10 August, 1922).

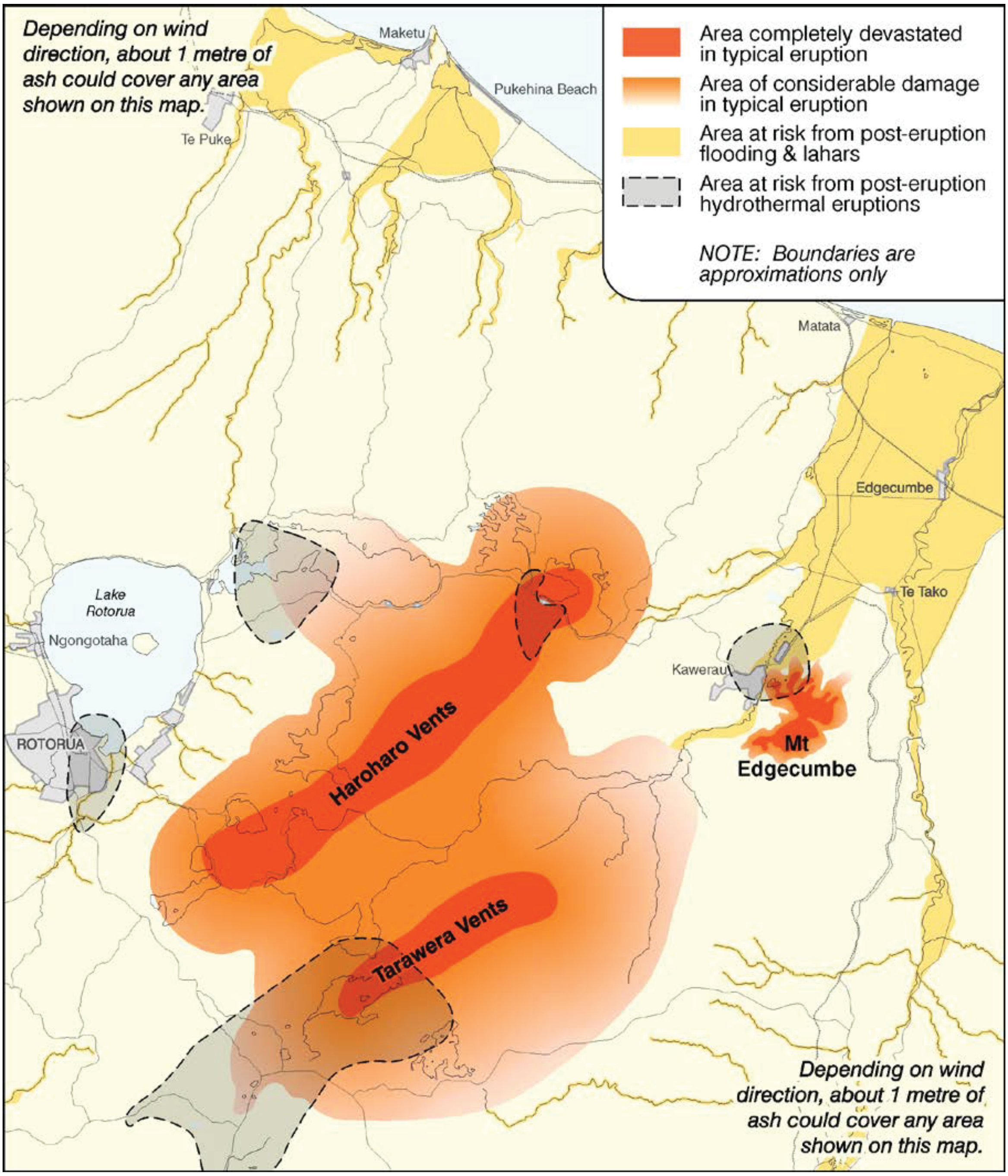

Figure 3 An example of a volcanic eruption hazard map for the Okataina Volcanic Centre (Scott & Nairn, 1998). Areas with orange and red shading have a higher probability of damage, depending on vent location.

2.3.3 Economic

The impact on the local economy may also be lessened with robust but flexible business continuity plans. This will enable the local economy to continue to function throughout even extended periods of unrest, as well as in the period of recovery afterwards. This is particularly the case for larger companies who employ many in the community. Rural, agricultural and industrial sector requirements need to be considered, including hydropower and geothermal power stations. Developing recovery plans for the range of eruptive and non-eruptive scenarios is likely to be beneficial. Lessons learnt elsewhere could be incorporated, including from the repeated Canterbury earthquakes of 2010-12.

2.3.4 Future research

The unrest histories of New Zealand's calderas are largely unknown – only Taupo's history has been (recently) completed. Further research into these histories, the hazards of volcanic unrest and caldera eruptions and increasing awareness of international unrest and eruption events will improve our state of knowledge and capacity to react to future events in New Zealand. Research into the effects of unrest on the community and local and national economies, as well as methods of mitigation will contribute towards the resilience of New Zealand's population who live with restless calderas.

2.3.5 General preparation

As can be seen from the suggested examples of actions which need to occur during unrest, it is going to be very helpful to have everything which can possibly take place during quiescence completed, so that during the event adequate time is left for addressing the media and public, and for focussing on arising issues.

The various sectors, including those related to lifelines, health, agriculture and the environment, as well as individual households can prepare for a caldera unrest event in a similar way to preparing for any natural hazard. In particular, refer to advice given by MCDEM for earthquake and volcanic eruption hazards.

3.0 NEW ZEALAND'S CALDERAS – ERUPTIONS AND HISTORICAL UNREST

The North Island of New Zealand is situated next to a plate tectonic boundary with the Pacific Plate in the east subducting beneath the Australian Plate in the west, with subduction starting from offshore east of the island. The Taupo Volcanic Zone (TVZ) stretches approximately 300 km in length and up to 60 km in width from Mt Ruapehu in the southwest to White Island in the northeast (Houghton et al., 1995a) (Figure 1). It is an area of thinner crust and high heat flow which is more susceptible to large-scale volcanism (Bibby et al., 1995). The middle section of the TVZ contains the Taupo, Whakamaru, Mangakino, Reporoa, Ohakuri, Kapenga, Okataina and Rotorua calderas. Of these calderas, only Taupo and Okataina have erupted in the past 2,000 years, and only Taupo has produced a large caldera-forming eruption in that timeframe. The remainder have not erupted for a very long time, so while the possibility of a future eruption remains, it is less likely that these will erupt than the more frequently and recently active calderas. The TVZ also accommodates a large number of fractures and faults (including the active Taupo Fault Belt) and numerous geothermal fields.

Mayor Island volcano lies just outside of the TVZ boundary (Figure 1). The underlying tectonic plate structure is different to that of the TVZ caldera volcanoes, which influences the magma chemistry, and therefore its eruption styles.

Raoul and Macauley Islands are part of the Kermadec Islands, which lie 750 – 1000 km northeast of the coast of New Zealand (inset of Figure 1). The Kermadec Islands are predominately volcanic, and were formed by the continuation northward of the subduction processes occurring beneath the North Island of New Zealand. Several active submarine volcanoes are also know in the area between the Bay of Plenty coast and the Kermadec islands. A large sea-raft of pumice (Loisels Pumice) was deposited on New Zealand's eastern coastline from two eruptions at approximately 1000-1500 years Before Present (yrs BP) and 650 yrs BP (Shane et al., 1998). The source of these eruptions is thought to be from volcanoes (potentially calderas) in the Kermadec ridge area (Shane et al., 1998). This deposit indicates that future large-scale pumice rafts could affect the coast and ports of New Zealand, particularly on the east coast.

New Zealand's calderas have displayed an enormous range in eruption sizes. For Taupo caldera alone, the eruption size has varied by four or five orders of magnitude in the past 27,000 years (Wilson, 1993). This causes uncertainties in the prediction of future eruptive activity. Further uncertainty exists due to the reliance on the geological record for knowledge of past eruptions. Many small eruptions are likely to be missing or poorly recorded in the geological record as these leave only thin ash deposits (if any at all), which can later be eroded away, destroying any record that the eruption occurred. This is particularly the case for the calderas in the middle of the TVZ which have not been active for hundreds of thousands of years. Therefore many more small eruptions have occurred at New Zealand's calderas than are known.

During an eruption or potential eruption at any of these central TVZ volcanoes, the airspace closure may impact domestic flight paths crossing the area, although due to the dominant wind direction being westerly, it is likely international flight paths will be largely unaffected and the ash will be deposited in the eastern North Island and the Pacific Ocean.

As many of the TVZ calderas are bordered by active networks of faults and geothermal fields, and situated on a back-arc rift formed by a subduction zone, it is difficult to determine the cause of seismic and deformation activity within and surrounding each caldera. Earthquakes and deformation could occur from the tectonic plate collision, regional extension, the local fault belts, geothermal activity or a magmatic intrusion, with the magmatic intrusion the most potentially hazardous. In addition, geothermal systems have their own processes causing fluctuations in activity without further input by volcanic or tectonic processes. Therefore increases in activity at the geothermal fields do not necessarily indicate caldera unrest.

The Earthquake Commission (EQC) funded GeoNet project run by GNS Science manages a GPS, seismic and geochemical (at hydrothermal areas) monitoring network to observe activity at the calderas (Scott & Travers, 2009). In the following section the monitoring, eruptive and unrest history of each caldera is summarised and discussed in more detail.

3.1 Raoul Island

Raoul Island is part of New Zealand's territory, therefore the government is obligated to assess and reduce risks for this area. The island has an area of 30 km^2 and is the surface portion of a volcano approximately 35 km by 20 km in size, rising 1.5 km from its base on the Kermadec Ridge. Raoul Island contains two calderas (shown in oblique view in Figure 4) – Raoul Caldera in the middle of the island is approximately 2 km x 3 km, and Denham Bay Caldera is approximately 3 km x 3 km in size. Past eruptions from Raoul Island, even those involving caldera collapses, have been of similar size to the smaller, non-collapse-related caldera eruptions in the TVZ. This is because Raoul magmas are not rhyolitic. The magma chemistry at Raoul changed from basaltic and andesitic to become dacitic, a more viscous (i.e. flows less easily) and explosive type of molten rock in approximately 2200 B.C. Of the eruptions after this, only one, 1700 years ago was entirely basaltic. No rhyolitic deposits have been found on or originating from Raoul Island (Latter et al., 1992). The island contains two volcanic crater lakes and minor areas of hot springs and fumaroles.

Caldera unrest and eruptions at Raoul Island are likely to be hazardous for visitors to the island, including the Department of Conservation (DOC) workers who run the nature reserve year-round. An eruption at Raoul Island could impact the airspace around it, potentially disrupting flights from New Zealand to the Pacific Islands, and generate rafts of pumice on the sea, disrupting shipping. The most recent eruption at Raoul Island was in 2006.

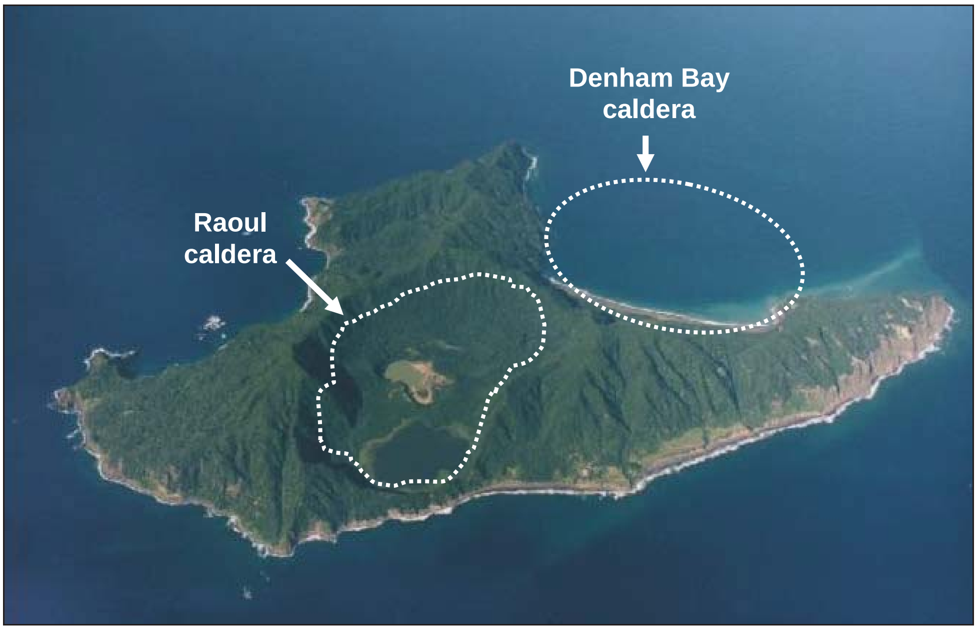

Figure 4 Oblique aerial photo of Raoul Island, looking towards the southwest. The caldera boundaries are indicated. Green Lake is near the centre of Raoul caldera. RNZAF photo.

3.1.1 Eruptions

The oldest volcanic rocks on Raoul Island are up to one and a half million years old (Lloyd & Nathan, 1981; Latter et al., 1992). However Raoul Island didn't emerge from the sea until approximately half a million years ago as a basaltic and andesitic stratovolcano, created by alternating layers of tephra deposits and lava flows. Raoul Caldera began to form in approximately 2000 B.C. during a large eruption, and Denham Bay Caldera formed in approximately 200 B.C. during the largest eruption that has taken place at Raoul in the past 4000 years (Lloyd & Nathan, 1981; Latter et al., 1992). About 16 eruptions have taken place at Raoul in the past 4000 years including the previously mentioned caldera forming eruptions, and historical eruptions in 1814, 1870, 1886 (submarine), 1964 and 2006.

An eruption at Denham Bay on 9 March 1814 was witnessed by a boat which, at the time, was 30 km offshore from Raoul Island. The eruption included the emission of "a strong, fetid, and almost suffocating vapour", and a tall ash column was observed. When the newly formed tephra island was visited two months later, it was "3 miles in circuit, kidney-shaped", and "still smoking" (Lloyd & Nathan, 1981). The island had disappeared by 1854 when it was revisited.

Raoul Island may have erupted many times between 1869 and 1872, but the only confirmed eruptions occurred between June and October 1870 at both Raoul and Denham Bay Calderas (Lloyd & Nathan, 1981). In Raoul Caldera, the eruption began phreatically (steam-driven) with the emission of fine ash, and proceeded to erupt small rock fragments, pumice and mud, killing nearby vegetation. It is thought that no fresh magma was involved in this eruption. A 600 m wide crater was formed, now the site of Green Lake (Figure 4). The eruption lasted for approximately 4 months, endangering the family living on the island at the time. In Denham Bay, the eruption began in June as a submarine eruption, killing fish and causing the water to be discoloured. By July the eruption was forming steam columns estimated to be 600 – 900 m in height and by October of the same year two islands had been formed in Denham Bay. These islands had disappeared by September 1872 (Lloyd & Nathan, 1981).

The submarine eruption in 1886 occurred approximately 8 km from the coast of Raoul Island, probably forming the 240 m high seamount (up to 560 m below the sea surface) currently situated there (Lloyd & Nathan, 1981). Smith (1887, 1888 cited in Lloyd & Nathan, 1981) states that the seismicity and hydrothermal activity at Raoul Island had declined three months after this eruption.

Lloyd and Nathan (1981) describe the 21 November 1964 eruption. It was preceded by constant seismic tremor, lake level changes and ground deformation. The main eruption was centred in Raoul Caldera beginning as a phreatic eruption near Green Lake and lasting for 30 minutes. The eruption included pyroclastic base surges (hot, gassy ash flows), ballistics thrown up to 700 m from the crater and an eruption column up to 1.2 km high. An area of 0.8 km^2 was devastated by the eruption. A pumice slick and discoloured area of water were intermittently seen in Denham Bay from 12 November 1964 until April 1965 and was thought to be caused by gas and possibly fresh lava emerging on the sea floor.

The most recent eruption at any of New Zealand's calderas occurred at Raoul Island in March 2006. It was a very brief (~3 minutes), small phreatic eruption of rocks, pumice debris and lake sediments, centred in Raoul caldera. The eruption was likely to be indirectly triggered by magma (Christenson et al., 2007) however no fresh magma material was found at the surface from this eruption (Rosenberg et al., 2007). This eruption caused the death of a Department of Conservation worker who was sampling in the area at the time of the eruption.

3.1.2 Historical unrest

Due to the lack of population on or near Raoul Island for most of the historic record, the observations of volcanic unrest are very limited and represent an absolute minimum level.

The 1870 eruption was preceded by "almost incessant earthquakes", sulphur fumes and submarine explosions in Denham Bay caldera (Lloyd & Nathan, 1981).

Unrest preceding the 21 November 1964 eruption consisted of 11 days of increased seismic activity up to a magnitude of 5.9 (MM7), including volcanic earthquakes and tremor. The water level in Green Lake (within Raoul Caldera) rose by 6m and the lake temperature increased. Increased activity at springs and high-temperature fumaroles was also reported, and the ground displayed signs of cracking.

An area of vegetation was killed in 1980 near Green Lake due to high ground temperatures (Cole et al., 2006). No eruption occurred.

Between 1989 and 1995, six episodes of unrest consisting of earthquake swarms were recorded which included low-frequency volcanic earthquakes. The individual swarms included more than 300 recorded earthquakes. Monitoring was increased following the 1993 earthquake swarm. There were also changes to the water level of Green Lake during some of these unrest episodes (Scott, 1995).

Precursors to the 2006 eruption are described in Cole et al., (2006). Earthquakes were recorded for five days before the 2006 eruption, opening with a particularly intense swarm lasting for 14 hours, which then died away. Their epicentres were judged to be reasonably far away from the island, and no low-frequency volcanic earthquakes or volcanic tremor were recorded. No other precursory unrest phenomena were observed before the 17 March 2006 eruption.

No significant unrest episodes have occurred since the 2006 eruption.

3.1.3 Potential future activity

Given the frequency of caldera unrest in the past, it seems likely that there will be unrest at Raoul Island in the future. Many unrest episodes have been recorded in the limited period of time with which monitoring networks have been established, with no resulting eruption. This will make predictions of the outcome of future unrest episodes difficult. Eruptions have occurred during historical times with noticeable unrest periods ranging from virtually non-existent to weeks. The unrest behaviour of Raoul Island is likely to be different to the other calderas in New Zealand due to its magma chemistry (i.e. non-rhyolitic). Generally, less silicic volcanoes have shorter and more predictable unrest episodes than rhyolitic volcanoes.

Future eruptions from Raoul Island are unlikely to affect the mainland of New Zealand unless they are exceptionally large (Latter et al., 1992). This would be in the form of tephra deposition over a wide area, and tsunami caused by explosions affecting the water surrounding Raoul Island. Smaller eruptions will endanger all life on the island, and boats and aircraft nearby. Latter et al., (1992) and Blong (1984) further describe possible volcanic hazards.

Today Raoul Island is monitored by GNS Science in conjunction with DOC. Techniques include monitoring seismicity (two sites), deformation using GPS, Green and Blue Lake temperature and water levels and selected hot spring temperatures. The crater lakes and selected hot springs are regularly sampled and sent to the mainland for chemical analysis.

3.2 Macauley Caldera

Macauley Island is the highest point on the mostly submerged Macauley Caldera, located 110 km south-south-west of Raoul Island in the Kermadecs (Figure 1). Macauley Caldera is 13 km x 11 km in size and 1000 m deep and is thought to have been formed during an eruption of magma volume <100 km^3 at 6310 ± 90 yrs BP (Latter et al., 1992; Lloyd et al., 1996). This large eruption was dacitic in composition and produced an ignimbrite deposit as well as widespread tephra (Latter et al., 1992). Basaltic lava eruptions have occurred both before and after the caldera-forming eruption (Latter et al., 1992). Unconfirmed eruptions have been reported in the Macauley area during historical times, including in 1825 and 1887 (Lloyd et al., 1996). Given that Macauley is not rhyolitic it is expected to produce eruptions substantially smaller than TVZ rhyolite calderas, even in caldera-forming eruptions.

Based on the frequency of past eruptions, future eruptions at Macauley Caldera are likely to occur, and will most probably be submarine eruptions from the small cone in the south eastern portion of the caldera. They will probably produce eruption columns which may affect the aviation industry, nearby islands and even mainland New Zealand if there is a northeasterly wind. However the prevailing westerly wind will most likely deposit the tephra into the sparsely populated Pacific Ocean. Pyroclastic flows may enter the sea endangering nearby shipping, and the potential collapse of parts of Macauley Island may cause destructive tsunami.

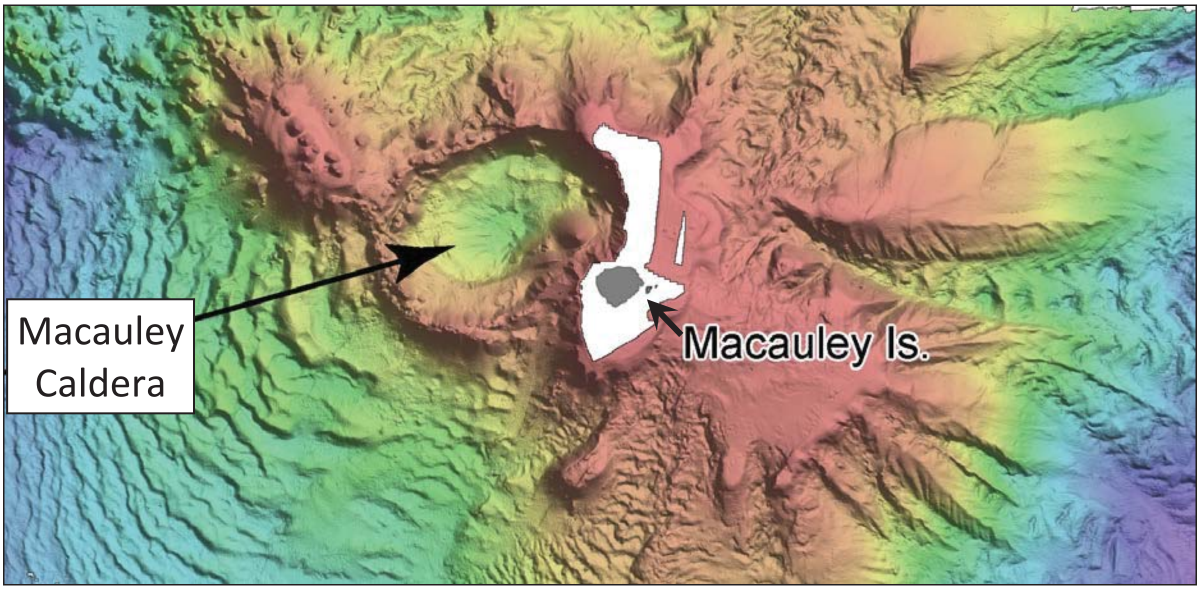

Figure 5 The mostly submerged Macauley Caldera (indicated by the arrow) in the Kermadec Islands (see Figure 1 for location) as seen in a multibeam high resolution image. Macauley Island, shown in grey, is the highest point on Macauley Caldera and the only above-sea portion. Image from NIWA.

3.3 Mayor Island / Tuhua

Mayor Island is located 26 km off the coast of the Bay of Plenty (Figure 1), outside the boundaries of the Taupo Volcanic Zone. The island is the above-surface portion of a 700 m high, 15 km wide shield volcano, which contains a 3 km wide caldera on top (Figure 6). It has erupted on average once every 3000 years for the past 130,000 years (Houghton et al., 1995b). Most major periods of quiescence, such as the one we are in now, have been at least 1000 years in duration, however others have been much longer.

The volcano's rhyolitic magma chemistry has been very constant for most of its life, but unusually it has displayed a range of eruptive styles and sizes (Houghton et al., 1995b). Almost every style of volcanic eruption has occurred at Mayor Island at some stage in its history, ranging from lava fountaining usually only seen at basaltic volcanoes, through to large explosive, ignimbrite-forming plinian eruptions. The size of eruptions has varied by more than three orders of magnitude (Houghton et al., 1995b).

Figure 6 Oblique aerial view of Mayor Island, looking towards the west at the caldera floor which is covered by younger lava domes. Photo Lloyd Homer, GNS Science.

3.3.1 Eruptions

Three phases of volcanic activity have taken place at Mayor Island (Houghton et al., 1995b). The first, between 130,000 and 36,000 yrs BP, consisted of numerous lava flows and explosive eruptions (including plinian or subplinian, strombolian and phreatomagmatic events, see glossary for details) building up the shield volcano. This phase culminated in the first caldera collapse, possibly caused by several small eruptions (Houghton et al., 1995b).

The second phase occurred between 33,000 and 8,000 yrs BP as the volcanic shield continued to grow within the caldera boundary. Lava domes, lava ponds and pumice cones were created during this time, and at least one explosive (subplinian) eruption occurred, causing minor caldera collapse (Houghton et al., 1995b). Approximately 6,350 yrs BP a second major caldera collapse occurred during a large plinian eruption, which deposited up to 70 cm of pumice on the mainland. Pyroclastic flows entered the sea, probably causing a large tsunami on the mainland.

The third phase of eruptive activity from 6,350 yrs BP until today has included numerous lava flows which have formed domes, and minor explosive activity. The erupted material from this phase has different chemistry to previous deposits, indicating a possible change in the magma source. The most recent eruption occurred less than 1,000 years ago (Houghton et al., 1995b; Buck, 1985).

3.3.2 Historical unrest

No historical unrest is known to have occurred at Mayor Island Caldera. Virtually no earthquakes at all have been located beneath the island in the past ten years.

3.3.3 Potential future activity

Mayor Island is currently in a period of quiescence which has been shorter than previous periods of quiescence (Buck, 1985). This indicates that it is still an active volcano and future activity is possible. Predicting the style of the next eruption at Mayor Island is nearly impossible due to its wide range of styles in the past. Previous periods of quiescence abruptly ended in small but explosive (Vulcanian-style) eruptions, effectively clearing the vent, which then progressed to larger plinian eruptions (Buck, 1985). The most recent eruption probably also started with a small explosive eruption and then became more effusive (containing less gas and therefore less explosive), building a 250 m high lava dome on the caldera floor. It is likely that these styles of eruptive activity will occur again in the future. The entire island is at risk from future eruptive products, especially inside the low-lying caldera, as well as down-wind areas on the mainland during a larger eruption. Tsunami in the Bay of Plenty are a significant hazard during future eruptions (Buck, 1985).

For further details of volcanic hazards resulting from an eruption at Mayor Island, see Houghton et al., (1995b) and a hazard map and recommendations for the emergency management sector are given by Buck (1985).

Mayor Island is monitored for unrest activity by GNS Science using a seismometer. There are two slightly heated crater lakes on the island, and there have been reports of warm springs on western beaches, however no regular sampling currently takes place.

3.4 Okataina Volcanic Centre

The Okataina Volcanic Centre (OVC) has been the source of multiple, mostly rhyolitic eruptions for over 550,000 years. A number of caldera collapses have occurred producing very large eruptions, collectively forming a 16 km x 27 km topographical rim as shown in red in Figure 7 (Nairn, 2002). The complex series of collapses in the north and south of the OVC is called the Haroharo Caldera. More recent intra-caldera eruptions deposited lava domes (such as the voluminous Tarawera and Haroharo dome complexes) and pyroclastics on the caldera floor, covering many of the older individual structure outlines. Lakes lie on the caldera floor between the caldera rim and younger lava domes, in places concealing the caldera rim. Parts of the rim are also hidden by ignimbrites originating from neighbouring calderas, such as in the south-western area of OVC. Tectonic faulting has continued to alter the area (Cole et al., 2010).

The eruptions at Okataina in the last 26,500 years have generally followed a similar pattern – explosive pyroclastic eruptions which have produced widespread ashfalls, followed by the extrusion of thick rhyolitic lava flows with associated near-source block-and-ash flows. Multiple vents were active at the same time, often separated by several kilometres (Nairn, 1991). This is likely to be repeated in future eruptions. However some eruptions show that low viscosity basalt has been involved as well (such as the most recent eruption in 1886). The styles of eruptions can vary when mixed magma types are involved. Very large, caldera-forming eruptions have also occurred in the past. Magma interacting with shallow groundwater or surface water has also occurred at OVC, causing large steam explosions. This occurred in 1886 at Rotomahana during the Tarawera eruption, causing most of the casualties from this event (Nairn, 1991). Periods of quiescence between volcanic activity have varied between 700 and 3000 years (Nairn, 1991).

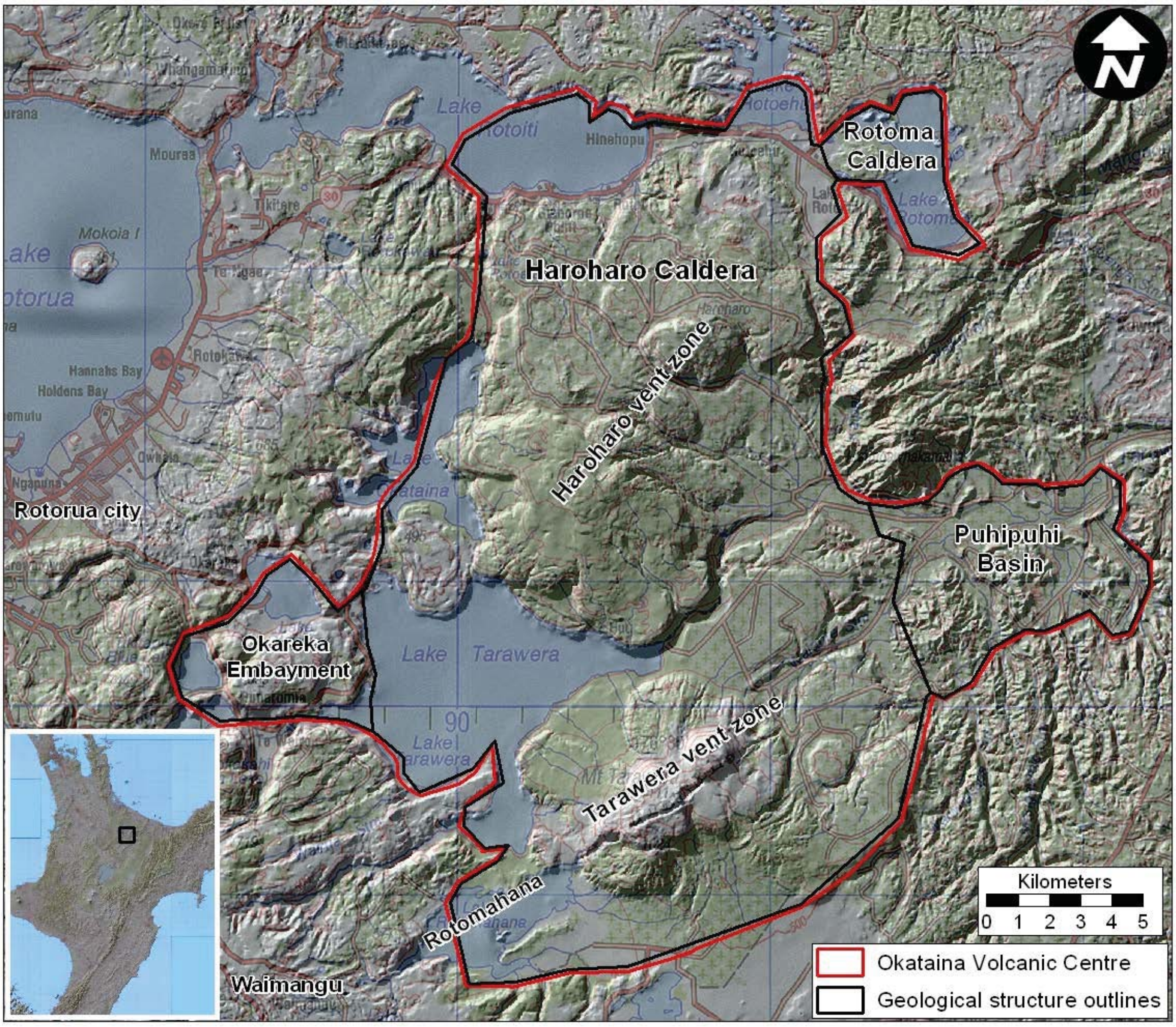

Figure 7 Okataina Volcanic Centre and major geological structures. Inset bottom left shows the map position in the North Island. Based on Nairn (2002).

3.4.1 Eruptions

A large ignimbrite forming eruption (with an erupted magma volume of possibly 90 km^3), which was probably accompanied by caldera collapse, occurred at 550,000 yrs BP with a vent source in the southern part of the OVC and covers earlier dissected lava domes in the OVC area (Cole et al., 2010). Further eruptions occurred 320,000 yrs BP (Leonard et al., 2010), culminating in an enormous 160 km^3 rhyolitic eruption, producing a pyroclastic flow that reached the Bay of Plenty coast, forming the Matahina Ignimbrite deposit (Nairn, 2002). This contributed to caldera collapse of the southern portion of the OVC and possibly the Puhipuhi Basin (Figure 7) (Nairn, 2002). The Puhipuhi Basin was afterwards filled by a lake. This lake deposited sediments which were subsequently uplifted and a dacitic eruption occurred here (date unknown but older than 61,000 yrs BP; Nairn, 2002; Cole et al., 2010).

There are several lava dome and dome complexes preserved at the surface dated between 550,000 and 61,000 years ago (Leonard et al., 2010), with others likely obliterated by younger caldera eruptions or buried. These probably followed broadly similar eruption styles to those of the younger Haroharo and Tarawera lava domes. Following further rhyolitic lava and pyroclastic eruptions, the northern part of the OVC collapsed approximately 61,000 yrs BP in a large (>100 km^3) rhyolitic eruption called the Rotoiti episode and formed part of the

Haroharo Caldera (Cole et al., 2010). This eruption may have been triggered by a basaltic scoria eruption (Pullar & Nairn, 1972; cited in Nairn, 2002). Between 61,000 yrs BP and 26,500 yrs BP, at least 12 plinian eruptions of the Mangaone Subgroup occurred, as well as two pyroclastic flows (Cole et al., 2010). This includes the ~20 km^3 Kawerau ignimbrite eruption, approximately 33,000k yrs BP which may have caused minor caldera collapse in the southern OVC (Spinks, 2005; cited in Cole et al., 2010). Rotoma and Okareka areas collapsed due to lateral magma migration during this eruption (Cole et al., 2010).

Nine rhyolitic eruptions have taken place in the past 26,500 years building the Tarawera and Haroharo dome complexes within the Haroharo Caldera rim, with a combined erupted magma volume of 85 km^3 (Nairn, 2002). These differ from the preceding Mangaone Subgroup in that they have a significant lava volume, rather than being mostly pyroclastic. The various OVC caldera structural outlines have largely been buried by these younger deposits. The Haroharo complex consists of rhyolitic lava flows and domes, and plinian pyroclastic fall and flow deposits (Cole et al., 2010). There was a small basaltic rift eruption near the western margin of the caldera 3400 years ago (Nairn, 2002). There are other small basalt eruption deposits in the Okataina area, and overlapping with the edge of the Rotorua area.

The Tarawera complex (or vent zone, Figure 7) is slightly younger and includes block-and-ash flow deposits. It was the source of eruptions in 1314 AD (Leonard et al., 2010) and 1886 (Cole et al., 2010), the two most recent eruptions from OVC. The rhyolitic Kaharoa eruption in 1314 (AD) had a duration of approximately 4 years, and erupted 4 km^3 of material. It was the largest eruption in New Zealand in the past 1,000 years, and the most recent rhyolitic eruption in New Zealand (Leonard et al., 2010; Johnston et al., 2004). The source of this eruption was an 8 km line of vents across the Tarawera dome complex (Nairn et al., 2001, 2004). The eruption included plinian events, phreatomagmatic explosions, pyroclastic flows, and the extrusion of lava domes which collapsed and caused block-and-ash flows. It is thought to have been triggered by a basaltic intrusion (Leonard et al., 2002). A large breakout flood occurred when the temporary blockage consisting of eruption debris at the lake outlet was breached, after the Kaharoa eruption (Hodgson & Nairn, 2005). A similar but smaller event occurred in November 1904 after the 1886 Mt. Tarawera eruption.

The 10 June 1886 Tarawera Rift eruption produced basaltic scoria from Mt. Tarawera and a mix of basalt and phreatomagmatic mud and breccia from the neighbouring Rotomahana basin and Waimangu Valley (Figure 7). This marked a significant difference in the magma composition compared to a long history of predominantly rhyolitic eruptions. This eruption is the largest to have occurred in New Zealand’s recorded history. The eruption began at about 1:30 am from vents along the top of Mt. Tarawera, producing an ash column 10 km high and deposits of basaltic scoria (Nairn, 1991). Within an hour, Rotomahana and Waimangu, both southwest of the Tarawera vent lineation, were also in eruption, totalling 17 km of active rift eruptions. The rift on Mt. Tarawera as it looks today is shown in Figure 8.

Figure 8 Rift on Mt. Tarawera, Okataina Volcanic Centre, formed in the 1886 basaltic eruption, showing the red scoria deposits. View towards the southwest. Photo GNS Science.

The eruptions at Rotomahana were particularly explosive, caused by the interaction of basaltic magma and a large hot hydrothermal system. This generated very violent pyroclastic surges and thick deposits of mud, which caused the collapse of buildings and contributed towards most of the fatalities from this eruption (Nairn, 1991). Extensive lightning took place in the eruption cloud, setting fire to a house and the forest, and fissures in the ground caused travel difficulties post-eruption. Strong winds (possibly eruption blasts) caused trees to be knocked over, and volcanic gases caused breathing difficulties (Nairn, 1991). Tephra was deposited on the land and sea in a north-eastern direction, and caused darkness during the day over a wide area. The eruption ceased at approximately 6 am, after killing 108 people (Nairn, 1991). Hydrothermal explosions continued to occur in the area for several weeks, and steam was emitted from the volcanic vents for months (Simmons et al., 1993). The Rotomahana-Waimangu area is now host to a large new surface expression of a geothermal system (Scott, 1994).

3.4.2 Historical unrest

Research by Leonard et al., (2002), Nairn et al., (2004) and Sherburn and Nairn (2004) on the 1314 AD Kaharoa rhyolitic eruption from Okataina Caldera suggest precursors to this eruption may have been detected up to years in advance had the current monitoring network been in place (Johnston et al., 2004).

In contrast to the interpretation the rhyolitic Kaharoa event, no significant unrest was recorded in the days or months prior to the 1886 basaltic eruption at Mt. Tarawera. “Peculiar waves” were seen on Lake Tarawera, 0.3 m high, 10 days before the eruption which may have resulted from magma-related ground movements (Nairn, 1991). One hour before the onset of the eruption, earthquakes were felt in nearby areas, increasing in intensity until the eruption (Keam, 1988; Nairn, 1991).

Historical unrest of the OVC has not been studied in detail. Volcano monitoring equipment has recorded height changes across the caldera (including approximately 50 mm of subsidence between 1980 and 1984) (Scott, 1989), activity in the Waimangu hydrothermal system, including relatively frequent hydrothermal eruptions as described by Scott (1994), and seismic activity (GNS Science earthquake catalogue). The best recorded seismic swarm occurred in April 1998, centred on the Haroharo vent zone. Over 400 earthquakes >M1.7 were recorded, however only 4 were reported as felt. The maximum earthquake had a magnitude of 4.7, and a felt intensity of MM4.

Another seismic swarm was centred on Rotoehu in 2004, over the boundary of the northern caldera margin. Over 1,300 earthquakes (>M1.7) were recorded from July 1st – August 5th, with magnitudes of up to 5.1. This event was interpreted by GNS Science staff to be a mainshock-aftershock event (Hurst et al., 2008).

3.4.3 Potential future activity

The 1886 Mt. Tarawera eruption was small compared to most OVC eruptions, with a different magma composition, therefore it is unlikely to be representative of future eruptions. It is expected that the next eruption will be larger and more similar to the majority of the eruptions from the past 60,000 years, following the pattern of a rhyolitic pyroclastic eruption (tall ash columns, ash fall and flows), followed by the extrusion of lava flows and domes, with associated block-and-ash flows (Nairn, 1991, 2002). The likely unrest is reviewed by Sherburn and Nairn (2004). A description of the volcanic hazards is in Nairn (1991) and Scott and Nairn (1998) (Figure 3).

Today there are nine seismic monitoring sites and seven cGPS sites monitoring deformation in the OVC. The geothermal systems are monitored by collecting the temperature and water levels or overflows of the large crater lakes at Waimangu and by chemical sampling of selected hot springs.

3.5 Rotorua

Rotorua Caldera collapsed at the end of the very large (145 km^3) Mamaku plateau formation eruption in 240,000 yrs BP (Gravley et al., 2007). This eruption coincided with the Ohakuri eruption 30 km to the south. The Kapenga area collapsed associated with this eruption, probably due to magma withdrawl, and this is the only confirmed collapse episode in the Kapenga area. The ignimbrites from the two sources were emplaced only a few weeks apart, and in some areas overlap. At some stage after these explosive eruptions rhyolitic lava was extruded forming domes including Ngongotaha and Mokoia Island (Leonard et al., 2010). It is unknown when the most recent eruption at Rotorua Caldera occurred, but it appears to be at least 20,000 years ago.

Rotorua Caldera incorporates the Rotorua and Eastern Rotorua geothermal fields (Leonard et al., 2010). Parts of these geothermal fields have been developed as popular tourism attractions, bringing people to these areas. Hydrothermal explosions have occurred in the city of Rotorua a number of times, possibly due to changes to the geothermal system introduced by exploitation. The most recent significant (but relatively small) hydrothermal explosions occurred at Kuirau Park (an inner-city park containing a number of hydrothermal features) in January 2001 (Figure 9) and December 2006. A number of deaths have occurred from people (mainly children) falling into boiling mud pools and hot springs. The main gases emitted by Rotorua's geothermal system are hydrogen sulphide (H_2S) and carbon dioxide (CO_2), both of which are denser than air and toxic (Durand & Scott, 2005). 14 fatalities have occurred from gas poisoning in this district of approximately 70,000 people. These have occurred in small, low, constricted spaces such as natural hot spa baths, when patrons have been overcome by H_2S gas (Durand & Scott, 2005). A study by Durand and Scott (2005) on several Rotorua city buildings showed potentially dangerous and damaging levels of gas (H_2S and CO_2), emitting from cracks in paving, from waste water drains and in narrow, low down spaces, as well as inside buildings.

Land use management can restrict development of geothermal areas at risk of future hazardous activity, during caldera unrest or regular geothermal system processes. Mitigation measures typically include set backs from surface activity for buildings and infrastructure, and restrictions on covering warm and hot ground. Significant geothermal features are typically fenced for safety.

Figure 9 Kuirau Park hydrothermal crater (bottom right) and deposits, 2001, in Rotorua city. Photo by the Daily Post.

No major seismic swarms have occurred inside the Rotorua Caldera in the past ten years, however there is an area of potentially higher seismicity in the southern portion of the caldera (Bryan et al., 1999). Small swarms have been recorded, including those in 1994, 1998, 1999, 2000 and 2001. The 2001 overnight seismic swarm was the largest, with magnitudes of up to 3.2, and over 50 earthquakes recorded in 2 hours, 14 of which were recorded as felt.

GeoNet has four seismometers and one strong motion seismograph within the Rotorua caldera and three GPS stations. They also conduct regular sampling of selected hot springs and bores. The BOP Regional Council has a monitoring programme in place to record the surface geothermal features and borehole pressures and temperatures.

3.6 Kapenga

Gravley et al., (2007) suggest much of the Kapenga collapse structure formed during the Mamaku plateau formation (from Rotorua Caldera) and Ohakuri eruptions 240,000 yrs BP, rather than from an eruption at Kapenga itself. Kapenga has been suggested as the source of a number of ignimbrite and other eruption deposits, but this is unconfirmed (Leonard et al., 2010), and it should be referred to as a volcano-tectonic depression rather than a caldera due to the lack of caldera-collapse vents. This includes ignimbrite-forming eruptions in 300,000 yrs BP and 275,000 yrs BP, the latter with a volume of 100 km^3 of magma (Gravley et al., 2007; Leonard, 2003). Alternatively these could well have been from vents or calderas now buried below the Mamaku plateau.

Smaller, generally rhyolitic eruptions have occurred in the Kapenga area, forming lava domes and scoria deposits. Hydrothermal explosion deposits have also been identified within Kapenga (Leonard et al., 2010).

Due to the length of time this caldera has been dormant, it is unlikely (but cannot be ruled out) that Kapenga will erupt again in the future. No research has been done on historical unrest at Kapenga, therefore no unrest episodes are known to have occurred. Many shallow earthquakes are recorded in the Kapenga area, however it is difficult to determine the source of these events. The Rotorua-Taupo Fault belt runs through the area so much of the seismicity is probably tectonic.

GeoNet has two seismometers in this area and four more nearby that would help locate events. There are also two GPS stations.

3.7 Ohakuri Caldera and Maroa Volcanic Centre

The >100 km^3 ignimbrite-forming Ohakuri eruption probably occurred at ca. 224,000 yrs BP (Gravley et al., 2007). This eruption caused the collapse of Ohakuri Caldera (Leonard et al., 2010). The Ohakuri eruption coincided with a large eruption at Rotorua Caldera which formed the Mamaku ignimbrite (Mamaku Plateau Formation), and it is likely have also caused subsidence of the Kapenga area (Gravley et al., 2007).

Whilst Maroa Volcanic Centre contains no caldera, a brief summary of its volcanic history is included here as it borders Ohakuri caldera closely. There is no clear link between the magmatic systems of these two centres (Leonard, 2003). Volcanism at Maroa was most intense prior to 200,000 yrs BP (Leonard, 2003). In the past 61,000 years, there have been at least four eruptions from this centre, all relatively small (with magma volumes of <0.2 km^3), in 45,000, 43,000 and 40,000 yrs BP (Wilson et al., 2009). Rhyolitic lava domes and dome complexes dot the surface of the Maroa Volcanic Centre, along with ignimbrite deposits. The most recent eruption from the Maroa Volcanic Centre was 16,500 yrs BP, with a volume of 0.14 km^3 (Lloyd, 1972; Leonard, 2003).

Leonard (2003) stated that the probability of a future eruption is at the Maroa Volcanic Centre, based on the rhyolite and basalt eruptive episode history of the centre over the last 100,000 years, approximately 0.7% in an 80 year lifetime, and the most probable eruption size in the future is (<0.1 km^3) based on the more recent eruptions. No known historical unrest has been recorded at Maroa Volcanic Centre except for regional earthquake activity and hydrothermal eruptions at Orakei Korako.

GeoNet has four seismometers in this area and three more nearby that would help locate events. There is also one strong motion instrument.

3.8 Reporoa

Reporoa Caldera collapsed during a single eruptive episode (Nairn et al., 1994; Leonard et al., 2010). The Kaingaroa Formation was deposited in 230,000 yrs BP (Houghton et al., 1995a) in the form of a widespread ignimbrite deposit (Nairn, 2002; Leonard et al., 2010). Rhyolitic lava domes have been erupted in the Reporoa area, dated as both older and younger than the Kaingaroa Formation (Leonard et al., 2010). Small basalt eruptions have occasionally occurred in this area.

Due to the length of time this caldera has been dormant, it is unlikely (but cannot be ruled out) that Reporoa Caldera will erupt in the near future. No research has been done on historical unrest at Reporoa Caldera, therefore no unrest episodes are known to have occurred. The area does experience regional earthquake activity and there are two areas of hot springs.

GeoNet has three seismometers in this area and three more nearby that would help locate events. There is also one strong motion instrument.

3.9 Mangakino

Very large ignimbrite-forming eruptions have been attributed to the Mangakino Caldera, occurring between 1.6 million and 950,000 yrs BP, the latter with a volume of 50 km^3 (Houghton et al., 1995a). Rhyolitic lava domes were also erupted during this period (Leonard et al., 2010).

No research has been done on historical unrest at Mangakino Caldera, therefore no unrest episodes are known to have occurred. Due to the length of time this caldera has been dormant, including a lack of any known smaller intra-caldera eruptions, it is unlikely that Mangakino Caldera will erupt in the near future, but this older caldera system is included here for completeness.

GeoNet has one seismometer in this area.

3.10 Whakamaru

Whakamaru Caldera was the source of a very large eruption about 350,000 yrs BP, erupting 1,500 km^3 of magma (Leonard et al., 2010; Wilson et al., 2009). An eruption 10,000 years later deposited an additional 500 km^3 of magma (Wilson et al., 2009). This is the most recent caldera-forming eruption at Whakamaru. It seems unlikely that Whakamaru will erupt in the near future; this is due to (a) the very long time period since these eruptions, and (b) the presence of the younger Maroa Volcanic Centre and part of Taupo Caldera overlapping the older Whakamaru Caldera – both have different magma chemistry to the older eruptions, suggesting that a quite different magma system configuration in the area now exists.

No research has been done on historical unrest at Whakamaru Caldera, therefore no unrest episodes are known to have occurred. However the estimated Whakamaru Caldera boundary envelops a large area of the TVZ, and includes the Wairakei-Tauhara, Rotokawa and Mokai geothermal fields, and parts of the Orakei-Korako and Atiamuri geothermal fields (Leonard et al., 2010), numerous active fault lines (including the Taupo Fault Belt), and part of the Taupo and Maroa Volcanic Centres. Therefore the Whakamaru Caldera area has been the source of numerous hydrothermal explosions, deformation and seismicity in the geological and historical past, but these events cannot be attributed to (or in fact excluded from) caldera processes.

GeoNet has three seismometers in this area and three more nearby that would help locate events.

3.11 Taupo

Taupo caldera is located in the central North Island of New Zealand and is the southernmost caldera of the TVZ (Figure 1). It has a complex history of both very large and very small eruptions, most of which were rhyolitic in composition. The most recent eruption in 232 AD (A. Hogg, pers. comm., 2010) was very large and destructive, but not representative of the most common size of eruption over the past 27,000 years (Wilson, 1993).

Figure 10 Taupo caldera viewed towards the southwest, with Taupo township located on the north-eastern shore. The Waikato River (in the foreground) is the outlet from Lake Taupo and a source of water and electricity generation for the upper North Island. Photo by Lloyd Homer, GNS Science.

3.11.1 Eruptions

Taupo volcano has been active for at least 330,000 years (Pringle et al., 1992; Wilson et al., 1986). The eruptive history between 330,000 yrs BP and 65,000 yrs BP is poorly understood as the deposits have been either buried or destroyed by subsequent eruptions (Wilson, 1993). Between 65,000 yrs BP and 27,000 yrs BP there were approximately ten eruptions from the Taupo Volcanic Centre, at least five of which were explosive (Vucetich & Howorth, 1976; Wilson et al., 2009). Taupo has an average magma output rate of 0.2 m^3s^{-1} over the past 65,000 years, and is the most productive individual rhyolitic volcano in the world (Crisp, 1984; Wilson, 1993). Small basalt eruptions have also occasionally occurred in the Taupo Volcanic Centre.

The Taupo caldera was largely formed during the cataclysmic Oruanui eruption (Wilson, 1993) at 27,000 yrs BP (Bard, 1998; Wilson et al., 1988). This event had a total magma equivalent volume of 530 km^3 that was erupted episodically over a period of several months (Wilson, 2001). The eruptive style was a complex interaction of magma and water, producing widespread tephra falls interspersed with pyroclastic density currents (Wilson, 2001). Deposits from this eruption formed a dam containing a large volume of water, producing huge floods down the Waikato River when it collapsed.

Twenty-seven of the twenty-eight eruptions that are known to have occurred after the Oruanui eruption formed pyroclastic (tephra and/or pyroclastic density current) deposits, with only one deposit consisting solely of a lava extrusion. Periods of quiescence varied between approximately 20 to 6000 years, and eruption size varied as the volumes of magma erupted ranged from 0.01 (a similar size to Ruapehu's 1995-96 eruption) to 35 km^3 (Wilson, 1993; Wilson et al., 2009). Eruption styles were widely diverse, which will cause difficulties in predictions for future eruptions.

The most recent eruption from the Taupo Volcanic Centre was in 232 ±5 AD (A. Hogg, pers. comm. 2010), which altered the shape of the caldera (Wilson, 1993). This eruption devastated 20,000 km^2 of surrounding land due to widespread tephra falls and ignimbrite-forming pyroclastic flows travelling up to 70 km away from the lake (Wilson & Walker, 1985). It started with a small, wet eruption and increased in size and violence, with the occasional pause of up to three weeks. The majority of the deposits were emplaced in the final stage of the eruption when the magma chamber roof collapsed and a particularly energetic pyroclastic flow travelled at a velocity of 200-300 ms^{-1} radially outwards from the vent in the north-east part of Lake Taupo, lasting about 6.5 minutes (Froggatt, 1981; Walker, 1984; Wilson & Walker 1985). Following this eruption, the lake refilled over several years reaching a level approximately 30 m higher than the present day level for 15 – 40 years (Manville et al., 1999). Once the water cut through the ignimbrite layers damming the lake, it overflowed with a volume of up to 35,000 m^3/s, flooding large areas downstream and lowering the lake level to approximately 10 m higher than the present day level. At this stage, Wilson and Walker (1985) state a further small lava extrusion occurred, possibly forming Horomatangi Reef. Large pumice blocks floated to the surface and came to rest at the lake edge nearby.

3.11.2 Historical unrest

European settlement and the act of writing down events in the Taupo region began in the mid-nineteenth century. There is no unrest record before this time. Four previously recognised episodes of caldera unrest have occurred at Taupo in 1895, 1922, 1964-5 and 1983 (Johnston et al., 2002) as described below. Recent research by one of the authors (Potter) has indicated many more episodes of unrest have occurred at Taupo caldera than had previously been recognised. These episodes range in magnitude from minor unrest (such as earthquake swarms with 15 – 20 earthquakes felt in one day), to months of seismic swarms causing building damage. This research will be published in the near future. Taupo's unrest episodes have included deformation, hydrothermal activity and earthquake swarms, resulting in public alarm, self-evacuations and decreased levels of tourism. They indicate that, had the current VAL system existed during these episodes, they may have been assigned a level of VAL 1 or even up to VAL 2.

Unrest in 1895 began on 17th August with an earthquake of shaking intensity MM8 (Eiby, 1968) striking Taupo and causing widespread damage. Most of the town's chimneys collapsed, bottles and crockery were smashed, and "chaos reigned supreme" (Poverty Bay Herald, 19 and 20 August 1895). Landslides blocked roads around the lake, and residents and visitors camped outside overnight. A 0.6m wave was seen on Lake Taupo and springs in the Hatepe region emitted quantities of fine pumice (Hawke's Bay Herald, 20 August 1895).

Springs changed temperature and tremors continued until at least September 1895 (Poverty Bay Herald, 2 September 1895). It is uncertain whether an event such as this should be classed as unrest, or if it was just a large regional tectonic earthquake.

The largest episode of caldera unrest known to have occurred in New Zealand during historical times (without an eruption) was in Taupo, lasting for 10 months from April 1922 until January 1923. Earthquakes were felt in the Taupo region throughout this period, with the most severe shake on 10th June, and 57 earthquakes felt in 8 hours on 25th June (The Evening Post, 28 June 1922). Fissuring and faulting, landslides and minor changes to activity at hot springs and geysers were reported. Subsidence of 3.7 m caused a sunken shoreline at Whakaipo Bay on the northern side of Lake Taupo, along with hundreds of water fountains emerging from ground cracks, causing flooding (Evening Post, 14 July 1922). Several chimneys collapsed in Taupo, Oruanui and Wairakei, bottles, crockery, books and other items were thrown on the floor, and the Taupo town clock stopped. Tourism was affected in not only Taupo, but also Rotorua due to incorrect international reporting (Evening Post, 7 July 1922).

Earthquakes increased in number and intensity from September 1964, and peaked in December 1964 with magnitudes of up to 4.8 (Eiby, 1966). 140 events per day were reported and over 1100 earthquakes over magnitude 2.7 were felt in two months (Gibowicz, 1973). Seismicity decreased again until February 1965 and a further small swarm occurred in December 1965. The epicentres migrated from Western Bay, Lake Taupo in early December 1964, to northern Lake Taupo by 21st December and then to Horomatangi Reef and Waihaha area by January 1965 (Gibowicz, 1973). Possible uplift of 90 mm near Horomatangi Reef was observed (Grindley & Hull, 1986) otherwise no faulting or deformation was reported.

Seismicity clustered in February and June 1983 with up to 30 tremors recorded a day. Uplift of 55 mm was followed by equivalent subsidence at a block west of Kaiapo fault, which ruptured on 23rd June (Otway et al., 2002). Minor damage from the earthquakes was reported, including cracked chimneys and fallen ornaments (Otway et al., 1984).

Hydrothermal eruptions have occurred in geothermal fields near Taupo, such as at the Wairakei Geothermal Field in July 1960, likely due to geothermal field developments, as well as in 2000 and March 2001. The Tauhara geothermal field had a hydrothermal eruption in June 1981 (Scott & Cody, 1982). It is unknown whether these were indicators of caldera unrest, were part of the normal hydrothermal system processes or induced by the production from the geothermal systems.

3.11.3 Potential future activity

Based on the frequency of unrest at Taupo caldera since European settlement, it seems likely that unrest activity will occur in the future. The lengthy swarms of earthquakes, metres of ground deformation and hydrothermal explosions seen in the past episodes will almost certainly be repeated in the future at varying intensities. Future episodes of unrest may include those larger than previously witnessed during Taupo's short settlement history, reflecting the scale of caldera unrest seen internationally. The town and surrounding areas should be prepared for large, damaging earthquakes and other hazardous unrest phenomena.

Future eruptive activity has been speculated on by Froggatt (1997) in the Civil Defence 'Volcanic Hazards at Taupo Volcanic Centre' publication (in the 'Yellow Book' series). He states that the next Taupo eruption is [more] likely to be on or near the Horomatangi Reef, where 32% of the eruptions in the past 27,000 years have taken place (Froggatt, 1997; Wilson, 1993). The chance of large pyroclastic flows in future eruptions is small, however the likelihood of magma/water interaction is high, which causes more explosive, rather than effusive, eruptions. The eruption size is most likely going to be small to medium and be preceded by significant deformation and geothermal changes (Froggatt, 1997). It is important to consider that nearly 70% of recent eruptions have, however been elsewhere in the northeastern part of the Taupo Volcanic Centre.

GeoNet monitors Taupo caldera with 6 permanent seismographs, 3 additional strong motion seismic sites, and 8 telemetered cGPS sites. There is a network of lake levelling sites around Lake Taupo, which is used as a giant spirit level to monitor tilt of the ground surface.

4.0 INTERNATIONAL CALDERAS – ERUPTIONS AND HISTORICAL UNREST

4.1 Introduction

A number of volcanoes worldwide are similar in magma chemistry, tectonic setting and past eruption styles to New Zealand's calderas. The examples used in this section are rhyolitic calderas of various sizes, some of which have erupted during historical times. New Zealand can learn from these occurrences, particularly from countries with long written records, to supplement the short history of this country. Campi Flegrei Caldera in Italy, and Long Valley Caldera in California (US) have shown moderate levels of unrest in the last few decades, raising concern over the management of these unpredictable and complex volcanoes. Building damage resulting from high levels of seismicity at Campi Flegrei prompted an evacuation of over 40,000 people, while in Long Valley, a nearby tourist resort town suffered economically from the unrest event. Unrest at Yellowstone National Park (US) is carefully monitored due to the very large eruptions in the geological past, and the high number of visitors to the park. Smaller historical eruptions have occurred at Rabaul, Papua New Guinea, following decades of unrest; Chaitén, Chile; Sakurajima in Aira Caldera, Japan; Taal in the Philippines; and the largest rhyolitic eruption in recorded history at Novarupta in Alaska (US). The locations of these calderas are shown in Figure 11, and a comparison of selected caldera activity summarised in Table 4.

4.2 Campi Flegrei (Italy)

Campi Flegrei Caldera is located on the edge of the city of Naples, Italy (Figure 11), which has a population of approximately 3.8 million people in the metropolitan area. It has a reasonably similar eruptive history to Taupo and Okataina, with large plinian, caldera-forming eruptions having occurred in the past. The most recent eruption within the caldera was a small cone-building eruption in 1538 AD. It is one of the only calderas in the world to have had a witnessed eruption (with prior unrest) from a rhyolitic caldera. Campi Flegrei has undergone intense volcanic unrest in the past few decades, with metres of uplift and damaging seismicity, with no resulting eruption. This unrest has caused serious social consequences including mass evacuations, as described below.

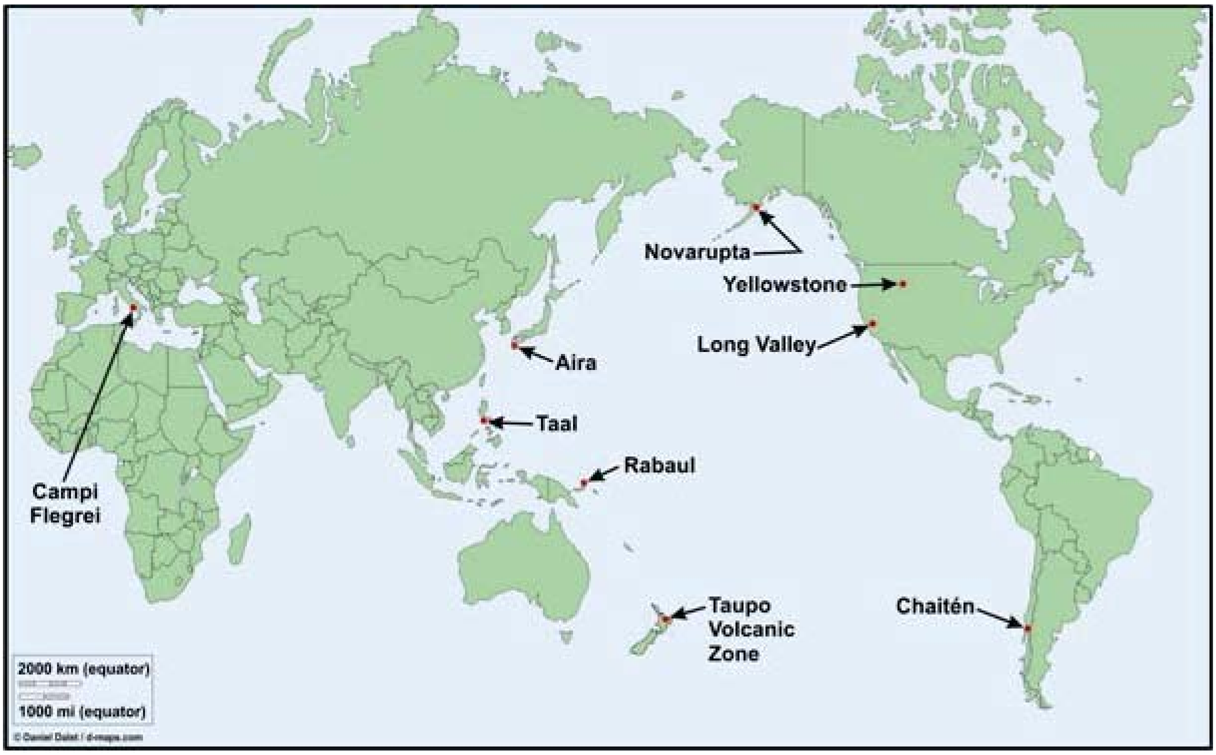

Figure 11 World map showing locations of young case study calderas similar to the Taupo Volcanic Zone calderas.

4.2.1 Eruptions

A large (~150 km^3) caldera-forming eruption occurred at Campi Flegrei approximately 39,000 yrs BP (De Vivo et al., 2001), with a further eruption (~40 km^3) 15,000 yrs BP (Deino et al., 2004). Prior to a period of intense volcanism 4,000 yrs BP, Campi Flegrei exhibited caldera-wide deformation of tens of metres (Isaia et al., 2009). At least 60 smaller eruptions have also occurred, the most recent in 1538 AD (Di Vito et al., 1999).

The 1538 AD eruption created a small cone called Monte Nuovo, centred within the Campi Flegrei Caldera boundary near the harbour town of Pozzuoli (Figure 12). The Campi Flegrei area was home to a few thousand people at the time (Dvorak & Gasparini, 1991). The unrest phenomena observed before this eruption are described in Table 5. The eruption began on 29th September 1538 with an explosive phreatomagmatic phase. It consisted of small pyroclastic flows for two days, and included pumice falling 8 km from the vent (Guidoboni & Ciuccarelli, 2011), followed by four days of only minor explosive activity (Di Vito et al., 1987). On 6th October an explosive eruption of scoria and small pyroclastic flows killed 24 people who were ascending the cone (Di Vito et al., 1987; Guidoboni & Ciuccarelli, 2011). The newly formed Monte Nuovo has an estimated volume of 0.025 km^3 and is 130 m high (Di Vito et al., 1987; Dvorak & Gasparini, 1991). The erupted scoria is phono-trachytic in composition (Piochi et al., 2005) with less silica than rhyolite (more similar to andesite and dacite), but more alkali content resulting in differences in the eruption style.

Table 4 Summary of selected international caldera unrest episodes. Refer to text for more details.

Caldera name	Date of episode	Seismicity	Deformation	Hydrothermal/ Gravity	Social response	Eruption?
Campi Flegrei Refer to section 4.2	1982-84	Hundreds of felt earthquakes, some large (<M4.2). Damaged buildings.	3.5 m uplift at Pozzuoli	Increase in the concentrations of gases such as H_2S and CH_4 at Solfatara, gravity measurements suggested a growing magma chamber.	40,000 evacuated	No
Long Valley Refer to section 4.3	1979-84	Seismicity waxed and waned from1982-84. 3 M6 earthquakes in 1 day, another was large enough to knock out electricity in 1983.	25 cm of uplift in < 6 months in the caldera, a further 7 cm over 4 years.		Anger, uncertainty and frustration felt by the public and some officials over the issue of a Volcanic Hazard Notice and its perceived effect on the economy. Plans updated and an extra access road ploughed.	No
Rabaul Refer to section 4.4	1983-85	Hundreds recorded per hour at times <M5.1. Low frequency earthquakes recorded.	3.5 m uplift from 1971 – 1984. <0.1 m per individual crisis (lasting hours to days).	Gravity changes measured between 1973-83.	Emergency plans developed, evacuation drills undertaken. Previous eruptions memorable so unrest readily accepted.	No (see text for 1994 eruption description)
Chaitén Refer to section 4.5	2008	24 hours of seismicity recorded on distant monitoring equipment before the eruption. Earthquakes large enough to knock objects off shelves in the town of Chaitén 10 km distant. 15-20 recorded per hour.	Not monitored	Not monitored	Town of Chaitén evacuated after start of eruption, subsequently overrun by lahars. Very short lead in time before eruption, but volcano wasn't monitored before the eruption.	Yes

Table 5 A description of the potential caldera unrest reported for 70 years prior to the 1538 AD Monte Nuovo eruption, Campi Flegrei, Italy. Based on Guidoboni and Ciuccarelli (2011).

Date	Seismicity	Deformation	Other
1470 – 1472	Intense seismicity (<MM7), causing damage to buildings in Pozzuoli		Increase in gas emissions, damage to vegetation
1475 – 1499	Occasional moderate sized earthquakes (background levels?)		
1500 – 1511	Large earthquakes (<MM8) in 1505 and 1508	Uplift in the order of meters at Pozzuoli in ~1502 as well as ~1510	
1512 – 1536	Only 1 reported earthquake, in 1520 (<MM7). Unconfirmed reports of a large earthquake and aftershocks in 1534		
1536	MM5 earthquake in Aug., period of seismic activity from Sep – Dec (<MM4)		Increase in gas emissions
1537	Intense earthquakes in Jan and Feb causing building damage (<MM8). Seismic activity continues for the rest of the year (<MM4)		Gas emissions continue to increase
Apr – Aug 1538	Earthquake in Naples on April 20th (MM6). Seismicity progressively intensifies		Earthquakes cause “great fear among the population”
1-27th Sep 1538	Intense seismicity (<MM6). Damage to buildings, residents sleep outdoors.		
28th Sep 1538	25 – 12 hours before the eruption, ~20 earthquakes felt. All buildings badly damaged.	31 hours prior to eruption, uplift (<4.5m[a]) of sea floor begins.	Dry wells fill with water
29th Sep 1538	Increase of seismicity (<MM6)	11 hours prior to eruption, ground subsides by 4m at vent site. 7 hours prior to eruption (until the time of the eruption), subsiding area starts to rise.	A water spring emerges at centre of depression Water emerges from cracks on uplifted area Vent opens in nearby sea floor, the activity advances to the uplifted area over half an hour, increasing in intensity
18:30, 29th Sep 1538	Very strong earthquakes accompany eruption		Eruption begins explosively, and lasts for at least 3 weeks (exact length unspecified)

[a]Uplift prior to this eruption could be as high as 8 m (Parascandola, 1946, cited in Dvorak & Gasparini, 1991).

Figure 12 Campi Flegrei Caldera map, showing the location of the cities of Pozzuoli and Naples, the geothermal field Solfatara and Monte Nuovo, formed in the 1538 AD eruption. From Dvorak and Gasparini (1991).

4.2.2 Caldera unrest

A number of unrest episodes have occurred at Campi Flegrei during historical times, involving deformation, hydrothermal system changes, gas emissions and damaging seismicity. After the 1538 AD eruption, further seismic swarms occurred periodically at Campi Flegrei without any eruptions (including in 1564, 1582, 1594, 1970-72, 1983-84) (Dvorak & Gasparini, 1991).

Ground deformation has been recorded unintentionally at the harbour town of Pozzuoli, near the centre of Campi Flegrei caldera by the presence of a Roman marketplace, thought to have been built during the first and second centuries A.D. (Dvorak & Mastrolorenzo, 1991).

The marketplace, called Serapis or Macellum, contains three 13 m high marble columns (Figure 13). Approximately 4 m above the floor of the marketplace, the columns contain a 3 m band of holes created by marine molluscs. This indicates that this area has been submerged into the sea in the past 2,000 years, and then uplifted again. After the 1538 AD eruption, the elevation of the land around Pozzuoli was not substantially altered until the mid-1800's (Dvorak & Gasparini, 1991). Further Roman ruins can be found on the sea floor at Pozzuoli, 14 m below present sea level, demonstrating the overall trend of subsidence over the past few decades (Barberi et al., 1984; Dvorak & Mastrolorenzo, 1991).

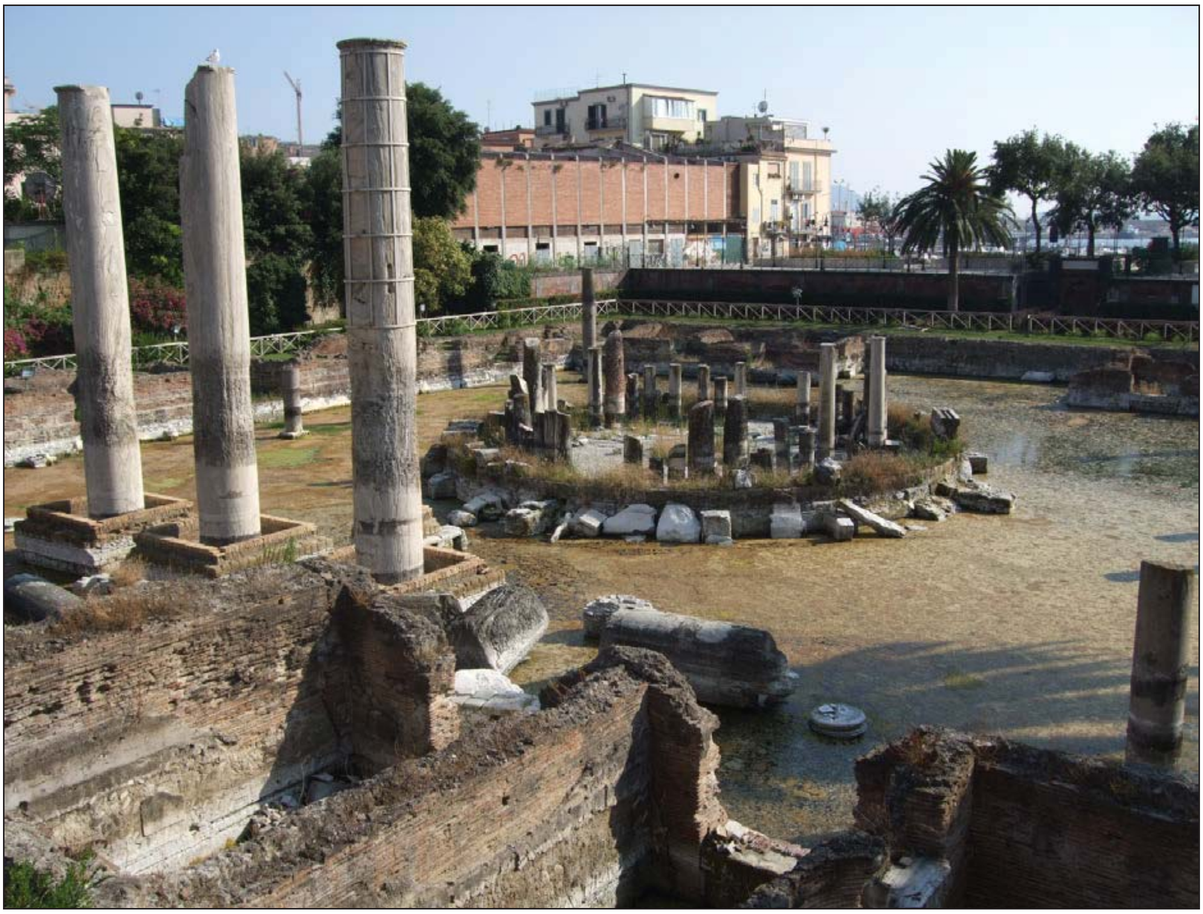

Figure 13 Serapis (or Macellum) Roman marketplace in Pozzuoli, with 13 m tall marble columns (left) showing discoloured bands of holes created by marine molluscs when submerged beneath the sea (which can be seen at the top right of the photo) during the past 2000 years. Photo by S. Potter.

Rapid uplift occurred during unrest episodes in 1969-72 and 1982-84 (Dvorak & Mastrolorenzo, 1991). The unrest episode from 1969-72 consisted of a net uplift of 1.5 m at Pozzuoli, and few felt earthquakes (seismicity was poorly monitored at that time) (Barberi & Carapezza, 1996). In 1970, an evacuation order was issued for 3000 people in Pozzuoli, which caused mass confusion and arguments over the need for evacuation, involving mass-media and lasting for the rest of the decade (Barberi et al., 1984). Different scientific panels were created and the separation of responsibility between the two was unclear, causing conflict. The need for one official Civil Defence Authority, and one official scientific agency with a minimum monitoring standard was identified. Unrest died down for the remainder of the 1970's.

Unrest in 1982-84 began with the local geothermal field (Solfatara) showing geochemical changes in the fumarole emissions, and with increases in the concentrations of gases such as H_2S and CH_4, however the temperatures stayed the same (Carapezza et al., 1984, cited in Barberi & Carapezza, 1996). This occurred before the onset of a net uplift of 3.5 m around Pozzuoli (De Natale et al., 2006). This in turn was followed seven months later by earthquake swarms causing damage to buildings, with magnitudes of up to 4.0 (Barberi & Carapezza, 1996). An evacuation of nearly 40,000 people occurred in 1983, many of whom had lived in the building structures which later collapsed (Barberi et. al., 1984). Gravity measurements were interpreted suggesting the growth of a subsurface magma chamber, however no upward migration of earthquake epicentres occurred (Barberi & Carapezza, 1996). Geochemical changes, seismicity and uplift had begun to decline by autumn 1984 (Barberi & Carapezza, 1996).

Minor unrest again occurred in 2004-06 in the form of small earthquake swarms, including periods of intense long period signals (Saccorotti et al., 2007). Based on the past, future eruptions will most likely be preceded by periods of uplift at Campi Flegrei. Whilst no eruption occurred as a result of these unrest episodes, eruptions at calderas may be a result of cumulative episodes of unrest (Dvorak & Gasparini, 1991). Therefore future episodes of unrest at this caldera will create high levels of uncertainty.

4.3 Long Valley (USA)

The Long Valley Caldera is located in eastern California, USA (Figure 14), and contains the ski resort town of Mammoth Lakes, with the neighbouring popular ski field Mammoth Mountain. Long Valley Caldera is approximately 30 km x 15 km in size, and Mammoth Mountain is a dacitic stratovolcano on the rim of the caldera boundary, which has exhibited unrest in the past few decades (Hughes, 2011). The population of this area is now approximately 8,000 permanent residents, with holiday and weekend tourists drawing an additional 15-20,000 skiers to the area per day (Mader & Blair, 1987). Volcanic eruptions at Long Valley Caldera most recently occurred approximately 250 years ago from the Mono-Inyo craters (Figure 14), and much of the area is covered in deposits from large eruptions in the past (Hildreth, 2004). Caldera unrest during the 1980's caused high levels of concern for the public and business owners due to the noticeable earthquakes as well as the perceived effect of the unrest and the way it was managed.

4.3.1 Eruptions

The Long Valley caldera-forming eruption occurred 760,000 yrs BP (Hill, 2006). Following this, a resurgent dome formed within the caldera. Smaller eruptions have also taken place to the northwest of the caldera, forming the Mono-Inyo domes, including the most recent (andesitic) eruption 250 years ago (Bursik & Sieh, 1989, cited in Hill, 2006). Tephra and ignimbrites have covered the area of the present day location of Mammoth Lakes town, indicating that it may be in danger during future eruption events (Kaye et al., 2009).

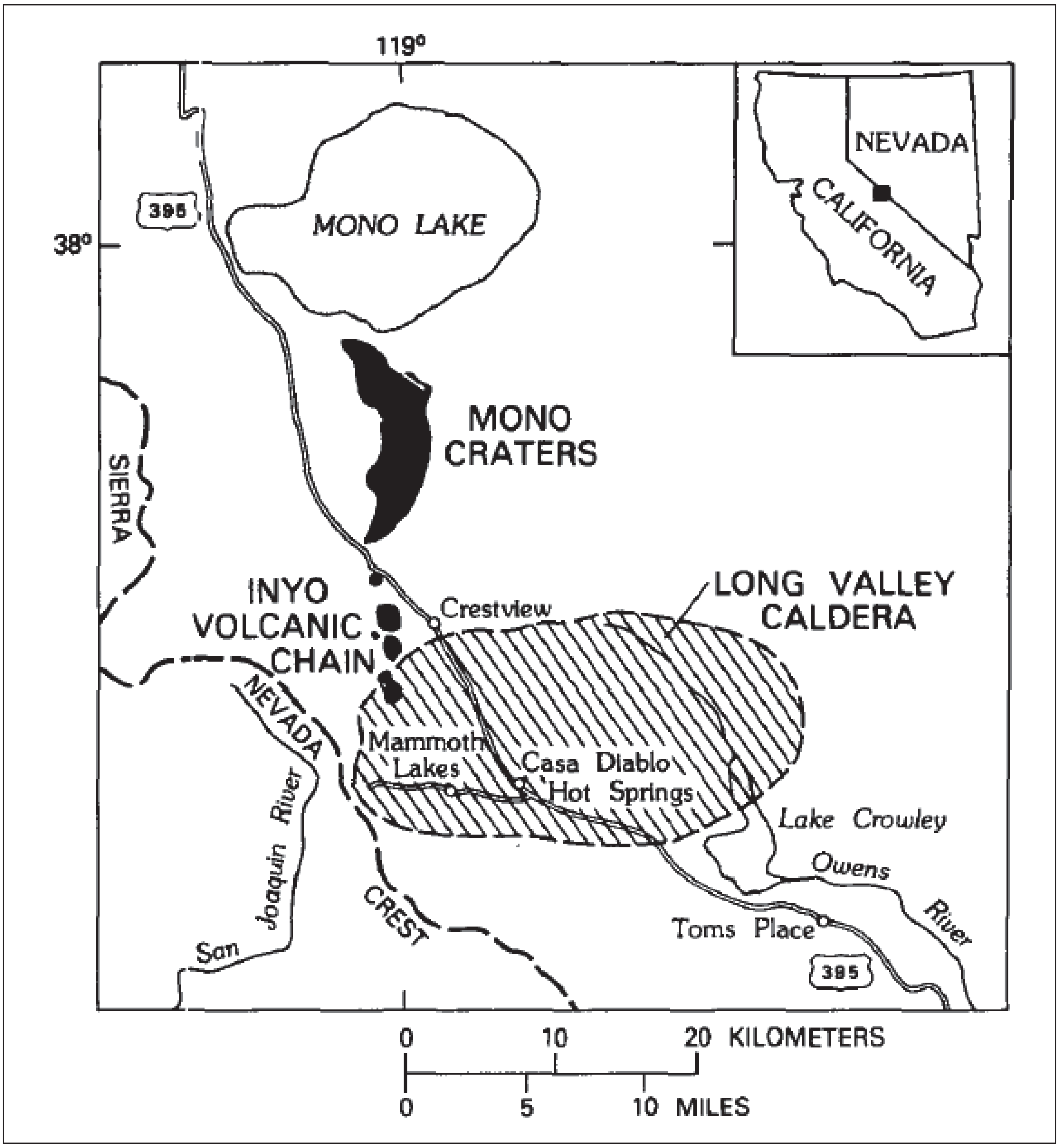

Figure 14 Long Valley Caldera, California map with the more recently active Mono-Inyo craters in black. The town of Mammoth Lakes lies within the caldera boundary on the road leading to the Mammoth Mountain ski area at the caldera margin. From Miller (1985).

4.3.2 Caldera unrest

Intensified unrest at Long Valley began in 1979, with seismicity culminating in three magnitude 6 earthquakes on 25th May 1980 (Mader & Blair, 1987). This prompted an official Earthquake Hazard Watch to be issued for the area two days later by the United States Geological Survey (USGS). Another magnitude 6 earthquake was felt later that day. Between the summer of 1979 and 1980, approximately 25 cm of uplift was recorded within the caldera (Savage & Clark, 1982, cited in Hill, 2006). Uplift continued by small amounts (7 cm) coinciding with seismic swarms until mid-1984 (Savage & Cockerham, 1984, cited in Hill, 2006). This combined with continuing seismicity of up to magnitude 5.9 just 2-3 km south of the caldera (Hill, 2006) resulted in a Notice of Potential Volcanic Hazard to be issued in May 1982.

The Notice caused outcry and alarm from the affected towns (particularly local business owners) due to the impact it had on the economy and tourist industry – the notice was seen as more of a problem than the hazard (Mader & Blair, 1987). This feeling was exacerbated by the Notice being leaked to and published by the media the day before it was officially released to the district officials and local public. It also happened to be Memorial Day Weekend, one of the busiest weekends of the year for the tourist town. The sense of mistrust of the scientists continued throughout much of the episode of unrest, to the point where there were reportedly incidents involving a scientist's car tyres being slashed, and death threats received. There was a perception that the Notice was dissuading tourists from visiting the town, however this is difficult to prove due to contributing factors, including a national recession, the bad weather during the start of the ski season, and the towns perceived negative image (Mader & Blair, 1987). The investment market and real estate industry declines were blamed on the volcanic hazard. Many of the public officials refused to believe their town was in danger from a volcanic event. This feeling continued until frequent earthquakes were felt, including shakes large enough to cause power outages in early 1983, at which time emergency plans including the construction of a second access road to the town were quickly arranged (Mader & Blair, 1987).

A change in the USGS volcanic hazard notification system in 1984 saw the removal of the Volcanic Hazard Notice. Residents saw the removal of this notice as the hazard terminating, rather than the change of system it really was (Mader & Blair, 1987). Since this time, improvements have been made in disaster preparedness and the monitoring network for the Long Valley area. The coordination of agencies and leadership of politicians proved vital during the unrest period. More cohesive systems have subsequently been developed (Mader & Blair, 1987). While unrest has declined since 1999, it continues at lower levels, including regional earthquake sequences and an average of 5 – 10 small earthquakes recorded per day in the area. Relatively high levels of CO_2 gas were emitted from 1989 to 2005 (Hill, 2006; Sorey et al., 2000), killing trees in the region and causing symptoms of asphyxia to be reported. Three members of a ski patrol died from gas poisoning on Mammoth Mountain, Long Valley caldera after falling into a snow cave melted by a fumarole (LVO monthly bulletins, GVP website). The USGS California Volcano Observatory (CalVO) website (http://volcanoes.usgs.gov/observatories/calvo/) describes the activity, of which no significant deformation changes have occurred since 2003.

4.4 Rabaul (Papua New Guinea)

Rabaul Caldera is located on the eastern end of New Britain Island, Papua New Guinea (Figures 11 and 15). It has a history of both very large and relatively small eruptions. Historical eruptions with preceding unrest have been witnessed, and eruptions from the small intra-caldera cone of Tavurvur are still occurring (Global Volcanism Program website). On the northern edge of the caldera is the town of Rabaul. The current population of Rabaul is approximately 8,000 people, however before the 1994-5 eruptions the surrounding area contained 70,000 people (McKee et al., 1985), most of whom were evacuated during the eruptive crisis.

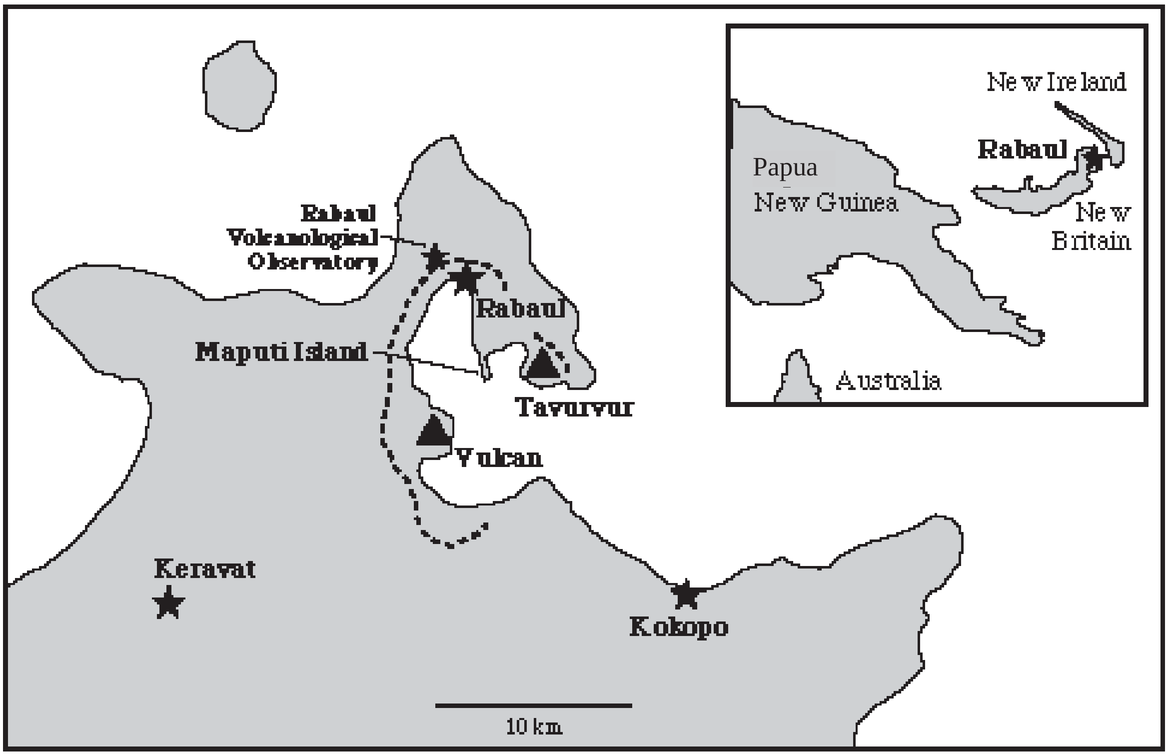

Figure 15 USGS map of Rabaul caldera (dashed line) showing location of Rabaul town and the recently active vents of Tavurvur and Vulcan (http://hvo.wr.usgs.gov/volcanowatch/1994).

4.4.1 Pre-historic eruptions

Rabaul volcano began as a largely basaltic shield, becoming more silicic over time, but it is important to recognise that it is still not rhyolitic and as such is somewhat unlike Taupo Volcanic Zone calderas. At least ten large eruptions have occurred in the 500,000 year life of the volcano (Nairn et al., 1995). The summit caldera formed to its present shape (8 km x 14 km) during the most recent of these large eruptions in 600 AD (Walker et al., 1981; Davies, 1995a). The caldera filled with water and is breached on the eastern side forming an entrance to the harbour of Blanche Bay. All 8 eruptions from within the caldera in the past 200 years have been small (0.3 km^3) (Davies, 1995a; Nairn et al., 1995). These small eruptions have built three basaltic to dacitic cones within the caldera. A number of the past eruptions at Rabaul were rhyolitic, however they are thought to have been triggered by a basaltic magma injection. This is similar to the triggering of eruptions at the Okataina Volcanic Centre in New Zealand (Nairn et al., 1995).

4.4.2 Historical caldera unrest and eruptions

Historical eruptions have occurred at Rabaul in 1767, 1791, 1850, and both Tavurvur and Vulcan erupted in 1878, 1937-43 and 1994 (McKee et al., 1985; Davies, 1995a).

The eruption in 1937 caused more than 500 fatalities in the first part of the four-day eruption (McKee et al., 1985). Precursors to this eruption included several days of intensifying seismicity, including a MM7 earthquake 30 hours before the onset of eruptive activity (Fisher, 1939, cited in McKee et al., 1985). No monitoring equipment was installed so it is not possible to accurately know the frequency and intensity of seismicity, or the amount of deformation. Johnson and Threlfall (1985), however, provide a description of the preliminary earthquakes, which were large enough to cause damage to buildings, and injure a small number of people. Rapid uplift of the harbour floor also occurred in the hours before the eruption (Johnson & Threlfall, 1985). This was in the order of metres and located within the caldera, and the resulting island was an object of curiosity that drew spectators and fish collectors to it. While some of these people escaped the eruption which began very soon after, others were killed. The eruption from Vulcan, at the site of the uplift, deposited a thick layer of ash, mud and pumice mainly towards the west. The eruption proceeded swiftly to catch the residents unaware and engulf them in darkness caused by the ash clouds. An informal evacuation of the affected areas occurred in response to the natural warning signs. Fallen trees and abandoned vehicles became obstacles as residents attempted to flee in the impenetrable darkness caused by the densely falling tephra. Issues arising during and immediately after this eruption included deep ravines in the ash deposits caused by erosion from heavy rain, flooding, electric shocks as the electricity remained on despite fallen powerlines, and suspected gas poisoning due to emissions from volcanic vents. The threat of disease was also attributed to rotting food left behind in the evacuation and standing puddles contributing towards outbreaks of malaria (Johnson & Threlfall, 1985).

The eruption of Tavurvur in June 1941 was preceded by a rise in ground temperature in the 1878 crater on Tavurvur, a large earthquake a few months before the eruption (which may or may not be related to the volcanic activity), increases in hydrothermal activity and changes in gas chemistry as recorded by the newly installed volcano observatory (Johnson & Threlfall, 1985). The eruption lasted until early to mid-1942, by which stage Rabaul town had switched from being the base for Australian WWII soldiers, to become home to the invading Japanese army. This eruption period had fluctuations in eruptive intensity, with weeks of quiescence. Rocks were thrown more than a kilometre from the active vent, setting fire to surrounding dry grass, and ash and gas clouds covered Rabaul town. No eruptive activity took place from mid-1942 until November 1943. A Japanese seismologist monitoring the volcanoes noted increasing earthquakes and ground tilt of the volcano before this last short eruptive period within the 1941 – 1943 episode (Johnson & Threlfall, 1985).

McKee et al., (1985) describe the unrest events of the 1970’s and 1980’s. Two large (M8.0) tectonic earthquakes occurred in the nearby Solomon Sea in 1971, after which changes at Rabaul Caldera began to be noticed. Uplift, tilt and changes in gravity data were accompanied by seismic swarms containing hundreds of shallow earthquakes (with a maximum magnitude of 5.2 in 1980), creating an elevated background level of activity. The level of unrest escalated in 1983, perhaps in relation to a M7.6 earthquake 200 km east of Rabaul in March 1983. The unrest consisted of short periods described as “crises”, which typically contained hundreds of recorded earthquakes in the space of an hour, with a maximum felt intensity of MM3-4 in Rabaul. Uplift within the caldera increased from a background level of 8 mm per month in the 1970's, to an average rate of 50 mm per month from November 1983 until May 1984. The maximum amount of uplift during an individual crisis was 100 mm. There was a total uplift of 3.5 m between 1971 and 1984. Gravity changes and horizontal deformation were recorded. Low frequency earthquakes were recorded, however no shallowing trend of any seismicity was observed and the crisis periods did not continue to intensify.

According to Davies (1995b), this unrest episode caused some preparedness actions to take place. An additional airstrip and wharf were constructed, and the private sector took measures to protect their equipment by storing it in safer areas. Response plans and legislation were updated. For the next decade, occasional episodes of increased seismicity and deformation occurred (Nairn & Scott, 1995). In 1990 six people were killed when overcome with CO_2 gas poisoning while collecting bird eggs in a small crater on the side of Tavurvur cone (as described by Rabaul Volcano Observatory bulletins, Global Volcanism Program website (www.volcano.si.edu)).

In September 1994 two vents within the caldera (Tavurvur and Vulcan) began erupting just 27 hours after the most recent onset of unrest in the form of two M5.1 earthquakes. Uplift of up to 6 m was observed just hours before the eruption commenced, and there was a 2 – 3 m tsunami in the harbour. There were concerns that the small eruptions could lead into a large scale eruption (Davies, 1995b). 45,000 people were evacuated, and the eruption claimed five lives (Davies, 1995a). The eruption from the Tavurvur cone (Figure 16) has remained intermittent since 1994, albeit at a smaller scale than the initial outbreak of activity. The Global Volcanism Program website contains updated information on the Rabaul eruption.

Figure 16 Tavurvur in eruption in November 2008 with the town of Rabaul in the foreground. The topography forming the southern caldera rim is in the background. Photo B.J. Scott.

Volcanic hazards including air-fall tephra and the fall of mud-rain, pyroclastic flows and surges, pumice rafts in the water, volcanic gas discharges, lightning strikes, tsunami, earthquakes, torrential runoff and lahars (volcanic mudflows) have been involved in previous eruptions at Rabaul, and are likely to be hazards in future eruptions. Very large caldera-forming eruptions could also occur in the future, causing large areas of destruction from eruption products, ground shaking and tsunami.

After the 1937 eruption, a recommendation to move the town of Rabaul was made, but the attraction of the port overrode this, and the town suffered again in the 1994 eruption (Davies, 1995b). During historical times, eruptions have occurred at Rabaul at intervals of between 24 and 59 years (Davies, 1995b), however the eruption which began in 1994 has continued (intermittently) until the present day.

Due to the rarity of the rhyolitic eruptions it is unknown how the precursory activity at these basaltic to dacitic volcanic eruptions (from within a large, previously rhyolitic volcano) differ from precursors before a predominately rhyolitic eruption, which is most likely to occur at Taupo Caldera and the Okataina Volcanic Centre.

4.5 Chaitén (Chile)

Chaitén volcano is located in the Chilean Andes (Figure 11), 10 km from the coastal town also named Chaitén. It is a rhyolitic volcano with a small (2.5 km x 4 km) summit caldera, which contains rhyolitic lava domes. Chaitén's most recent, and first historical eruption in 2008 is estimated to be the largest volcanic eruption in the world since the 1991 eruption of Hudson, also in Chile, and the largest explosive rhyolitic eruption in the world since the 1912 eruption of Novarupta, Alaska (Martin et al., 2009). The effects of this 2008 eruption included the evacuation of over 5000 people from surrounding areas as lahars swept through the town of Chaitén, airborne tephra causing airport closures disrupting international and domestic flights and impacts on the eco-tourism and aquaculture industries (Carn et al., 2009). Chaitén volcano was not scientifically monitored prior to the 2008 eruption, therefore low levels of unrest preceding the eruption would not have been recorded. Obvious signs of unrest (felt earthquakes) were only recognised for 24 hours prior to the onset of the eruption, implying unusually fast rates of rhyolitic magma movement beneath the surface. This is also supported by studies on the chemistry of the rocks (Castro & Dingwell, 2009). This has implications for hazard mitigation at rhyolitic volcanoes, particularly those not well-monitored, due to the very limited warning time.

4.5.1 Eruptions

The caldera-forming eruption at Chaitén occurred at approximately 9,370 yrs BP (Naranjo & Stern, 2004). This eruption was small to medium in size and consisted of a pyroclastic surge and tephra fall, followed by the deposition of mafic scoria (Naranjo & Stern, 2004). Following this eruption the caldera was partially filled by a rhyolitic lava dome.

The historical eruption of Chaitén began either in the evening of 1st May (Carn et al., 2009; Castro & Dingwell, 2009) or on the morning of 2nd May 2008 (Martin et al., 2009; Global Volcanism Program (GVP) monthly reports). Plinian eruptions with ash columns up to 21 km in height continued for a week before the growth of a new lava dome in the caldera began, and continued for nearly 3 years (Castro & Dingwell, 2009; GVP website: Chaitén monthly reports). A section of the lava dome collapsed in February 2009, resulting in a lateral blast, pyroclastic flows and ashfall in surrounding areas (Carn et al., 2009). Further block and ash flows have occurred as portions of the lava dome continued to collapse. Within a few days of the onset of eruptive activity the entire town of Chaitén was evacuated. The town was subsequently overrun with lahars. Growth of the lava dome diminished throughout 2011 (GVP website: Chaitén monthly reports).

4.5.2 Caldera unrest

Prior to the 2008 eruption at Chaitén, earthquakes were observed on monitoring equipment up to 300 km distant from the volcano on the evening of 30th April. The seismicity included volcano-tectonic earthquakes, with up to 15-20 per hour seen in retrospective analysis (Carn et al., 2009). These earthquakes were felt in the town of Chaitén, and were strong enough to knock objects off shelves (Castro & Dingwell, 2009). No hydrothermal, gas or deformation measurements were made. Castro and Dingwell (2009) analysed crystals from the deposits of the following eruption and interpreted the results to conclude the magma ascended from a depth of 5 km to the surface in just 4 hours. This very rapid movement of magma has not been documented at a rhyolitic volcano before. It has implications on the amount of warning time which can occur before an eruption takes place. While the Chaitén summit caldera is quite small compared to Taupo and Okataina calderas, it is a rhyolitic volcano with a history of explosive eruptions, one of which occurred in the recent past. Unlike the more recent eruptions at Rabaul, Long Valley, Campi Flegrei and Okataina volcanic centres, the Chaitén historical eruption consisted of rhyolitic magma. Its rapid onset of eruptive activity after only one day of unrest demonstrates the possibilities for future behaviour at New Zealand's calderas.

4.6 Yellowstone (U.S.A.)

Yellowstone Plateau volcanic field is located in Wyoming, United States (Figure 17). It contains three calderas and a number of smaller vents outside of the caldera boundaries. The Yellowstone National Park surrounds this area, drawing millions of tourists every year. Regular caldera unrest continues to occur, requiring multi-agency coordination to manage the potential volcanic hazards. The geographical size of Yellowstone's calderas are comparable to those of the Taupo Volcanic Zone (Figure 17), and both have a similar discharge rate of magma in the past 2.2 million years (Houghton et al., 1995a). However the TVZ has had more frequent and smaller eruptions than Yellowstone (Houghton et al., 1995a).

4.6.1 Eruptions

The volcanic history of the Yellowstone Plateau volcanic field, including its calderas, is described by Christiansen (2001). The first caldera-forming rhyolitic eruption at Yellowstone Plateau volcanic field occurred just over 2 million yrs BP, erupting a volume of approximately 2,500 km^3. Further large eruptions occurred 1.3 and 0.64 million yrs BP, with volumes of 280 km^3 and 1000 km^3 respectively. This most recent caldera-forming eruption affected the Earth's climate by reducing the intensity of solar radiation entering the Earth's atmosphere (Dzurisin et al., 1995).

Figure 17 USGS map of Yellowstone National Park and the caldera boundary from the 0.64 million yrs BP eruption. It also shows epicentres of large earthquakes in the past, and major hydrothermal features.

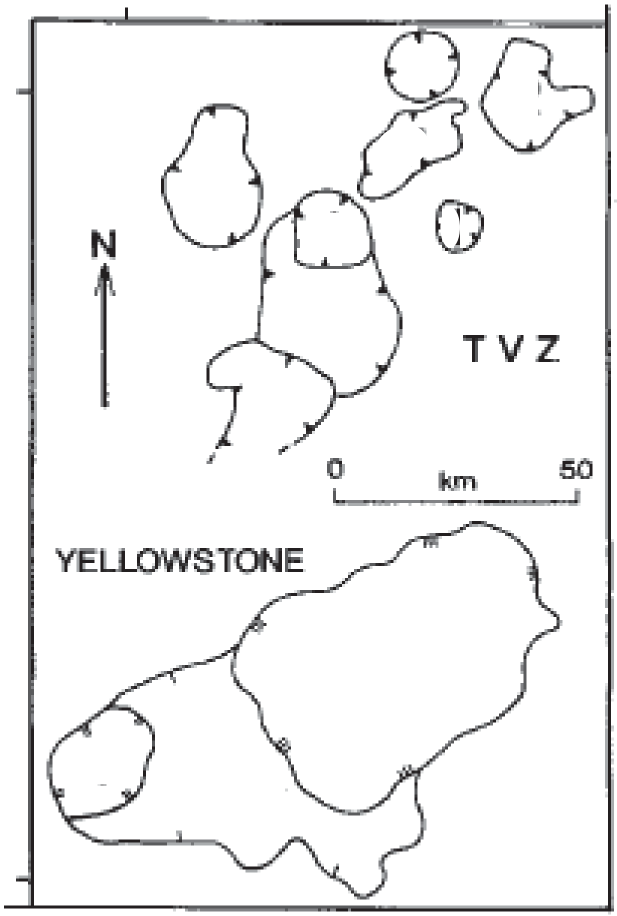

Figure 18 A comparison in size of calderas in the Taupo Volcanic Zone (TVZ), New Zealand (top, see Figure 1 for further details), to Yellowstone (bottom). From Houghton et al., (1995a).

Prior to each of these large eruptions, rhyolitic lavas (with volumes of over 10 km^3) were extruded. Following the youngest of these caldera-forming eruptions, rhyolitic magma was injected beneath the caldera floor to form resurgent domes. Basaltic lava has also been erupted around the edges of the calderas. The most recent eruption from within the Yellowstone Caldera was a rhyolitic lava extrusion, at approximately 72,000 yrs BP (Christiansen et al., 2007).

4.6.2 Caldera unrest

The region is intensely monitored for volcanic unrest by the USGS at the Yellowstone Volcano Observatory (YVO) and the University of Utah. The Yellowstone area undergoes regional seismicity including potentially large earthquakes from local fault lines (such as a M6.1 earthquake in 1975) and neighbouring mountain ranges (such as a nearby M7.5 earthquake in 1959 which costed 28 lives; Dzurisin et al., 1995). Smaller earthquake swarms within the caldera area are also experienced. The largest seismic swarm to be recorded at Yellowstone occurred in 1985, coinciding with subsidence of the caldera (Waite & Smith, 2002; cited in Christiansen et al., 2007)). Further swarms were recorded in 2004, 2009 and January-April 2010. This latter swarm included 16 earthquakes >M3.0, a few of which were felt (YVO 2010 news archive).

Ground deformation has also occurred at Yellowstone and in the surrounding area. Deformation during historical times at Yellowstone has included uplift of 23 mm per year from 1976-83, then subsidence of up to 35 mm per year until 1987 (Dzurisin & Yamashita, 1987; Dzurisin et al., 1990, both cited in Christiansen et al., 2007). Subsidence and uplift at rates of up to 60 mm per year continued to occur; most recently slight subsidence is being experienced (YVO October monthly update; Christiansen et al., 2007). In the past 10,000 years, the centre of Yellowstone caldera has moved up and down by about 20 m at least three times (Dzurisin et al., 1995).

In more than 130 years of historical records for Yellowstone National Park, at least 25 hydrothermal eruptions have occurred. Hydrothermal eruption craters several kilometres across have formed within Yellowstone National Park, however none have been associated with a volcanic event (Christiansen et al., 2007).

Due to its geological past and unrest during historical times, Yellowstone Plateau has similarities with the calderas of the Taupo Volcanic Zone, despite the Yellowstone Plateau's tectonic setting as a hotspot rather than on a subduction zone. Yellowstone has a different situation regarding risk, as it has a very low permanent population, but a high number of seasonal tourists during the day.

4.7 Aira Caldera and Sakurajima (Japan)

Aira Caldera is one of the largest volcanoes in the southern Japanese island of Kyushu. It forms the northern end of Kagoshima Bay, and contains the post-caldera cone of Sakurajima, one of the most active volcanoes in Japan. Kagoshima city, with a population of over 600,000, is located near the south-western caldera boundary (Figure 18). The residents have adapted to living with the effects of frequent tephra fall from this reawakened rhyolitic caldera.

4.7.1 Eruptions

Aira Caldera formed approximately 22,000 yrs BP during a large, ignimbrite-forming eruption (Kigoshi et al., 1972; cited in Aramaki, 1984). This rhyolitic eruption included widespread pumice falls and pyroclastic flows, with a total erupted volume of >140 km^3 (Aramaki, 1984). In the 22,000 years after this eruption, three small post-caldera cones and a small caldera were formed, which lie submerged on the caldera floor in Kagoshima Bay, at least one of which shows vigorous fumarolic activity releasing CO_2 gas (Aramaki, 1984). Sakurajima stratocone is the largest and most active post-caldera vent. This andesitic to dacitic cone formed on the southern caldera rim at least 13,000 yrs BP (Fukuyama, 1978; cited in Aramaki, 1984), and is now one of Japan's most active volcanoes. The larger historical eruptions from Sakurajima cone occurred in 1471-76, 1779 and 1914.

Figure 19 Sakurajima post-caldera volcano, located in Aira caldera, emitting steam. Kagoshima city is in the foreground.

Historical eruptions from Sakurajima have caused frequent deposits of tephra on the city of Kagoshima, located 8 km from the summit of the active cone across Kagoshima Bay. Sakurajima has had ongoing eruptions since 1955 with frequent but relatively small ash columns. The city of Kagoshima has adapted to the frequent eruptions from this nearby volcano by implementing measures to deal with volcanic hazards. Many of the buildings have large, overhanging roofs covering balconies to limit the build-up of tephra on these weak structures. Some roofs don't have gutters, but have a channel on the ground beneath the roof to enable easy cleaning of the tephra off the roof. Hard hats have been issued to children walking to school, and firefighters make regular patrols during eruptions. Further examples of Kagoshima adapting to regular eruptions are on the Taranaki Blowout exercise webpage (http://www.trc.govt.nz/taranaki-blowout-background-info). Lessons for New Zealand taken from Kagoshima on coping with frequent ashfall is described in a GNS Science report by Durand et al., (2001).

4.7.2 Caldera unrest

Aira Caldera has undergone frequent unrest during historical times, as described by Newhall and Dzurisin (1988), particularly before and after each eruption at Sakurajima cone. An example of this is before and after the 1914 eruption of <2 km^3 of dacitic magma from Sakurajima. In the preceding approximately 50 years, uplift occurred on Sakurajima's west coast of at least 1.5 m, and on the northwestern shoreline of Kagoshima Bay of 1 m. The rate of uplift increased until the eruption. In June 1913, earthquake swarms were centred 55 km and 15 km from Kagoshima, and springs changed temperature and flow rate on the edge of Sakurajima Island. Seismic activity continued in the week before the eruption, increasing in intensity in the final 30 hours at Kagoshima city, while ten times as many were felt on Sakurajima. On the morning of the onset of eruptive activity, hot and cold springs emerged around Sakurajima island, some spouting to a height of 1 m. The eruption began small, and one of the largest known earthquakes associated with volcanic activity occurred 8 hours after the start of the eruption, with a magnitude of 7.0 (Abe, 1981; cited in Newhall & Dzurisin, 1988). Dacitic lava flowed down Sakurajima's flanks during this eruption, joining the island to the mainland.

After the 1914 eruption, the caldera floor subsided by up to 6 m, and then started to slowly uplift for the remainder of the century. In the months following the eruption, areas of hot soil killed vegetation 600 m from the vent, and volcanic gases killed an ox and made people ill (Omori, 1916; cited in Newhall & Dzurisin, 1988). After a year the soil temperature returned to normal. Unrest continues to occur at Aira Caldera, accompanied by eruptions from its frequently active Sakurajima cone.

4.8 Taal (Philippines)

Taal caldera is located in southwestern Luzon in the Philippines, and formed between 100,000 and 500,000 yrs BP (Listanco, 1994; cited in Lowry et al., 1991). The 15 km x 25 km caldera contains Lake Taal. Within Lake Taal is the 5 km wide Volcano Island, the source of all of the historical eruptions, and home to several thousand people. On Volcano Island is a small (3 km) caldera lake (called Main Crater Lake) which itself has a small island, a remnant of historical eruptions. At least 33 eruptions have been witnessed at Taal since the 16th Century (Punongbayan & Tilling, 1989; cited in Bartel et al., 2003), including pyroclastic flows and surges which have caused many fatalities, especially from villages on Volcano Island. These eruptions have been basaltic to dacitic in composition (Bartel et al., 2003). An eruption in 1911 from Volcano Island killed about 1335 people from pyroclastic flows (Blong, 1984). The most recent eruption ceased in 1977 (GVP website).

Unrest occurred at Taal Caldera in 1992 and 1994, without resulting in an eruption (Bartel et al., 2003). Rates of uplift in 1992 were up to 21 cm per day (Gabinete, 1999; cited in Bartel et al., 2003). Other unrest phenomena during this and the 1994 episode included heightened seismicity, and changes in the lake water chemistry and temperature. Both of these unrest episodes have been attributed to dike intrusions (Bartel et al., 2003). Geysering has been observed, including in 1998 and 1999. Deformation has fluctuated in the past couple of decades between inflation and deflation, each trend lasting on the order of months (Bartel et al., 2003). Volcanic earthquakes occurred in August 2008, which were heard and felt by the island residents. Between April and June 2010 the number and intensity of earthquakes increased, there was a slight inflation noted, gas emissions changed, fumaroles intermittently increased output and the temperature of the Main Crater Lake increased by a few degrees (according to the Philippine Institute of Volcanology and Seismology (PHIVOLCS) as seen on the GVP website). Residents were advised (but not ordered) to leave, however most did not comply (*Philippine Daily Inquirer*, cited on the GVP website). Further changes to the volcanic parameters continued at lower levels throughout 2010 and into 2011, before abating in mid-2011 (GVP and PHIVOLCS (http://www.phivolcs.dost.gov.ph) websites).

4.9 Novarupta and Katmai (U.S.A)

The largest eruption in the world during the 20th Century took place from 6 – 9 June 1912 in a remote area of Alaska, U.S.A, and is described by Hildreth (1983, 1991). Due to this area's highly remote location, unrest phenomena preceding this rhyolitic eruption unfortunately remain unknown.

The eruption formed a new vent called Novarupta. Approximately 15 km^3 of magma was erupted, covering the valley floor in up to 250 m of pyroclastic material including ignimbrite sheets. The valley is surrounded by five dacitic to andesitic stratovolcanoes, and was named the 'Valley of Ten Thousand Smokes' due to the hot ignimbrite deposits issuing steam through cracks for many years. Mt Katmai lies 10 km to the east of the 1912 vent. During the

Novarupta eruption, the Mt Katmai summit caldera (with a 1.5 km diameter) formed due to magma withdrawal, and this eruption has often mistakenly been attributed to Mt Katmai rather than Novarupta. The first half of the Novarupta eruption was rhyolitic, depositing pumice and destructive pyroclastic flow deposits. The remaining deposits indicate dacitic magma (Hildreth, 1991).

No recorded unrest has been observed at Novarupta since it formed in 1912. Nearby volcanoes, such as the stratovolcano Trident have however erupted during historical times. The permanent monitoring network at Novarupta was installed in the 1990s by the USGS Alaska Volcano Observatory.

5.0 GLOSSARY

Andesite (Or andesitic) Volcanic rock (or lava) containing 54 to 62% silica and moderate amounts of iron and magnesium.

Ash Fine particles of pulverized rock (tephra) erupted from the vent of a volcano. Particles smaller than 2 mm in diameter are termed as ash, and may be solid or molten when first erupted.

Ashfall Volcanic ash that has fallen through the air from an eruption cloud.

Ballistic Large tephra particles with diameters of over 64mm. Includes blocks and bombs.

Ballistic projectile A block or bomb explosively ejected from the vent that is not carried upwards by the eruption column.

Basalt (Or basaltic) Volcanic rock (or lava) containing less silica than andesite, commonly producing more effusive, runny and less explosive lava.

Base surge Volcanic density current pulse that moves laterally outwards formed of a dilute, turbulent mixture of hot gas (steam), water and solid ejecta.

Block Angular chunk of solid rock ejected during an eruption, with diameters of over 64 mm.

Block and ash flow An avalanche of ash, hot gas and potentially large blocks from oversteepening of a lava front or dome. These can travel at tens of kilometres per hour, can be hundreds of degrees in temperature and cover distances of several kilometers.

Bomb Fragment of molten or semi-molten rock, with a diameter of over 64 mm. Because of their plastic condition, bombs are often modified in shape during their flight or upon impact.

Caldera	A volcanic depression with a diameter many times larger than the size of the individual vents, usually formed during large volcanic eruptions.
CDEM	Civil Defence and Emergency Management
CO	Carbon monoxide.
CO_2	Carbon dioxide.
Conduit	A passage followed by magma within a volcano.
Country Rocks	The existing rock intruded by and surrounding an igneous intrusion (magma).
Crater	A commonly circular depression formed by either explosion or collapse at a volcanic vent, from which volcanic material is ejected.
Dacite	(Or dacitic) Fine-grained rock intermediate in composition between andesite and rhyolite.
Debris Avalanche	A rapid and unusually sudden sliding or flow of unsorted rock and other material (such as fragmented cold and hot volcanic rock, water, snow/ice and trees).
Deformation	Ground movement in a vertical or horizontal direction.
Dome	A steep-sided mass of viscous lava extruded from a volcanic vent. Its surface is often rough and blocky as a result of fragmentation of the cooler, outer crust during growth of the dome.
Ejecta	Material that is thrown out by a volcano, including tephra.
Eruption Column	The cloud of gases, steam and tephra rising from a crater or other vent, driven by thermal convection and gas pressure. If it is of sufficient volume and velocity, this column may reach many kilometers into the stratosphere, where winds may carry it long distances. Eruption columns can collapse and form pyroclastic density currents.
Eruptive Vent	The opening through which volcanic material is emitted.
Extinct Volcano	A volcano that is not presently erupting and is not likely to do so for a very long time in the future, if ever.
Extrusion	The emission of magmatic material at the earth's surface. Also, the structure or form produced by the process (e.g. lava flow, volcanic dome).

Fault	Fracture or zone of fractures along which displacement takes place or has taken place in the past.
Fissures	Elongated fractures or cracks on the slopes of a volcano. Fissures can host eruptions, which typically consist of runny lava flows and fountains, but pyroclastics (tephra) may also be ejected.
Flank Eruption	An eruption from the side of a volcano (in contrast to a summit eruption.)
Fumarole	A vent or hole through which steam and other gases emit.
Gravimetric	The measurement of microgravity, which can indicate the presence of a subsurface magma body.
H_2S	Hydrogen Sulphide, a poisonous gas.
Harmonic Tremor	A continuous release of seismic energy typically associated with the underground movement of magma. It contrasts distinctly with the sudden release and rapid decrease of seismic energy associated with the more common type of earthquake caused by slippage along a fault.
Hydrothermal eruption	Explosion driven by the transformation of hot groundwater to steam.
Igneous	The type of rocks formed during volcanic activity, both above and below the ground surface.
Ignimbrite	The rock formed by the widespread deposition and consolidation of hot pyroclastic flows. The term was originally applied only to densely welded deposits but now includes non-welded deposits.
Intensity	A measure of the effects of an earthquake at a particular place. Intensity depends not only on the magnitude of the earthquake, but also on the distance from the epicenter and the local geology.
Intrusion	The process of emplacement of magma in pre-existing rock. Also, the term refers to the igneous rock mass so formed within the surrounding rock.
Lahar	A flow of water-saturated, typically dense volcanic material, resembling a flow of wet concrete. Lahars usually follow topographical lows, however may overtop banks. They may be unaccompanied by an eruption by remobilisation of volcanic material.
Lapilli	Literally, "little stones." Round to angular erupted rock fragments (tephra) measuring 2 to 64 mm in size in diameter, which may be ejected in either a solid or molten state.

Lava Magma which has reached the surface through a volcanic eruption. The term is most commonly applied to the flowing rock that emits from a crater or fissure, however it also refers to cooled and solidified rock formed this way. Lava varies in viscosity (runniness and therefore speed of movement), chemistry and temperature.

Lava Dome Mass of sticky lava, that has built a dome-shaped pile at a vent.

Liquefaction A saturated soil loses strength and behaves as a liquid due to an applied stress, usually earthquake shaking.

Lithic Particle of previously formed rock.

Mafic Magma with a silica content of less than about 55%.

Magma Molten rock beneath the surface of the earth. Magma that reaches the surface erupts as lava or pyroclasts.

Magma Chamber The underground reservoir containing the molten magma beneath a volcano.

Magnitude Earthquake magnitudes in this report represented by a single ‘M’ (i.e. M5.0) refer to the Richter Magnitude scale.

Mantle The zone of the earth below the earth’s crust and above the core.

MM Modified Mercalli earthquake intensity scale (see the GeoNet website: http://www.geonet.org.nz/earthquake/modified-mercalli-intensity-scale.html).

Phreatic Eruption (Or phreatically) An explosion caused when water and heated volcanic rocks interact to produce a violent expulsion of steam and pulverized rocks. Magma is not involved.

Phreatomagmatic An explosive volcanic eruption that results from the interaction of surface or subsurface water and magma.

Plinian An eruption with a powerful, convecting column reaching up to 45 km high, usually requiring the eruption of high viscosity magma (such as dacite and rhyolite). Plinian eruptions often lead to the formation of pyroclastic density currents.

Ppm parts per million.

Pumice Light-coloured, frothy volcanic rock, formed by the expansion of gas in erupting, sticky lava during an eruption. Pumice commonly floats on water and can travel further than other rocks of a similar size during an eruption due to their low density.

Pyroclastic	Erupted material which starts out hot (pyro) and consists of fragmented rock (clastic) material formed by a volcanic explosion.
Pyroclastic [Base] Surge	A type of pyroclastic density current which has high gas content, is turbulent and the material is well mixed.
Pyroclastic Density Current	A gravity-controlled, laterally moving mixture of pyroclasts and gas.
Pyroclastic Flow	A turbulent mixture of hot gases and rock fragments that can move at high speed (up to 900 km an hour) down the sides of the volcano. A type of pyroclastic density current, which usually follows topographical lows. Generated by the collapse or partial collapse of an eruption column.
Quaternary	The period of Earth's history from about 2 million years ago to the present; also, the rocks and deposits of that age.
Quiescence	The periods of time between eruptions.
Rhyolite	Volcanic rock, light coloured, with a high silica content.
Scoria	A pyroclast that is irregular in form and generally very vesicular. It is usually heavier, darker, and more crystalline than pumice.
Seismograph	An instrument that records seismic waves (earthquakes).
Seismologist	Scientists who study seismicity (earthquakes).
Silica	(Or silicic) A chemical combination of silicon and oxygen (SiO_2)
SO_2	Sulphur dioxide (gas)
Stratocone	See stratovolcano
Stratovolcano	A volcano composed of both lava flows and pyroclastic material.
Strombolian	Basaltic (low viscosity magma) eruptions, including a series of explosions.
Subduction Zone	The zone of convergence of two tectonic plates, one of which usually overrides the other.
Subplinian	Lower magnitude and intensity versions of the plinian eruption, can result in pyroclastic density currents.
Surge	A cloud of gas and suspended pyroclastic material that moves radially outward at high velocity from the base of a vertical eruption column accompanying a volcanic eruption.
Swarm	A group of many earthquakes of similar size occurring closely clustered in space and time with no dominant main shock.

Tephra Solid materials of all types and sizes that are erupted from a crater or volcanic vent and travelling through the air.

Tilt The angle between the slope of a part of a volcano and some reference. The reference may be the slope of the volcano at some previous time.

Tremor Low amplitude, continuous earthquake activity often associated with magma movement.

Tsunami A great sea wave produced by a submarine earthquake, volcanic eruption, or large landslide.

Vent The opening at the earth's surface through which volcanic materials emit, or emitted in the past.

Vesicle A small air pocket or cavity formed in volcanic rock during solidification.

Viscosity A measure of resistance to flow in a liquid (water has low viscosity while honey has a higher viscosity.)

Volcano A vent in the surface of the Earth through which magma and associated gases erupt, and the form or structure that is produced by the ejected material.

Volcanogenic A process attributed to a volcano or volcanic activity.

Vulcanian An eruption style of an explosive event of <1 km^3 in volume, but with an eruption column reaching 10-20 km high.

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APPENDIX 3: STATEMENT OF CONTRIBUTIONS

Chapters 5 and 6 have been submitted to the Bulletin of Volcanology for publication. Appendix 2 has been published as a GNS Science Report. A statement of contribution for each of these three publications is included here.

DRC 16

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GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Sally Potter

Name/Title of Principal Supervisor: David Johnston

Name of Published Research Output and full reference:

Potter, S.H., Scott, B.J., Jolly, G.E., Neall, V.E., Johnston, D.M., (submitted). Introducing the Volcanic Unrest Index (VUI): a tool to define and quantify the intensity of volcanic unrest. Bulletin of Volcanology.

In which Chapter is the Published Work: Chapter five

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 97%

  and / or

- Describe the contribution that the candidate has made to the Published Work:

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Potter, S.H., Scott, B.J., Jolly, G.E., Johnston, D.M., Neall, V.E., (submitted). Defining caldera unrest at Taupo Volcanic Centre, New Zealand, using the Volcanic Unrest Index (VUI). Bulletin of Volcanology.

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Potter, S.H., Scott, B.J., Jolly, G.E. (2012). Caldera unrest management sourcebook. GNS Science Report 2012/12. 73 p.

In which Chapter is the Published Work: Appendix 2

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APPENDIX 4: COMMUNICATION ADVICE DURING VOLCANIC EMERGENCIES

This communication advice is summarised from the “communication during volcanic emergencies” guidelines for Caribbean volcanoes (Benfield Greig Hazard Research Centre, 2003; see the Reference list at the end of the thesis for full reference details). It is targeted at scientists, Emergency Management Committees, and the media who may be involved during a volcanic crisis. The advice includes:

- Use simple, short messages, spoken slowly and clearly, with well-thought out content
- Avoid too much unnecessary scientific data, stick to the main message
- Avoid jargon and scientific measuring units, but if it is essential, explain what it means simply
- Use audio-visual aids wherever possible
- Use analogies
- Explain numbers, percentages or proportions carefully (what it means)
- Seek confirmation that the message has been understood, repeat as necessary
- Never be condescending or adopt a superior attitude
- Do not be too evasive, as this suggests you may be hiding information.
- Have a limited number of scientists as specialist communicators to increase trust
- Have general information on volcanoes, hazards and specific local information prepared, and have answers to potential interview questions prepared
- Coordinate communication with civil protection personnel
- Issue information regularly, even if conditions have not changed
- Focus attention on local media, as they are usually the most effective at informing the population at risk. Do not underestimate the media, and keep messages consistent through different media sources.
- Be approachable to ensure trustworthy science sources are used – always reply to journalists
- Do not make comments ‘off the record’.

APPENDIX 5: INTERVIEW GUIDELINES

Interview guidelines for end-users

These questions provided a guideline for open-ended interviews with end-users in the Volcanic Alert Level exploration research. Further details on the methodology are provided in Chapter 3.

1) What is your organisations general role during a volcanic event?

2) What is your personal role during a volcanic event?
    a. How long have you been in this role?
    b. Have you had any experiences in the past with any volcanic eruptions?

3) Suppose I was a new employee at _____ and you were training me, how would you describe the Volcanic Alert Level (VAL) system in New Zealand to me?
    a. What do you think is the purpose of the VAL system?

4) Where would you look to find the VAL table?

5) What is your opinion on the current Volcanic Alert Level system?
    a. What are your thoughts on the overall structure?
    b. Why do you think the current table is split between frequently active cone volcanoes and reawakening volcanoes?
    c. What are your thoughts on the level of content?
    d. What are your thoughts on indicative phenomena column?
    e. Has the current table got the right type of information on it for you, or would you prefer different information?

6) How satisfied are you with the current VAL system in NZ? (Likert scale provided)

7) If the VAL system changed to a new format, what would be the implications at _____, if any?

8) What information or advice do you expect to receive from GNS during changes in volcanic unrest or eruptive activity?

9) What is your opinion on this hypothetical VAL table, with one system for all of New Zealand's volcanoes? (*The participant was provided with Table A5.1, with an explanation of the differences to the current table.*)

Table A5.1. Hypothetical VAL table provided to end-user interview participants to prompt discussion[47]

Alert Level	Description of current volcanic activity
0	No unrest or eruptive activity
1	Possible unrest, with no threat of eruption
2	Volcanic unrest with threat of eruption
3	Minor eruptions in progress
4	Moderate to large scale eruptions in progress

10) If you received a Volcanic Alert Bulletin stating that Taupo Volcano was increasing in unrest activity, for example an increased number of earthquakes, or uplift, can you talk me through the actions you would take, if any, when the VAL is raised to 1?

11) What information or advice do you expect to receive from GNS during changes in volcanic unrest or eruptive activity?

12) Do you have any other comments or past experiences which you think might be relevant to tell me about?

[47] This hypothetical VAL system was created prior to the first interview. The purpose of its inclusion was to prompt responses by the participants on their opinions about certain aspects of the system which are different to the current VAL system. In particular, the lack of indicative phenomena column, highlight some of the potential wording issues, demonstrate two levels of unrest and five levels overall.

Interview guidelines for scientists

These questions provided a guideline for open-ended interviews with scientists in the Volcanic Alert Level exploration research. Further details on the methodology are provided in Chapter 3.

1) How would you describe your organisation's role during a volcanic event?
2) What is your personal role, if any, during a volcanic unrest or eruption event?
    a. Have you had any experiences with the VAL system in the past?
3) What do you think is the purpose of the VAL system?
4) What is your opinion on the current VAL system?
    a. What are your thoughts on the overall structure?
    b. What are your thoughts on content?
    c. What are your thoughts on indicative phenomena column?
5) Do you use the wording in the current VAL system as a minimum, where everything mentioned has to have happened in order to change alert level, basically like check boxes which need to be filled in to advance, or more as a general guideline?[48]
6) How satisfied are you with the current VAL system in NZ? (Likert scale provided)
7) On the frequently active volcano side of the VAL table, do you think another level would be useful between levels 1 and 2, to provide a more severe level of unrest to be acknowledged, or are you happy with it as it is?
8) What is your opinion on this hypothetical VAL table with one system for all of New Zealand's volcanoes? (*The participant was provided with Table A6.1, with an explanation of the differences to the current table.*)

[48] Only asked to voting GNS Scientists

Table A5.2. Hypothetical VAL table provided to scientist interview participants to prompt discussion[49]

Alert Level	Description of current volcanic activity
0	No unrest or eruptive activity
1	Possible unrest, with no threat of eruption
2	Volcanic unrest with threat of eruption
3	Minor eruptions in progress
4	Moderate to large scale eruptions in progress

9) Back to the current VAL table, what do you think would be the unrest phenomena specifically that would convince you to change the VAL for Taupo from 0 to 1?[1]
    a. What phenomena would you require to vote for a change from VAL 1 to 2?[1]
    b. How would you define unrest?
10) The current decision-making system for GNS Scientists to allocate the VAL is by discussion followed by a vote using hands – two thirds majority 'wins', and if this isn't met, the HOD has the power to make the decision. What is your opinion about decision-making methods, including this current system?
11) What implications (if any) do you think a VAL change from 0 to 1 for Taupo/Okataina/Auckland Volcanic Field[50] would have on the end-users, public and media?
    a. Do you think that would that affect your decision making?[1]
12) Have you had any past experiences changing the Volcanic Alert Level which had issues or difficulties, or you thought went really well?
13) Have you got any other comments you think might be relevant?

[49] This hypothetical VAL system was created prior to the first interview. The purpose of its inclusion was to prompt responses by the participants on their opinions about certain aspects of the system which are different to the current VAL system. In particular, the lack of indicative phenomena column, highlight some of the potential wording issues, demonstrate two levels of unrest and five levels overall.

[50] The volcano most appropriate to the interviewee was used

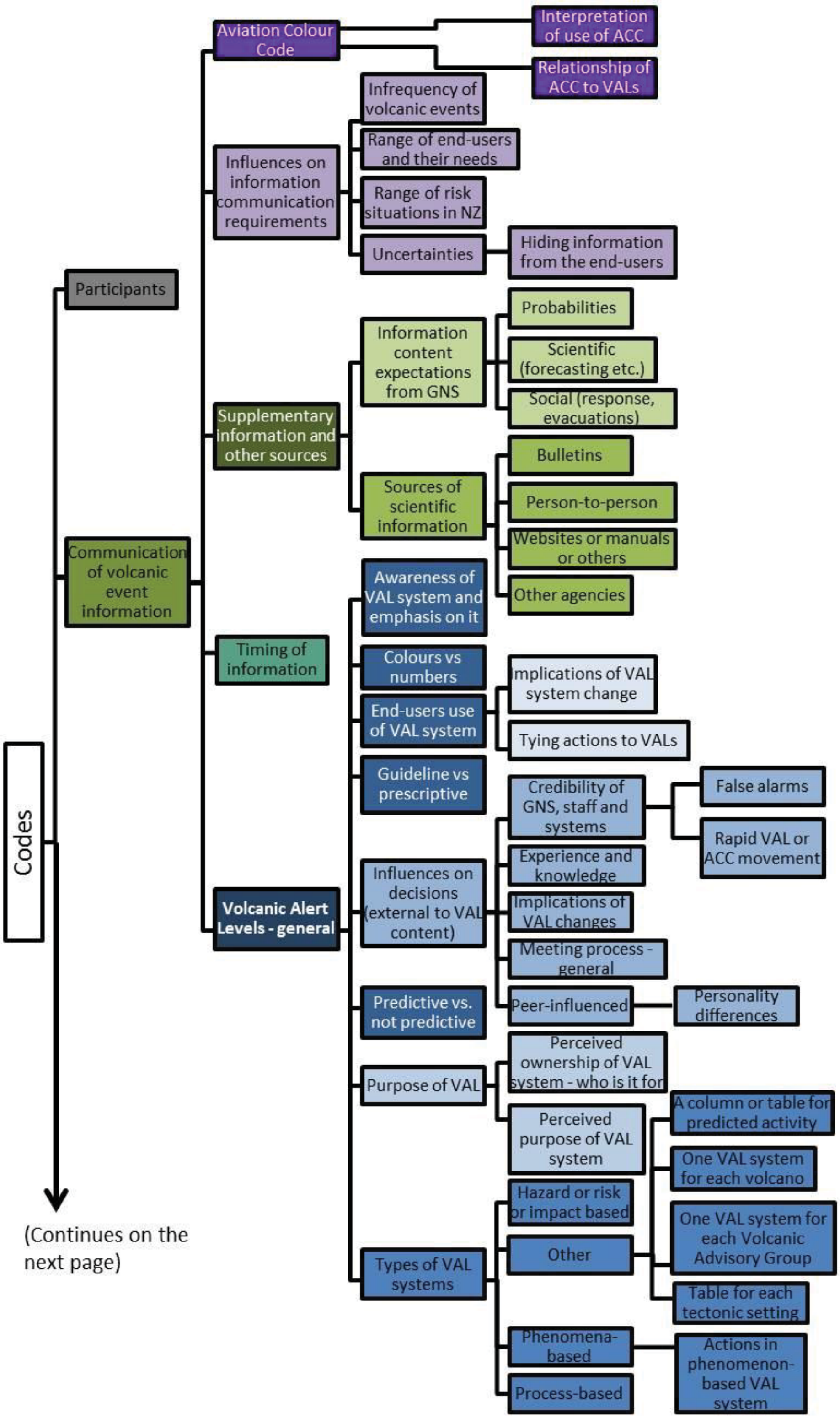
APPENDIX 6: PRE-CODING CODE STRUCTURE

Table A6.1. Structure of codes within levels of concepts, categories, and theory, created prior to coding, as part of thematic analysis. This is the starting point used for the analysis of interview transcripts, and is based on reading through interview transcripts, and supporting notes.

Sub-concept	Concept	Sub-category	Category	Theory
		Infrequency of volcanic events	Influences on information communication requirements	Communication of volcanic event information
		Uncertainties		
		Range of risk situations in NZ		
		Range of end-users & their needs		
		Timing of searching for or receiving scientific information	Timing of information	
	Bulletins	Source of information	Supplementary information/Other sources	
	Person-to-person			
	Websites/manuals/other			
	Scientific (forecasting etc.)	Information content expectations from GNS		
	Social (response, evacuations)			
	Probabilities			
		Interpretation of use of ACC	Aviation Colour Code	
		Relationship of ACC to VALs		
Voting & social processes	Peer-influenced	Influences on decisions (external to VAL content)	Volcanic Alert Level Systems	
Situational awareness	Implications of VAL changes			
Rapid level movement	Credibility of GNS, staff and system			
False alarms				
	Perceived purpose of VAL system	Purpose of VAL system		
	Ownership of VAL system			
		Predictive vs non-predictive, including trending up and down		
		Guideline vs prescriptive		
	Tying actions to levels	End-users use of VAL system		

<table>
<tr><th>Sub-concept</th><th>Concept</th><th>Sub-category</th><th>Category</th><th>Theory</th></tr>
<tr><td></td><td>Hazard/risk/impacts-based</td><td rowspan="4">Types of VAL systems</td><td rowspan="4"></td><td rowspan="4"></td></tr>
<tr><td></td><td>Process-based</td></tr>
<tr><td>Two tables – one like now, the other with predicted activity</td><td>Other</td></tr>
<tr><td>Current system</td><td>Phenomenon-based</td></tr>
<tr><td>Transitions (e.g., Raoul)</td><td rowspan="2">Placement of volcanoes</td><td rowspan="4">Structure – split</td><td rowspan="7">Structure</td><td rowspan="15">Current phenomena-based VAL system: opinions</td></tr>
<tr><td>Criteria used: ‘nature of “the beast”’</td></tr>
<tr><td></td><td>Positive</td></tr>
<tr><td></td><td>Negative</td></tr>
<tr><td></td><td></td><td>Number of levels</td></tr>
<tr><td></td><td></td><td>Overall appearance & layout</td></tr>
<tr><td></td><td></td><td>Colours vs. numbers</td></tr>
<tr><td></td><td>Definition of unrest</td><td rowspan="2">General terminology and definitions, language, jargon</td><td rowspan="5">Content</td></tr>
<tr><td></td><td>Definition of eruption</td></tr>
<tr><td></td><td>Perceived meanings of levels</td><td>Interpretation of content: “what does this actually mean?”</td></tr>
<tr><td></td><td></td><td>Appropriate for de-escalation?</td></tr>
<tr><td></td><td></td><td>Number of levels of unrest vs eruption, including increments (1.8 etc.)</td></tr>
<tr><td></td><td></td><td>Intention behind current system</td><td>Formation</td></tr>
<tr><td></td><td></td><td></td><td>Appropriate for NZ situations and riskscapes?</td></tr>
<tr><td></td><td></td><td>Overall satisfaction with current VAL system</td><td>Satisfaction of current VAL system</td></tr>
<tr><td></td><td></td><td></td><td>Future actions to improve EM crisis management of a volcanic crisis in NZ</td><td rowspan="3">Overall management of a volcanic crisis</td></tr>
<tr><td></td><td></td><td></td><td>Future actions to improve scientific management of a volcanic crisis in NZ</td></tr>
<tr><td></td><td></td><td></td><td>Communication of information</td></tr>
</table>

APPENDIX 7: POST-CODING CODES AND INITIAL STRUCTURE



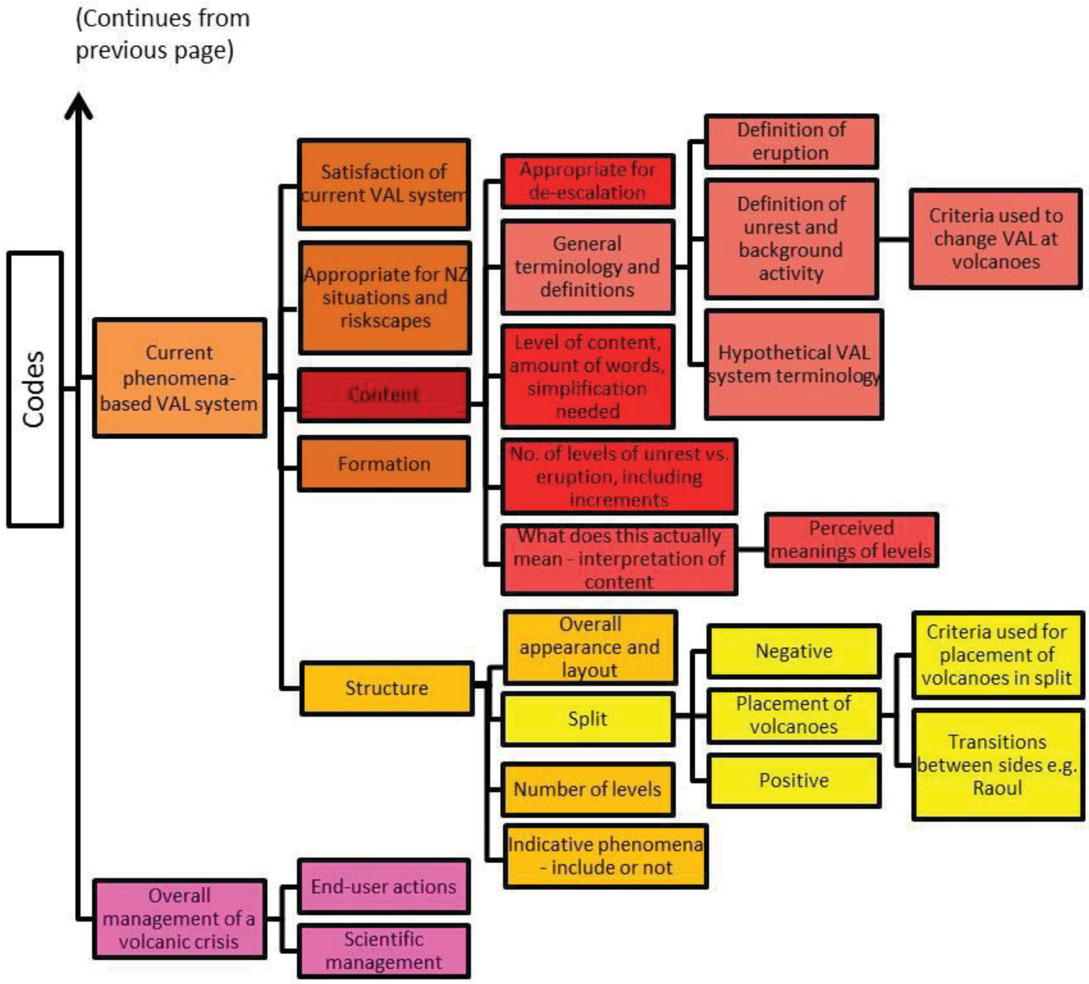


Figure A7.1. List of codes in initial concept structure, created after systematic coding. In addition to these codes, a code for each participant was created.

APPENDIX 8: FINAL LIST OF CODES USED

Table A8.1. The final list of codes used in thematic analysis of interviews, with contributions from observations and document analysis is presented, relating to the exploration of New Zealand's Volcanic Alert Level system. The codes are structured into concepts and themes. The 'number of sources coded' refers to the number of separate information sources (such as interview transcripts and memos), and the 'number of coding references' refers to the number of individual 'chunks' of text that have been assigned to each code.

Hierarchical Name	Number Of Sources Coded	Number Of Coding References
<u>Nodes\\VAL nodes\\Establishing the Context</u>		
Nodes\\VAL nodes\\Establishing the Context\Aviation Colour Code	17	42
Nodes\\VAL nodes\\Establishing the Context\Aviation Colour Code\Interpretation of use of ACC	5	11
Nodes\\VAL nodes\\Establishing the Context\Aviation Colour Code\Relationship of ACC to VALs	5	13
Nodes\\VAL nodes\\Establishing the Context\Information content expectations from GNS	4	8
Nodes\\VAL nodes\\Establishing the Context\Information content expectations from GNS\Probabilities	21	61
Nodes\\VAL nodes\\Establishing the Context\Information content expectations from GNS\Scientific (forecasting etc.)	24	65
Nodes\\VAL nodes\\Establishing the Context\Information content expectations from GNS\Social (response, evacuations)	14	39
Nodes\\VAL nodes\\Establishing the Context\Purpose of VAL	18	34
Nodes\\VAL nodes\\Establishing the Context\Purpose of VAL\Perceived ownership of VAL system – who is it for	10	13
Nodes\\VAL nodes\\Establishing the Context\Purpose of VAL\Perceived purpose of VAL system	18	31
Nodes\\VAL nodes\\Establishing the Context\Satisfaction of current VAL system	31	101
Nodes\\VAL nodes\\Establishing the Context\Satisfaction of current VAL system\Volcanic Alert Levels – general	5	9
Nodes\\VAL nodes\\Establishing the Context\Sources of information	3	5
Nodes\\VAL nodes\\Establishing the Context\Sources of information\Bulletins	20	29
Nodes\\VAL nodes\\Establishing the Context\Sources of information\Other agencies for scientific information	11	21
Nodes\\VAL nodes\\Establishing the Context\Sources of information\Person-to-person	11	37
Nodes\\VAL nodes\\Establishing the Context\Sources of information\Websites or manuals or other	11	40
<u>Nodes\\VAL nodes\\Future VAL system</u>		
Nodes\\VAL nodes\\Future VAL system\Appropriate for NZ situations and riskscapes	20	49

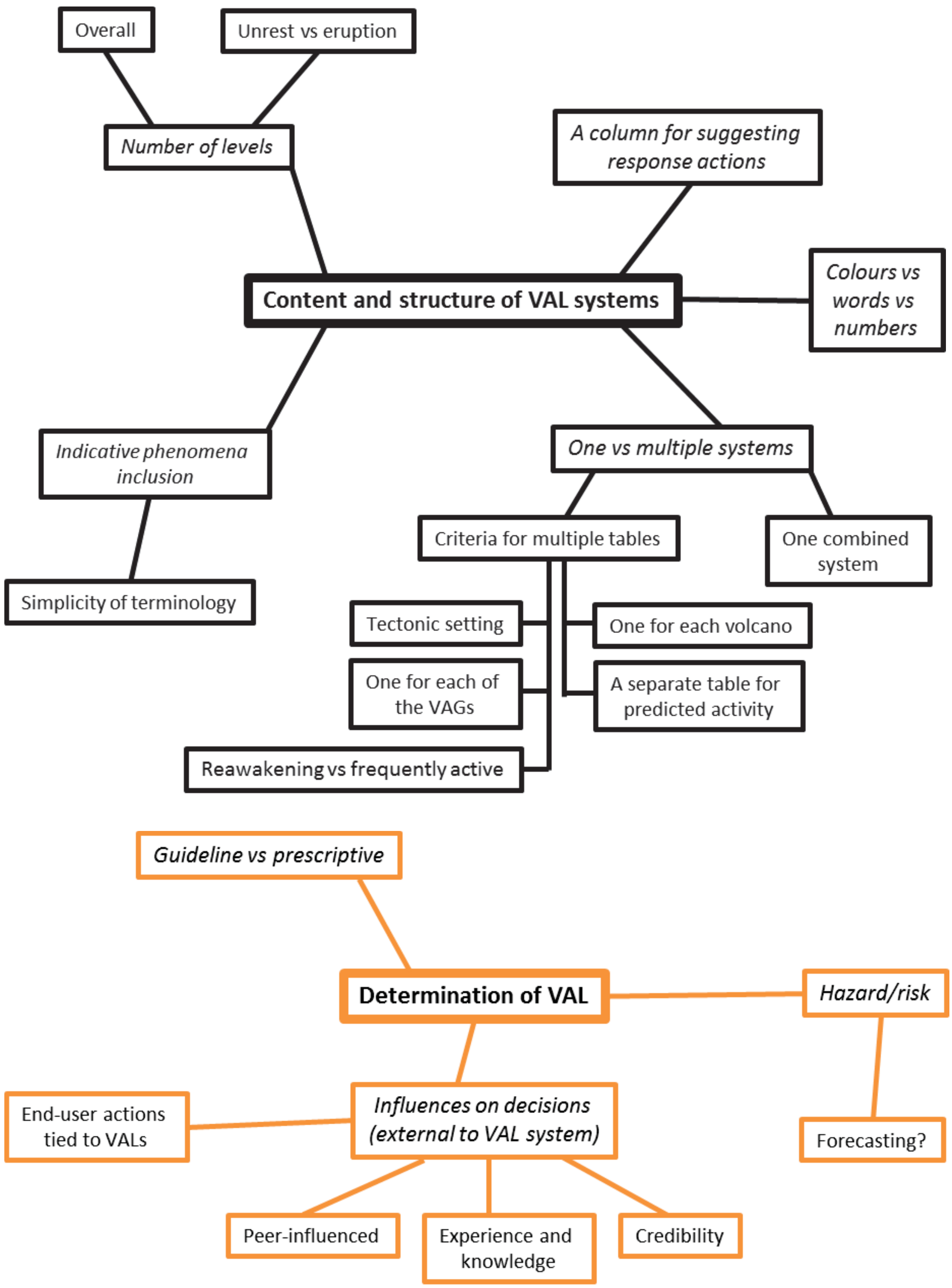
Hierarchical Name	Number Of Sources Coded	Number Of Coding References
Nodes\\VAL nodes\\Future VAL system\Predictive vs not predictive	22	99
Nodes\\VAL nodes\\Future VAL system\Types of VAL systems	2	2
Nodes\\VAL nodes\\Future VAL system\Types of VAL systems\Hazard or risk or impact based	21	111
Nodes\\VAL nodes\\Future VAL system\Types of VAL systems\Other	1	1
Nodes\\VAL nodes\\Future VAL system\Types of VAL systems\Other\A column or table for predicted activity	1	1
Nodes\\VAL nodes\\Future VAL system\Types of VAL systems\Other\One VAL system for each volcano	6	14
Nodes\\VAL nodes\\Future VAL system\Types of VAL systems\Other\One VAL system for each Volcano Advisory Group	1	4
Nodes\\VAL nodes\\Future VAL system\Types of VAL systems\Other\Table for each tectonic setting	2	6
Nodes\\VAL nodes\\Future VAL system\Types of VAL systems\Phenomena-based	10	33
Nodes\\VAL nodes\\Future VAL system\Types of VAL systems\Phenomena-based\Actions in phenomenon-based VAL system	8	25
Nodes\\VAL nodes\\Future VAL system\Types of VAL systems\Process-based	9	22
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)	10	28
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Credibility of GNS, staff and systems	5	14
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Credibility of GNS, staff and systems\Appropriate for de-escalation	9	17
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Credibility of GNS, staff and systems\False alarms	5	10
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Credibility of GNS, staff and systems\Perception that the scientists are hiding something from the end-users	3	6
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Credibility of GNS, staff and systems\Speed of movement between levels	12	29
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Credibility of GNS, staff and systems\Timing of Scientists' decision-making impacts credibility	2	2
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Experience and knowledge	26	66
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Experience and knowledge\Scientists' experience and knowledge influences determination of VAL	12	23
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Guideline vs prescriptive	21	79
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Guideline vs prescriptive\Guideline vs prescriptive GUIDELINE	5	10

Hierarchical Name	Number Of Sources Coded	Number Of Coding References
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Guideline vs prescriptive\Guideline vs prescriptive PRESCRIPTIVE	4	7
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Guideline vs prescriptive\Guideline vs prescriptive PRESCRIPTIVE\Prescriptive – Ruapehu example	2	6
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Guideline vs prescriptive\mixed between guideline and prescriptive	1	3
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Hazard risk influence on Scientists' decisions	2	2
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Implications of VAL changes	31	139
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Meeting process – general	19	100
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Peer influence on Scientific decisions	2	4
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Peer-influenced	10	33
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Peer-influenced\Personality differences	10	19
Nodes\\VAL nodes\\Influences on scientific decisions (external to VAL content)\Science – monitoring data and interpretation	4	4
Nodes\\VAL nodes\\Relationship between end-users and the current VAL system		
Nodes\\VAL nodes\\Relationship between end-users and the current VAL system\Awareness of VAL system and emphasis on it	19	41
Nodes\\VAL nodes\\Relationship between end-users and the current VAL system\Communication of volcanic event information	9	10
Nodes\\VAL nodes\\Relationship between end-users and the current VAL system\Communication of volcanic event information\Influences on information communication requirements	1	10
Nodes\\VAL nodes\\Relationship between end-users and the current VAL system\Communication of volcanic event information\Influences on information communication requirements\Infrequency of volcanic events	11	14
Nodes\\VAL nodes\\Relationship between end-users and the current VAL system\Communication of volcanic event information\Influences on information communication requirements\Range of end-users and their needs	8	11
Nodes\\VAL nodes\\Relationship between end-users and the current VAL system\Communication of volcanic event information\Influences on information communication requirements\Uncertainties	14	30
Nodes\\VAL nodes\\Relationship between end-users and the current VAL system\Communication of volcanic event information\Timing of information	14	30
Nodes\\VAL nodes\\Relationship between end-users and the current VAL system\End-users use of VAL system	21	48
Nodes\\VAL nodes\\Relationship between end-users and the current VAL system\End-users use of VAL system\Implications of VAL system change	11	24
Nodes\\VAL nodes\\Relationship between end-users and the current VAL system\End-users use of VAL system\Tying actions to VALs	17	63

Hierarchical Name	Number Of Sources Coded	Number Of Coding References
<u>Nodes\\VAL nodes\\VAL review</u>		
Nodes\\VAL nodes\\VAL review\Content	32	154
Nodes\\VAL nodes\\VAL review\Content\General terminology and definitions	24	74
Nodes\\VAL nodes\\VAL review\Content\General terminology and definitions\Definition of eruption	1	1
Nodes\\VAL nodes\\VAL review\Content\General terminology and definitions\Definition of unrest and background activity	17	65
Nodes\\VAL nodes\\VAL review\Content\General terminology and definitions\Hypothetical VAL system terminology	20	46
Nodes\\VAL nodes\\VAL review\Content\Interpretation of content	16	23
Nodes\\VAL nodes\\VAL review\Content\Interpretation of content\Perceived meanings of levels	21	56
Nodes\\VAL nodes\\VAL review\Content\Level of content, amount of words, simplification needed	22	54
Nodes\\VAL nodes\\VAL review\Structure	0	0
Nodes\\VAL nodes\\VAL review\Structure\Colours vs numbers	13	29
Nodes\\VAL nodes\\VAL review\Structure\Indicative phenomena – include or not	20	53
Nodes\\VAL nodes\\VAL review\Structure\No. of levels of unrest vs eruption, including increments	25	130
Nodes\\VAL nodes\\VAL review\Structure\Number of levels overall	22	53
Nodes\\VAL nodes\\VAL review\Structure\Overall appearance and layout	7	16
Nodes\\VAL nodes\\VAL review\Structure\Split	20	49
Nodes\\VAL nodes\\VAL review\Structure\Split\Intention behind current system	7	25
Nodes\\VAL nodes\\VAL review\Structure\Split\Negative	16	42
Nodes\\VAL nodes\\VAL review\Structure\Split\Placement of volcanoes	16	47
Nodes\\VAL nodes\\VAL review\Structure\Split\Placement of volcanoes\Criteria used for placement of volcanoes in split	10	26
Nodes\\VAL nodes\\VAL review\Structure\Split\Placement of volcanoes\Transitions between sides e.g., Raoul	9	29
Nodes\\VAL nodes\\VAL review\Structure\Split\Positive	10	18

APPENDIX 9: POST-CODING THEMATIC MAPS

Figure A9.1. Collection of example thematic maps, developed using the list of codes and thematic analysis technique. The thematic maps demonstrate relationships between concepts and themes, structured into hierarchies.




Range of end-user needs
Range of risk settings
De-escalation
Range of volcano types
Appropriate for all situations
Process-based
Basis of VAL systems
Hazard/risk-based
Phenomena-based
Reasons behind formation of current system
Volcanic Alert Bulletins
Other agencies
Person-to-Person
Websites, manuals
Other sources of scientific information
The purpose of VAL systems
Predictive vs non-predictive
Use of VALs
Aviation Colour Code
Awareness and emphasis
End-user's use of the VAL system
Intro: Feelings towards current VAL system
Overall satisfaction

APPENDIX 10: SUMMARY OF VAL RESEARCH FOR PARTICIPANT FEEDBACK

AN EXPLORATORY REVIEW OF NEW ZEALAND'S VOLCANIC ALERT LEVEL SYSTEM

Sally Potter

Introduction

The information included in this report summarises the results found during an exploratory assessment of New Zealand's Volcanic Alert Level (VAL) system. In order to make this summary as short and readable as possible, the results have been greatly simplified, with benefits and issues described in each section. Please refer to the accompanying document, titled 'VAL full results for participants.docx' (referred to in this document hereafter as "full results") for the detailed results and some of my related thoughts.

Overview of method

During 2011 and early 2012 I interviewed a total of 13 end-users and 19 scientists to ascertain their opinions on the current VAL system (Figure 1 of the full results). In these results, 'end-users' refers to participants involved in the use of the VAL system from a range of organisations including the Ministry of Civil Defence and Emergency Management (MCDEM), regional and district CDEM, Civil Aviation and insurance industries and the Department of Conservation (DOC). Scientist participants are volcanologists (or volcano technicians or scientists from other disciplines who may have a role during a volcanic crisis) from GNS Science and a range of universities in New Zealand. In accordance with the ethics consent forms that all participants in this research signed, the identities of every participant are kept confidential. I am happy to answer any questions, including on my qualitative analysis method.

The final stage of my method is to present these results back to the participants to gain any feedback that participants might want to share with me. This feedback will be analysed with the aim of incorporating it into the full results document, which will be included in my PhD dissertation (which will be available to all participants) for submission to Massey University in June 2013.

1 Volcanic Alert Level System Review – Results

1.1 Introduction

The results are presented in five major themes:

1) Establishing the context
2) Relationship between end-users and the current VAL system
3) A review of the current VAL system
4) Influences on scientists' determination of the VAL
5) Future VAL systems

1.2 Establishing the context

1.2.1 Scientific information in a crisis

The VAL is just one source of scientific information in a crisis; others provide more details and context and include the Volcanic Alert Bulletin (VAB) and International Aviation Colour Code (ACC). All are described further in the full results, along with information needs identified by end-user participants. End-users believe talking directly to the GNS scientists is very important to verify information and understand it from a local perspective, so detailed scientific information should continue to be communicated in this way. It is recommended that the ACC should be used to determine aviation Volcanic Hazard Zones.

1.2.2 Overall satisfaction of the current system

The participants were predominantly satisfied with the current VAL system, however the need for a general review and minor changes were identified.

1.2.3 What is the purpose of the VAL system?

The purpose of the current VAL system is a communication tool used by the GNS scientists to enable end-users to quickly understand the current state of activity at the volcanoes, from which they can decide what actions to carry out.

Given the increase in scientific knowledge since the formation of the current system, the purpose may need to change, which will influence what the basis of the future system should be.

1.3 Relationship between end-users and the current VAL system

1.3.1 Awareness and emphasis on VALs

Most participants were not familiar with the details of the current VAL system. Many end-user participants were unsure of the overall number and meanings of levels (and therefore at what level to put action plans in place). This lack of awareness of the VAL system was attributed by participants to the relative infrequency of volcanic crises, and to the high importance placed on person-to-person communication with scientists. Within the VAL system, levels relating to unrest were emphasised as being more important than those relating to eruptions by end-users.

While scientists' place emphasis on using supplementary information to provide details on an increase in activity within a VAL, many end-users do not read this information if the VAL has not changed. This promotes the need to use the VALs to indicate a change in activity, or within a VAL, present changes in activity explicitly.

1.3.2 End-user's actions influenced by the VAL system

The VAL system is used by end-users to understand the current state (and threat) of activity, on which to base their decisions and actions. Some organisations have planned response actions influenced by the level of volcanic activity, irrespective of the alert level. However a small proportion of actions have been arranged to coincide with specific changes in certain alert levels. Most of these are fairly generic actions, and are flexible arrangements. Other actions associated with VALs are more clear-cut, for example those used by the civil aviation industry.

Concern has been expressed by scientist participants over whether the tying of response actions to VALs is appropriate. The danger of this is seen to be end-user actions may not be appropriate at the same level in which the VAL is changed. Instead, it is thought that end-users should carefully consider the actions they need to take, including lead-in times, and only then look for appropriate levels of volcanic activity which might signal this point. Incorporating response advice into the system may compromise this flexibility.

1.4 A review of the current VAL system

The interview participants recognised the need for New Zealand's VAL system to accommodate a wide range of volcano types and potential eruption magnitudes, dormancy periods, eruption and hazard characteristics and risk environments.

1.4.1 Structure of the current VAL system

The current VAL system is perceived by some participants as too complicated and unclear with too many words, columns, and multiple duplications. The simplification of the overall structure is seen as being beneficial.

1.4.1.1 Colours vs. words vs. numbers

The current numeric system appears to be well received and understood despite the implications of using a linear, equal interval scale. Colours should not be used, and while the terms 'advisory', 'watch' and 'warning' are likely to cause confusion, other words may be able to be applied to future systems.

1.4.1.2 The Split

The reasoning behind the split between frequently active volcanoes and reawakening volcanoes and the perceived benefits of the split include:

- the outcome from unrest at reawakening volcanoes is uncertain, and calderas are less likely to lead to an eruption than stratocones (such as Ruapehu and White Island)
- by separating the two, it is hoped that there would be a change in the perception of end-users on expected resulting volcanic activity.
- However, the majority of participants would prefer one system for all volcanoes, because:
- it is seen as an unnecessary complication of a system intended to be a simple communication tool
- there may be confusion when a reawakening volcano is allocated a level with a different meaning to the more familiar frequently active levels, or if end-users do not realise there is a separate system (or scientists use the wrong system) and the wrong meaning is used, or if both systems were in use at the same time
- volcanoes changing from one system to the other is likely to be confusing
- the boundary between the two systems is undefined and seen as arbitrary.

Other parameters from which to base multiple VAL systems are explored in the full results, and include the type of volcano, type of magma, tectonic setting, typical speed of eruption onset, risk environments, potential size of eruption, volcanic advisory group areas and one system per volcano. The purpose of the VAL system as a simple communication tool may outweigh any benefits of multiple systems, particularly as the geographical area affected is relatively small, and number of people involved limited. Supplementary information could be the vehicle for more specific details.

1.4.1.3 Number of levels

Overall, participants were happy with the current number of levels, and (if the current phenomena-based system is retained) most end-users would like one level for no unrest, two for unrest and three levels for eruptions (small, medium and large). Having three levels for eruptions was wanted to help put the level of threat at any time into perspective with what the maximum event could be when communicating with the public, which is imposing a linear equal-interval scale (in terms of threat) on the system, instead of using the words it contains – labelling levels with words rather than numbers dispel this perception.

Most participants thought an extra level relating to heightened unrest for frequently active volcanoes is needed, mainly to give more 'leeway' and warning before an eruption, particularly at those volcanoes which always show low levels of unrest. Reasons against this perceived as are scientists wanting to micromanage within one level, changes could be stated in the VAB, and it would only be beneficial if the focus of the system changed to include forecasting or levels of hazard.

1.4.1.4 Indicative phenomena inclusion

Most participants would like to retain the indicative phenomena column, although some would like the words to be changed. The purpose and perceived benefits of its inclusion was identified to be for the scientists to use as a guideline for which alert level is most appropriate, and to provide end-users with more information on what the volcano status means, which is beneficial when talking to media, and provides transparency on scientific knowledge. Issues include:

- Its inclusion plays into the issue of using the VAL system as a guideline vs. prescriptively (discussed below), causing lengthy discussions and delays in decision-making, and giving less flexibility
- Very little scientific interpretation is included or can be applied
- Indicative phenomena overlap between the intention of the levels
- Monitoring technologies and knowledge develop over time and this is not currently reflected
- Indicative phenomena are different for every volcano
- The current terminology used is too technical
- It over-complicates the system

1.4.2 Review of VAL Content

Non-scientists are communicating science during a crisis based on their understanding of the information they have been given. Often, instead of the scientific details, it is the overall impression of the level of threat that is quite influential to the overall response to the situation. The content of scientific communication tools such as the VAL system is an important element of maintaining the correct message across all levels of communication.

Many participants stated that the current VAL system is complex, “verbose”, and requires detailed reading to understand it, running the risk that the message may be missed. To simplify the content, it is thought that the volcano status descriptions should be shortened, indicative phenomena taken out or simplified, and jargon assessed. Some of the words in the current system were identified as ambiguous and open to interpretation (see full results for specific details).

1.5 Influences on scientists’ determination of the VAL

Regardless of the content and structure of future VAL systems, scientists will continue to have difficulties and delays in determining the VAL due to decision-making influences. Identified influences, discussed in further detail in the full results, include:

- The science: monitoring data and interpretation
- Experience and knowledge
- Peer influence and social psychology influences
- Credibility, influenced by
    - The speed of movement between the levels of the VAL system (particularly during de-escalation)
    - Delays in determining the VAL
    - Disagreements between scientists on the appropriate VAL in the public arena
    - The perception that scientists are hiding information
    - The repeatability of determining the VAL
    - ‘False alarms’
    - The ability to justify decisions
- Guideline vs. prescriptive
- Interpretation of the VAL content, based on
    - an individual’s interpretation of the content of the VAL system
    - the perception of what the meanings were originally intended to be duration formation
    - the system is used as a linear numbered system with little emphasis on the wording.
- End-user actions associated with VAL changes (including socio-economic impacts)
- Incorporating a hazard or risk perspective and eruption forecasting

- Internal organisation pressure
- External organisation pressure
- Perceived purpose of the VAL
- Fieldwork intentions

2 Future VAL systems

2.2 A shifting of foundations

While New Zealand's current VAL system is predominantly based on phenomena with an element of hazards, other options were suggested by participants. Hypothetical new systems are presented below including phenomena-based, hazard-based, process-based, risk-based and a multi-foundation system. Benefits and issues relating to each are discussed in the full results document.

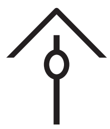
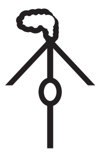
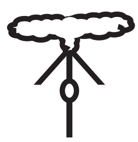
2.2.1 Phenomena-based

Hypothetical Phenomena-Based Volcanic Alert Level System	
Volcanic Alert Level	**Description of volcanic activity**
0	No volcanic unrest
1	Minor volcanic unrest
2	Moderate to heightened level of volcanic unrest
3	Minor volcanic eruption has recently occurred or is in progress
4	Moderate volcanic eruption has recently occurred or is in progress
5	Large volcanic eruption has recently occurred or is in progress

2.2.2 Hazard-based

Hypothetical Hazard-Based Volcanic Alert Level (or 'Hazard Level') System	
Hazard Level	**The Details**
Extreme	Very hazardous on and near volcano (hazards depend on eruption style) e.g., widespread ash, lava flows or domes, pyroclastic flows, lahars, flying rocks
High	Hazardous on volcano (hazards depend on eruption style) e.g., ash, lava flows or domes, pyroclastic flows, lahars, flying rocks
Moderate	Hazardous at areas near crater e.g., unpredictable small eruptions, poisonous gas, flying rocks, hot geysers
Low	Low level of hazards, associated with volcanic unrest e.g., unpredictable small steam eruptions, gas emissions, earthquakes
None	No volcanic hazards

2.2.3 Process-based

Hypothetical Process-based Volcanic Alert Level System				
VAL	**Hazard**	**Activity**	**Underlying process**	**Model**
0	No volcanic hazard	No unrest or eruptive activity	No magma	
1	Low level of hazard, associated with volcanic unrest e.g., steam eruptions, gas emissions, earthquakes	Minor volcanic unrest with no eruptions	Shallow, stable magma in rock beneath volcano	
2	Hazard to areas near vent e.g., small eruptions, poisonous gas, flying rocks, hot geysers	Heightened unrest with possibility of minor eruptions	Intrusion of fresh magma into rock beneath volcano	
3	Eruption hazards on volcano and downwind (hazards depend on eruption style), e.g., ash, lava flows, lava domes, pyroclastic flows, lahars, flying rocks	Minor to moderate volcanic eruption	Extrusion of magma (explosive or effusive)	
4	Very hazardous near volcano (hazards depend on eruption style), e.g., widespread ash, large lava flows, unstable lava domes, pyroclastic flows, lahars, flying rocks	Large volcanic eruption	Large extrusion of magma	

2.2.4 Risk-based

Estimated (generalised) levels of risk relating to levels of volcanic activity for every active volcano in New Zealand are given in the full results.

Risk Level
Extreme
Very High
High
Moderate
Low
Very Low

2.2.5 Multi-foundation system

This system uses a combination of phenomena and hazard foundations and incorporates risk in the setting of Hazard Zones. See full results for more information and an example of Hazard Zones.

Hypothetical Multi-Foundation Volcanic Alert Level System	
Volcanic Alert Level	
5	Hazardous in Zones A, B and C
4	Hazardous in Zones A and B
3	Hazardous in Zone A
2	Heightened unrest
1	Minor unrest
0	No unrest
Hazard Zone boundaries are shown in the Volcanic Alert Bulletin accompanying Volcanic Alert Level changes, and on the GeoNet website: www.geonet.org.nz	

2.3 Eruption forecasting inclusion ("what is going to happen next?")

There is a general desire by both scientists and end-user groups to include volcanic forecasting and predictive language in future VAL systems, yet the associated challenges relating to high levels of uncertainty (and potential 'false alarms') may be too difficult for the scientists to maintain credibility. Therefore this research is inconclusive with regards to the inclusion of eruption forecasting in the VAL system. It is recommended that the scientists attempt to explicitly include probabilities of several possible outcomes where possible in VABs.

2.4 Response advice inclusion

End-users often have difficulty interpreting the scientific information into response actions, and would like response advice to be included in future VAL systems. The wide range of end-users and their information needs is a difficult challenge to overcome in a simple communication tool. Agreed and coordinated response advice could be included in VABs according to the specific situation.

APPENDIX 11: LOW RISK ETHICS NOTIFICATION

This appendix contains the low risk ethics notification that was submitted to and received by the Massey University Research Ethics Committee. An amendment to the notification was granted, as detailed in the email.

Massey University
Te Kunenga ki Pūrehuroa

NOTIFICATION OF LOW RISK RESEARCH/EVALUATION INVOLVING HUMAN PARTICIPANTS

(All notifications are to be typed)
(Do not modify the content or formatting of this document in any way)

SECTION A:

1. **Project Title** The effective use of the Volcanic Alert Level system in New Zealand during volcanic unrest episodes

   Projected start date for data collection 1 May 2011 **Projected end date** 12 March 2013

   (Low risk notifications will not be processed if recruitment and/or data collection has already begun.)

2. **Applicant Details** *(Select the appropriate box and complete details)*

ACADEMIC STAFF NOTIFICATION

Full Name of Staff Applicant/s

School/Department/Institute

Region *(mark one only)* **Albany** [ ] **Palmerston North** [ ] **Wellington** [ ]

Telephone **Email Address**

STUDENT NOTIFICATION

Full Name of Student Applicant Sally Potter (nee Grant)

Postal Address [redacted], Taupo 3330

Telephone [redacted] **Email Address** [redacted]

Employer (if applicable)

Full Name of Supervisor(s) David Johnston

School/Department/Institute School of Psychology

Region *(mark one only)* **Albany** [ ] **Palmerston North** [ ] **Wellington** [X]

Telephone [redacted] **Email Address** [redacted]

GENERAL STAFF NOTIFICATION

Full Name of Applicant

Section

Region *(mark one only)* **Albany** [ ] **Palmerston North** [ ] **Wellington** [ ]

Telephone **Email Address**

Full Name of Line Manager

Section

Telephone **Email Address**

3 **Type of Project** *(provide detail as appropriate)*

Staff Research/Evaluation:		**Student Research:**		**If other, please specify:**
Academic Staff		**Name of Qualification**	PhD	
General Staff		**Credit Value of Research**	360	
Evaluation		**(e.g. 30, 60, 90, 120, 240, 360)**		

4. Describe the process that has been used to discuss and analyse the ethical issues present in this project.
(Please refer to the Low Risk Guidelines on the Massey University Human Ethics Committee website)

- The topic and nature of the research was discussed at a preliminary level with Massey staff (including Doctoral supervisor Assoc/Prof. David Johnston), at the researchers confirmation event and with colleagues at GNS Science.
- The researcher involved has read through the Code of Ethical Conduct.
- The researcher has reviewed the methodology associated with this research, and has considered all aspects such as: minimisation of harm, avoidance of deception, respect for persons, avoidance of conflict of interest, and social and cultural sensitivity.
- The screening checklist was followed to determine the appropriate ethics approval procedure. All questions were answered with a "No", and so it was determined that a "Low Risk Notification" should be prepared.

5. **Summary of Project**

Please outline the following (in no more than 200 words):

1. **The purpose of the research, and**

This research will assess how the New Zealand Volcanic Alert Level (VAL) system is used by both the end-users and the scientists, what the benefits and disadvantages are and the implications of changing the system in the future.

2. **The methods you will use.**

This research will be conducted in three phases, as follows:

Phase 1) Visits or phone calls to VAL end-users (such as Regional Council Emergency Managers) to undertake loosely structured interviews to see if and how they use the VAL, and to obtain relevant documents and reports.

Phase 2) Focus groups and interviews on hypothetical actions and decisions scientists would make to change the VAL during volcanic unrest, particularly in situations involving high levels of uncertainty, and to assess what their thoughts are on the current system. Focus groups and interviews will also occur with end-user participants to see what actions they (and their organisation) would take if the VAL changed, and what their thoughts are about the current system.

Phase 3) In the event of real unrest at one of NZ's volcanoes, this research would involve the observation of scientists during decision making for VAL changes, observations of end-users to assess their actions according to the VAL, and/or retrospective interviews of scientists and end-users on what actions were taken when the VAL changed.

The identity of the participants will only be known by the researcher, supervisor(s) and co-participants in the focus groups; the participants will not be identifiable from the results. Written and informed consent will be gained from all participants as described by the Massey University Code of Ethical Conduct, including when they are recorded by video or voice recorder, and this recording may be transcribed at a later date. Participants will be able to withdraw at any time if they wish. During observations of actions taken during real events, participants will be undertaking actions as they would normally do for their professional role, and the research will not cause participants embarrassment, harm or other detrimental effects, and there will be no intentional deception.

(Note: ALL the information provided in the notification is potentially available if a request is made under the Official Information Act. In the event that a request is made, the University, in the first instance, would endeavour to satisfy that request by providing this summary. Please ensure that the language used is comprehensible to all)

Please submit this Low Risk Notification (with the completed Screening Questionnaire) to:

The Ethics Administrator
Research Ethics Office
Sir Geoffrey Peren Building, PN221
Massey University
Private Bag 11 222
Palmerston North

Change to low risk notification

From: Sally Potter [[redacted]]
Sent: Tuesday, 4 June 2013 1:32 p.m.
To: [redacted]
Subject: RE: Question relating to use of observation data and a low risk notification

Hello,

Thanks for your email [redacted].

In April 2011 I submitted a low risk notification to the Massey University ethics committee for the project titled 'the effective use of the Volcanic Alert Level (VAL) system in New Zealand during volcanic unrest episodes", with a start date of 1 May 2011, and an end date of 12 March 2013. I would like to extend this end date to 30 April 2014 please, to allow me to complete my ethnographic research. Additionally, I would like to include as an amendment to the low risk notification the use of observation notes I have collected as a student and employee based at GNS Science during this research period, relating to the use of the Volcanic Alert Level system by GNS staff. I intend to gain informed consent from individuals who have been present at these meetings. All are aware of the research I have been doing, many have had conversations with me about it with the intention that I include their thoughts in my research, and all have been supplied with a copy of the results with the option of providing feedback. These observations have a minor contribution to the overall findings, but are important for the methodological description of my research.

Student ID: [redacted]
Full name: Sally Helen Potter

If you require any further details, please let me know.

Thank you,

Sally Potter
PhD candidate – Volcanology and Emergency Management
Joint Centre for Disaster Research
GNS Science/Massey University

From: "[redacted]>
To: Sally Potter <[redacted]>,
Cc: "Johnston, David" [redacted]>
Date: 04/06/2013 02:54 p.m.
Subject: RE: Question relating to use of observation data and a low risk notification

Hi Sally,

Many thanks for your update and clarification.

I will append this e-mail to your original notification and note the extension to the project dates and the change in methodology to include additional data collection on our database.

You may now proceed with this modification.

Regards,

[redacted]

APPENDIX 12: PARTICIPANT CONSENT FORMS – INTERVIEWS

The consent form signed by interview participants is on the next two pages.

ID: VALEU____

MASSEY UNIVERSITY

Participant Consent Form

Please take the time to read the following information carefully, and consider whether you would be willing to take part in this interview. Please contact the researchers using the details listed on the next page if there is anything that is not clear or if you would like more information.

Research information:

This research contributes towards Sally Potter's PhD through Massey University and GNS Science, titled '*towards the effective management of a volcanic crisis in New Zealand'.* This current research is investigating the use of New Zealand's Volcanic Alert Level system by end-users. The results from this research will contribute to her PhD thesis, which will be available publically through Massey University once completed. Results may also be included in GNS Science reports, and published in scientific journals and other publications. This research will contribute towards the improved management of a volcanic unrest crisis in the future.

What does this interview involve?

The researcher will be asking a number of questions involving the Volcanic Alert Level system in New Zealand, likely actions you would take during volcanic unrest or eruption, and background information.

Participant rights:

Whilst your contribution would be most appreciated, **you are under no obligation to participate in this research**. Following the Massey University Code of Ethical Conduct, if you choose to participate:

- your identity will be anonymous in the published results
- you may decline to answer any questions
- you may withdraw from the study at any time
- you may ask any questions about the study
- you can be given access to a summary of the project findings when it is concluded.

Data storage:

At the conclusion of the research, the data will be stored in a secure location at the Joint Centre for Disaster Research, which is part of the School of Psychology at Massey University, Wellington, New Zealand. All data collected will be held in this secure location for five years post research completion. The only persons with access to this data will be the current research team.

Information about the researchers:

Please feel free to contact one or all of the following people if you have questions about the research being undertaken.

Sally Potter, PhD student, Joint Centre for Disaster Research, Massey University, Wellington, and
GNS Science, Wairakei Research Centre, 114 Karetoto Road, Wairakei.
Email: S.Potter[at]gns.cri.nz, phone: [redacted]

Supervisors:

Assoc. Prof. David Johnston, Joint Centre for Disaster Research, Massey University, Wellington.
Email: David.Johnston[at]gns.cri.nz, phone: [redacted]

Dr. Gill Jolly, Wairakei Research Centre, GNS Science, 114 Karetoto Road, Wairakei.
Email: G.Jolly[at]gns.cri.nz, phone: [redacted]

ID: VALEU____

Consent:

If you have read the information on the previous page and are willing to participate in this research, please fill in the details below:	
Please print your name:	Date: / /
Signature:	
You have the right to decline to answer any question.	

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researchers named above are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you wish to raise with someone other than the researchers, please contact Professor John O'Neill, Director (Research Ethics), telephone 06 350 5249,email humanethics[at] massey.ac.nz.

To be completed by the interviewer:			
Activity:	Focus Group	Interview	Participant code:
M / F	Date: / /	Time: : am / pm	
Interview location:			
Participant name:			
Position/role:			
Organisation:			

Very satisfied	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied	Very dissatisfied

APPENDIX 13: PARTICIPANT CONSENT FORM – OBSERVATIONS

The consent form signed by participants who were observed is on the next two pages.

ID: Obs___

MASSEY UNIVERSITY

Participant Consent Form

Please take the time to read the following information carefully, and consider whether you would be willing to take part in this research. Please contact the researchers using the details listed on the next page if there is anything that is not clear or if you would like more information.

Research information:

This research contributes towards Sally Potter's PhD through Massey University and GNS Science, titled *'Towards an effective Volcano Early Warning System for New Zealand'.* In this part of the PhD, the use of New Zealand's Volcanic Alert Level (VAL) system by GNS scientists is investigated through the analysis of observations, as part of the assessment of the system. While the vast majority of the VAL review findings are based on interview data, these observations also contribute.

By signing this agreement, you are consenting to the use of Sally's observations while at GNS Science from May 2011 until the completion of her PhD (or 30 April 2014, whichever is soonest). You have been identified as having attended one or more of the volcano surveillance meetings and/or have communicated with Sally about the VAL system during this time, and she would like to use your input to her research.

These observations have contributed to the VAL findings document emailed to all scientists in May 2013. Please let Sally know if you would like another copy of these VAL findings, or if you would like any aspect relating to your contribution or identification altered or removed.

The results from this research will contribute to her PhD thesis, which will be available publically through Massey University once completed, and accessible to all participants. Summarised results may also be included in GNS Science reports, and published in scientific journals and other publications.

This research will contribute towards the improved management of a volcanic unrest crisis in the future, and to the evaluation of the future Volcanic Alert Level System.

Participant rights:

Whilst your contribution would be most appreciated, **you are under no obligation to participate in this research**. Following the Massey University Code of Ethical Conduct, if you choose to participate:

- **your identity will be anonymous in the published results**
- you may withdraw from the study at any time until the PhD thesis has been submitted
- you may ask any questions about the study
- you can be given access to a summary of the project findings when it is concluded.

ID: Obs___

Data storage:

At the conclusion of the research, the data will be stored in a secure location at the Joint Centre for Disaster Research, which is part of the School of Psychology at Massey University, Wellington, New Zealand. All data collected will be held in this secure location for five years post research completion. The only persons with access to this data will be the current research team.

Information about the researchers:

Please feel free to contact one or all of the following people if you have questions about the research being undertaken.

Sally Potter, PhD student, Joint Centre for Disaster Research, Massey University, Wellington, and GNS Science, Wairakei Research Centre, 114 Karetoto Road, Wairakei.
Email: [redacted], phone: [redacted]

Supervisors:

Assoc. Prof. David Johnston, Joint Centre for Disaster Research, Massey University, Wellington.
Email: [redacted], phone: [redacted]

Dr. Gill Jolly, Wairakei Research Centre, GNS Science, 114 Karetoto Road, Wairakei.
Email: [redacted], phone: [redacted]

Consent:

If you have read the information on the previous page and are willing to participate in this research, please fill in the details below:	
Please print your name:	Date: / /
Signature:	

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researchers named above are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you wish to raise with someone other than the researchers, please contact Professor John O'Neill, Director, Research Ethics, telephone 06 350 5249, email humanethics[at]massey.ac.nz.

APPENDIX 14: TRANSLATING QUALITATIVE PHRASES TO NUMERICAL DATA

Qualitative descriptions of natural phenomena were commonly used prior to the development of scientific monitoring. In order to plot the rate of seismicity and apply consistent thresholds throughout time, qualitative phrases can be assigned numbers. The process by which qualitative phrases were translated to numbers for Taupo Volcanic Centre (TVC) is described below.

Numbers were selected fairly subjectively with consideration of common usage, and used consistently (Table A14.1). The only exception to this was in assigning the numerical equivalents for the terms “earthquakes” and “tremors”, as these were found to be relative to the recent level of seismicity. For example, in isolated events, “earthquakes” was taken as two occurring, whereas “small earthquakes continue” in the days following hundreds of felt earthquakes was estimated as 10. If comparable language was used (for example “less frequent”), quantitative totals reflected this with consideration of the data from the recent past.

Minimums were used whenever quantitative descriptions were included in the original data source. For example, at least 10 earthquakes were reported as felt during the afternoon of 29 June 1922 at Oruanui (Seismological Observatory felt reports, 1922), and as no other earthquakes were reported for the morning, the rate of seismicity for that day was recorded as 10 earthquakes.

Table A14.1. Qualitative phrase translations to numerical data.

Qualitative description	Translation to numerical data
several	3
succession	5
unprecedented number	5
occasional	5
numerous	5
tremors/earthquakes	2–10[51]
frequent	10
many	10
considerable number	10

[51] The range in the number assigned to the term “earthquakes” varied according to the relative level of recent seismic events.

APPENDIX 15: CRITERIA FOR DEFINING EPISODES IN THE TVC UNREST CATALOGUE

The dataset created during this research includes thousands of earthquakes, long-duration periods of deformation, and many hydrothermal eruptions. The complete dataset is stored at GNS Science, New Zealand. From this dataset, episodes need to be defined to create a catalogue of unrest from which to estimate the VUI (presented in Chapter 6). This process was created for this research as no description has been found in the published literature of the methods used by other researchers who have created detailed multi-parameter volcanic unrest catalogues spanning a long time period with a wide variation in monitoring capabilities.

Due to time and funding constraints in the development of the catalogue, thresholds of activity for each parameter had to be determined to exclude the lower levels of activity from the catalogue, particularly small, isolated earthquakes. Additionally a consistent process to identify start and end dates of episodes needed to be created.

Thresholds used to identify events for the catalogue

If any of the criteria described in Table A15.1 were met or exceeded, the events were included in the catalogue in Chapter 6.

Table A15.1. Thresholds used to identify events for the TVC catalogue. The VUI was estimated for episodes in the catalogue, and unrest episodes identified.

Phenomena	Pre-1940	1940–1989	Post-1990
Local earthquakes			
Rate of high frequency earthquakes	≥2 felt events per calendar month	≥ 20, of all magnitudes per calendar month	≥ 50, of all magnitudes per calendar month
Tremor, low frequency and hybrid earthquakes	Any reported events	Any reported events	Any reported events
Local deformation	Any reported changes in the original sources	Any changes reported in original sources until monitoring began in 1979, and then episodes identified in the literature	Episodes identified in the literature
Geothermal systems and degassing	Any reported changes	Any reported changes	Any reported changes

Within each of the three time periods (pre-1940, 1940–1989, and post-1990, defined by monitoring capabilities at TVC over time), different thresholds for the rate of high frequency earthquakes were used to define episodes from the wider dataset. For the pre-1940 period, the threshold was a rate of ≥2 earthquakes per calendar month to exclude isolated earthquakes, and to include any unspecific, qualitative descriptions of multiple earthquakes (for example, “earthquakes occurred overnight”), where the exact number is unknown but is likely to have been a minimum of two. The thresholds for the periods of 1940 to 1989, and 1990 onwards were selected to identify episodes comparable to those from pre-1940, judged to be ≥ 20 earthquakes per month of any magnitude reported from 1940 to 1989, and ≥ 50 earthquakes per month of any magnitude reported post-1990 (Table A15.1). Only a few of the 20 or 50 earthquakes would have been felt. All reports of low frequency events or tremor were included.

All pre-monitoring reports potentially relating to deformation were included in the catalogue. Apart from seiches in Lake Taupo and rapid lake and river level changes, no ground deformation observations were found that had not already been identified in the published literature. Deformation monitoring data from TVC have previously been interpreted in the literature. Therefore the deformation in the catalogue has been based on the findings of researchers including Webb et al. (1986); Otway (1986, 1987); Otway and Sherburn (1994); Darby, Hodgkinson and Blick (2000); Otway et al. (2002); Smith et al. (2005); and Peltier et al. (2009).

All hydrothermal events and reported changes to surface features found in this research have been included in the catalogue.

Defining episodes for the catalogue

A framework has been utilised involving calendar months as time envelopes containing individual events. If the criteria described in the previous section were met, this constituted an ‘episode’. Episodes were combined into one if there was a period of less than six months separating them. They were divided into separate episodes if there was a six month gap where no parameters exceeded the thresholds described in Table A15.1. The decision to use six months as a minimum period of quiescence separating episodes was fairly subjective.

APPENDIX 16: REFERENCES FOR INFORMATION SOURCES FOR THE TVC UNREST CATALOGUE

This appendix lists the full references used to create the catalogue of caldera unrest at TVC, which is presented in Chapter 6. The reference numbers refer to the citations in Tables 6.3, 6.4, and 6.5.

Ref.	Source
NEID	National Earthquake Information Database, GNS Science, New Zealand
1	Transactions and Proceedings of the New Zealand Institute, 1872. Earthquakes reported in New Zealand during 1872 (Vol. 5, pp. xxi).
2	Daily Southern Cross, 30 September 1875. (Vol. XXXI, p. 5.).
3	Daily Southern Cross, 8 October 1875. (Vol. XXXI, p. 2.).
4	Hawke's Bay Herald, 10 April 1877. Telegrams (Vol. XX, p. 2).
5	Evening Post, 24 July 1877. Taupo (Vol. XV, p. 3).
6	Transactions and Proceedings of the New Zealand Institute, 1877. Earthquakes reported in New Zealand during 1877 (Vol. 10, pp. xxiii).
7	Taranaki Herald, 11 December 1877. New Zealand Telegrams (Vol. XXV, p. 2).
8	N.Z. Herald, 11 December 1877. Shocks of earthquake.
9	Waikato Times, 14 February 1878. Special Telegrams (Vol. XI, p. 2).
10	Bay of Plenty Times, 16 February 1878. Severe Earthquake (p. 3).
11	Evening Post, 20 February 1878. Taupo (Vol. XVI, p. 2).
12	Bay of Plenty Times, 23 February 1878. Local and General (Vol. VI, p. 3).
13	Evening Post, 22 March 1878. Taupo (Vol. XVI, p. 2).
14	Hawke’s Bay Herald, 23 April 1878. Taupo (Vol. XXI, p. 2).
15	Transactions and Proceedings of the New Zealand Institute, 1880. Earthquakes reported in New Zealand during 1880 (Vol. 13, pp. xxiii).
16	Evening Post, 28 June 1880. Sunday entertainments (Vol. XIX, p. 2).
17	Bay of Plenty Times, 29 June 1880. Alarming earthquakes at Taupo (Vol. IX, p. 3).
18	Hawke's Bay Herald, 19 July 1880. Taupo (Vol. XXI, p. 3).
19	New Zealand Tablet, 23 July 1880. Facts without comment (Vol. VII, p. 5).
20	Bay of Plenty Times, 31 July 1880. Another earthquake at Taupo (Vol. IX, p. 3).
21	Bay of Plenty Times, 24 August 1880. Taupo (Vol. IX, p. 3).
22	Hawke's Bay Herald, 20 September 1880. Taupo (Vol. XXI, p. 3).
23	Bay of Plenty Times, 28 September 1880. Taupo (Vol. IX, p. 2).
24	Hawke's Bay Herald, 8 June 1881. Telegraphic (Vol. XXI, p. 2).
25	Bay of Plenty Times, 30 July 1881. Taupo (Vol. X, p. 3).
26	Hawke's Bay Herald, 11 November 1881. Telegraphic (Vol. XXI, p. 2).

27 Hawke's Bay Herald, 1 March 1882. Telegraphic (Vol. XXI, p. 2).

28 Wanganui Herald, 23 January 1883. Severe earthquake at Taupo (Vol. XVII, p.3)

29 Wanganui Herald, 26 February 1883. Several earthquakes at Taupo (Vol. XVII, p. 3).

30 Transactions and Proceedings of the New Zealand Institute, 1883. Earthquakes reported in New Zealand during 1883 (Vol. 16, pp. xlv).

31 Nelson Evening Mail, 14 March 1883. New Zealand (Vol. XVIII, p. 2).

32 Wanganui Herald, 7 May 1883. Severe earthquake at Taupo (Vol. XVII, p. 2).

33 Hawke's Bay Herald, 7 May 1883. Telegraphic (Vol. XXI, p. 3).

34 Transactions and Proceedings of the New Zealand Institute, 1884. Earthquakes in New Zealand during 1884 (Vol. 17, pp. xlvii).

35 Wanganui Herald, 8 January 1884. Taupo (Vol. XIX, p. 2).

36 Evening Post, 10 January 1884. (Vol. XXVII, p. 2).

37 Wanganui Herald, 20 March 1884. News from Taupo (Vol. XIX, p. 3).

38 Star, 21 March 1884. Earthquake shocks (issue 4956, p. 2).

39 N.Z. Herald, 22 March 1884. New Zealand telegrams.

40 Hawke's Bay Herald, 29 March 1884. (Vol. XXI, p. 2.)

41 Wanganui Herald, 16 October 1884. Taupo (Vol. XIX, p.2).

42 Hawke's Bay Herald, 3 November 1884. Taupo (Vol. XXI, p.3).

43 Bay of Plenty Times, 6 January 1885. Taupo (Vol. XIII, p. 2).

44 Star, 14 June 1886. The disturbed area spreading (issue 5944, p. 3).

45 Feilding Star, 15 June 1886. More earthquakes (Vol. VIII, p. 3).

46 Star, 15 June 1886. Another explosion (issue 5645, p. 3).

47 Southland Times, 16 June 1886. The earthquakes (issue 9244, p. 2).

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66 Evening Post, 20 August 1895. The disturbances at Taupo (Vol. L, p. 3).

67 N.Z. Herald, 21 August 1895. The earthquake at Taupo.

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69 Poverty Bay Herald, 22 August 1895. The earthquake (Vol. XXII, p. 2).

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71 Taranaki Herald, 24 August 1895. Earthquake shocks at Taupo (Vol. XLIV, p. 2).

72 Thames Star, 27 August 1895. Earthquake shocks (Vol. XXVI, p. 2).

73 Evening Post, 24 July 1922. Taupo earthquakes (Vol. CIV, p. 5).

74 Observer, 26 September 1896. “Pars” about people (Vol. XVI, p. 22).

75 N.Z. Herald, 22 March 1897. Earthquake shock at Taupo.

76 Otago Daily Times, 23 March 1897. Telegrams (Issue 10757, p. 2).

77 Bruce Herald, 26 March 1897. New Zealand (Vol. XXVIII, p. 1).

78 Transactions of the New Zealand Institute, 1897. Earthquakes reported in New Zealand during 1897 (Vol. 30, pp. 595).

79 N.Z. Herald, 10 September 1897. Earthquake shocks at Taupo.

80 Star, 11 September 1897. Auckland news (issue 5973, p. 6).

81 N.Z. Herald, 14 September 1897. Earthquake shocks.

82 N.Z. Herald, 18 September 1897. Volcanic activity.

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84 N.Z. Herald, 20 September 1897. General telegraphic news.

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