Guidelines for Natural Hazard Risk Analysis on Public Conservation Lands and Waters

Part 6: Preliminary hazard and exposure analysis for volcanic and geothermal hazards

NI Deligne
GS Leonard
SJ de Vilder

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EXECUTIVE SUMMARY

This report presents a preliminary screening tool for exposure to volcanic and geothermal hazards at specific locations (‘point sites’) within public conservation lands and waters (Department-of-Conservation-managed land), such as huts, visitor centres and carparks, or at specific points along a linear site, such as tracks and roads. The preliminary screening tool covers life-safety considerations and can be used to identify and prioritise areas within public conservation lands and waters for further risk analysis and risk management actions.

The method can be used to estimate societal exposure, which is the most likely number of people at a site, to the volcanic and geothermal hazard, and the individual spatio-temporal probability of exposure of visitors and workers to the volcanic and geothermal hazard. The preliminary screening tool considers categories of volcano and geothermal eruptions: eruptions with no useful precursory activity indicating an eruption is imminent (Category A) and eruptions preceded by escalating volcanic unrest (Category B).

The hazard from Category A eruptions is based solely on distance from source areas, while, for Category B eruptions, the hazard level is based on eruption frequency within a specified distance from source regions. The hazard probability of occurrence and exposure are then used to define the hazard and exposure class (Class 1–3) for a site based on the hazard and exposure matrix. The risk management actions associated with hazard and exposure class are:

1. **Class 1**: No further risk analysis required. DOC should develop appropriate risk management plans and re-evaluate the risk management plan if there is a change in hazard activity or the number of people exposed
2. **Class 2:** Basic level of risk analysis required. The analysis should highlight and identify the potential impacts to persons on the public conservation lands and waters. Identified high-risk sites may require further advanced risk analysis and consideration of mitigation options.
3. **Class 3**: Advanced-level risk analysis of risk may be required. Class 3(a) represents the highest priority for further risk analysis and risk management actions.

Further risk management actions, including risk analysis, are at the discretion of the Department of Conservation on advice from the expert panel. It is also important to note that, for the preliminary screening methodology, the uncertainties on the information provided are relatively large.

1.0 INTRODUCTION

1.1 Purpose of Report

The purpose of the report is to outline and describe a method for undertaking volcanic and geothermal hazard and exposure analysis at point locations, either at point sites or along linear sites, within the public conservation lands and waters (Department-of-Conservation-managed land). The method forms a preliminary screening tool used to identify and prioritise areas within the public conservation lands and waters for further risk analysis and risk management actions.

1.2 Concept

The purpose of the preliminary screening tool is to identify whether more analysis is needed at a site, what the level of analysis should be and to assist in prioritising such studies. The Part 1 report sets out a flowchart that guides the user through the process, which ultimately ends with assigning the site a hazard class. It is intended that the hazards at each site are initially analysed using the screening tool. The results would then go to the Department of Conservation (DOC) to be reviewed and to the expert panel to confirm the level of any future analysis (see the Part 1 report).

The preliminary screening tool considers categories of volcano and geothermal eruptions: eruptions with no useful precursory activity indicating an eruption is imminent (Category A) and eruptions preceded by escalating volcanic unrest (Category B).

The hazard from Category A eruptions is based solely on distance from source areas, while, for Category B eruptions, the hazard level is based on eruption frequency within a specified distance from source regions. The method assesses hazard and exposure at point and linear sites in the public conservation lands and waters.

1.3 Scope of Report

The methodology is only concerned with life-safety considerations for visitors and workers within the public conservation lands and waters. Workers may include DOC staff, contractors, volunteers and concessionaires. The methodology provides a preliminary screening tool to identify when life-safety risk may need to be considered for visitors and staff at point sites (e.g. huts and carparks) and linear sites (e.g. tracks and roads) from volcanic unrest and/or eruptions or geothermal activity.

Not covered are:

- Volcanic hazards covered by the landslide risk analysis method (i.e. lahars, sector collapse), which are detailed in the Part 2, 3 and 4 reports.
- Tsunami caused by volcanic activity.
- Other hazards within volcanic areas unrelated to volcanic activity.
- Chronic exposure to volcanic hazards (e.g. volcanic gas).
- Physical point and/or linear site infrastructure damage.

1.4 Materials

It is assumed that the consultant undertaking the hazard and exposure analysis for a site has access to:

- An accurate ground model of the area. At a minimum, this is the 8 m National DEM as provided by LINZ (https://data.linz.govt.nz/), but higher-resolution ground models do exist for some areas and should be used if available.
- Information on exposure (occupancy and time spent), to be provided by DOC.
- GIS shapefile of vent locations on public conservation lands and waters, provided by DOC.

1.5 Structure of Report

Section 2 provides background information; further information is available in Appendices 1–5. Section 3 describes the specific steps required to conduct the hazard and exposure analysis preliminary screening tool. Section 4 outlines how the analysis and report should be recorded and presented, along with the information a consultant should generate to support their hazard rating. Section 5 comments on dynamic risk in the volcano context together with volcanic risk management plans. Section 6 summarises the report.

2.0 BACKGROUND

Volcanoes are “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 deposits or the eruption process.” [1] New Zealand is home to many volcanoes (Figure 2.1).

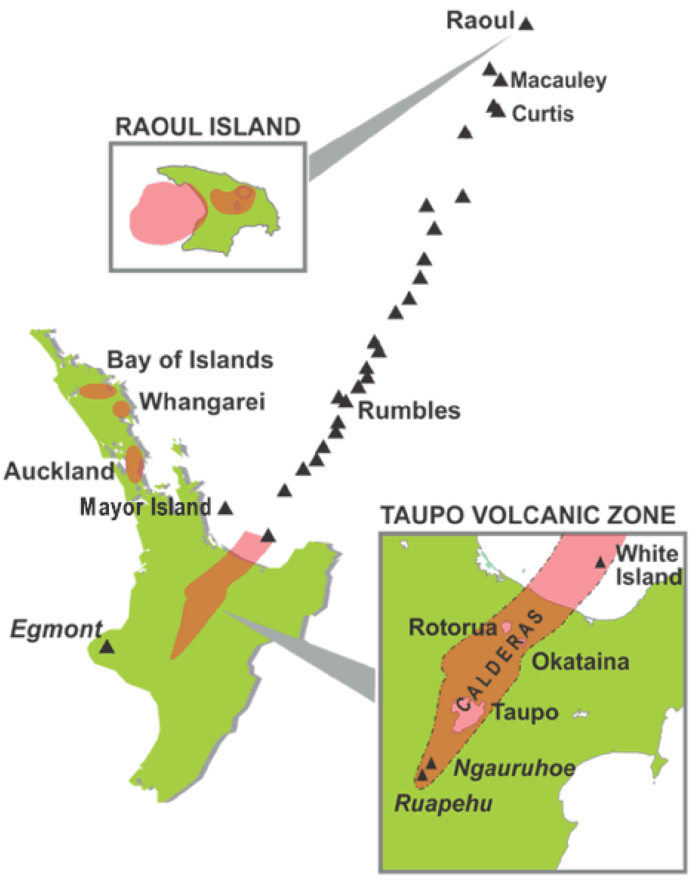

Figure 2.1 New Zealand’s volcanoes. Figure from https://www.gns.cri.nz/Home/Learning/Science-Topics/Volcanoes/New-Zealand-Volcanoes, accessed 28 November 2019.

New Zealand has three main types of volcano:

1. **Volcanic Fields** are regions where small eruptions occur over a wide geographic area. Each eruption builds a new single new volcano, which does not usually erupt again. Eruptions can be spaced decades or millennia apart. New Zealand examples include the Auckland Volcanic Field, the Bay of Islands Volcanic Field and the Whangarei Volcanic Field.
2. **Cone volcanoes** are characterised by a succession of small–moderate eruptions from one location. The products from the successive eruptions over thousands of years build the cones. Cone volcanoes are also called composite cones or stratovolcanoes. New Zealand examples include Ngauruhoe, Ruapehu, Taranaki, Tongariro and Whakaari / White Island.
3. **Caldera volcanoes** have a history of infrequent but moderate–large eruptions. The caldera-forming eruptions create super-craters 10–25 km in diameter and deposit cubic kilometres of ash and pumice. Calderas can also produce small–moderate eruptions. New Zealand examples include Mayor Island, Okataina and Taupō.

1 GNS website glossary; https://www.gns.cri.nz/Home/Learning/Glossary, accessed 28 November 2019.

New Zealand also has geothermal areas, which exist "due to high heat flow in the crust along the Pacific-Australian tectonic plate boundary." [2]

Both volcanoes and geothermal areas can produce eruptive hazards that pose an acute life-safety risk. This report provides a screening processes for identifying areas that may be at risk.

The following Appendices provide further background information concerning volcanic and geothermal hazards and their consequences:

- **Appendix 1:** Volcano monitoring in New Zealand and GeoNet products.
- **Appendix 2:** Types and sizes of volcanic and geothermal eruptions, including New-Zealand-specific content.
- **Appendix 3:** Volcanic hazards, including their occurrence at specific New Zealand volcanoes.
- **Appendix 4:** Human consequences of volcanic eruptions.
- **Appendix 5**: Eruptive histories of New Zealand volcanoes.

These appendices are not required to apply the preliminary screening tool but may provide a valuable starting point for more in-depth analysis.

2 GNS website; https://www.gns.cri.nz/Home/Learning/Science-Topics/Earth-Energy/Hot-Steamy-NZ/Geothermally-active-regions, accessed 8 May 2020.

3.0 PRELIMINARY HAZARD AND EXPOSURE ANALYSIS FOR VOLCANOES AND GEOTHERMAL AREAS

3.1 Overview

A simple relative hazard and exposure matrix has been developed to help DOC prioritise the sites in terms of future investigations and the possible requirements needed to manage them. The relative hazard and exposure matrix is broadly based on the risk management framework contained in the original Risk Management Guidelines Companion to AS/NZS 4360:2004, which is now superseded by 31000:2009.

The preliminary screening approach, standard for all hazards considered in the GNS Science risk analysis reports, is to identify at the site of interest the hazard frequency classification (Table 3.1) and the exposure for both Individual and Societal Risk analysis. The hazard frequency classification is based on a conservative assessment of how likely it is that a hazard caused by volcanic or geothermal area activity may occur at the site. The consequence/ exposure classifications are based on the number of people likely to be exposed to the hazard if it were to occur. A hazard and exposure matrix is then used to assign the hazard and exposure class for both individuals and groups of people (societal). Different actions are recommended based on the hazard and exposure class (Table 3.2).

Table 3.1 Hazard frequency classification used for all hazards considered in GNS Science risk analysis reports. Note that, for volcanic and geothermal hazards, the 'High' and 'Very High' indicative recurrence intervals have been combined into a single 'High' indicative recurrence interval.

Hazard Frequency		**Descriptor**
Indicative Recurrence Interval (Years)	**Approximate Annual Frequency (Temporal Probability)**	
<100	<0.01	High
100–1000	0.01–0.001	Medium
1000–10,000	0.001–0.0001	Low
>10,000	>0.0001	Very Low

Table 3.2 Risk management actions and associated hazard and exposure class; see the Part 1 report for more information.

	Risk Management Actions
Class 1	No further risk analysis required; however, DOC should develop appropriate risk management plans and re-evaluate the risk management plan if there is a change in hazard activity or the number of people exposed.
Class 2	Basic level of risk analysis required; methodology out of scope for this report.
Class 3	Advanced level of risk analysis required; methodology out of scope for this report.

In areas where the nearby volcano is at Volcano Alert Level (VAL) 0 (see Appendix 1), and geothermal hazards are not a particular concern (e.g. Taranaki at the time of writing in May 2020), volcanic hazards do not pose a life-safety risk to visitors and workers. A volcano can remain at VAL 0 for decades to centuries or longer. However, if there is volcanic unrest (VAL 1, 2) or eruption (VAL 3, 4, 5); or increased activity in a geothermal area, unrest and eruptive and geothermal hazards can pose a considerable risk to visitors and workers.

The method therefore firstly assesses if the site is within the lethal hazard footprint of a volcanic or geothermal hazard(s) from identified source area vents. The hazard footprint is defined as the area within which a lethal hazard might impact (Figure 3.1). Secondly, the method assesses background hazard levels, acknowledging that during periods of no or low activity there may be negligible risk posed to visitors and workers but, if volcanic activity escalates, these assets may be situated in suddenly unacceptable levels of risk. A robust and exercised dynamic risk management plan is a critical aspect of overall risk mitigation, especially in areas where wholescale avoidance (i.e. no asset) is not a realistic or desired mitigation approach.

For volcanic and geothermal areas, two categories of volcanic and geothermal eruptions are considered. Given a location, the preliminary screening tool determines a hazard and exposure class for each category of eruption, and the highest category class is assigned to the site (Figure 3.1).

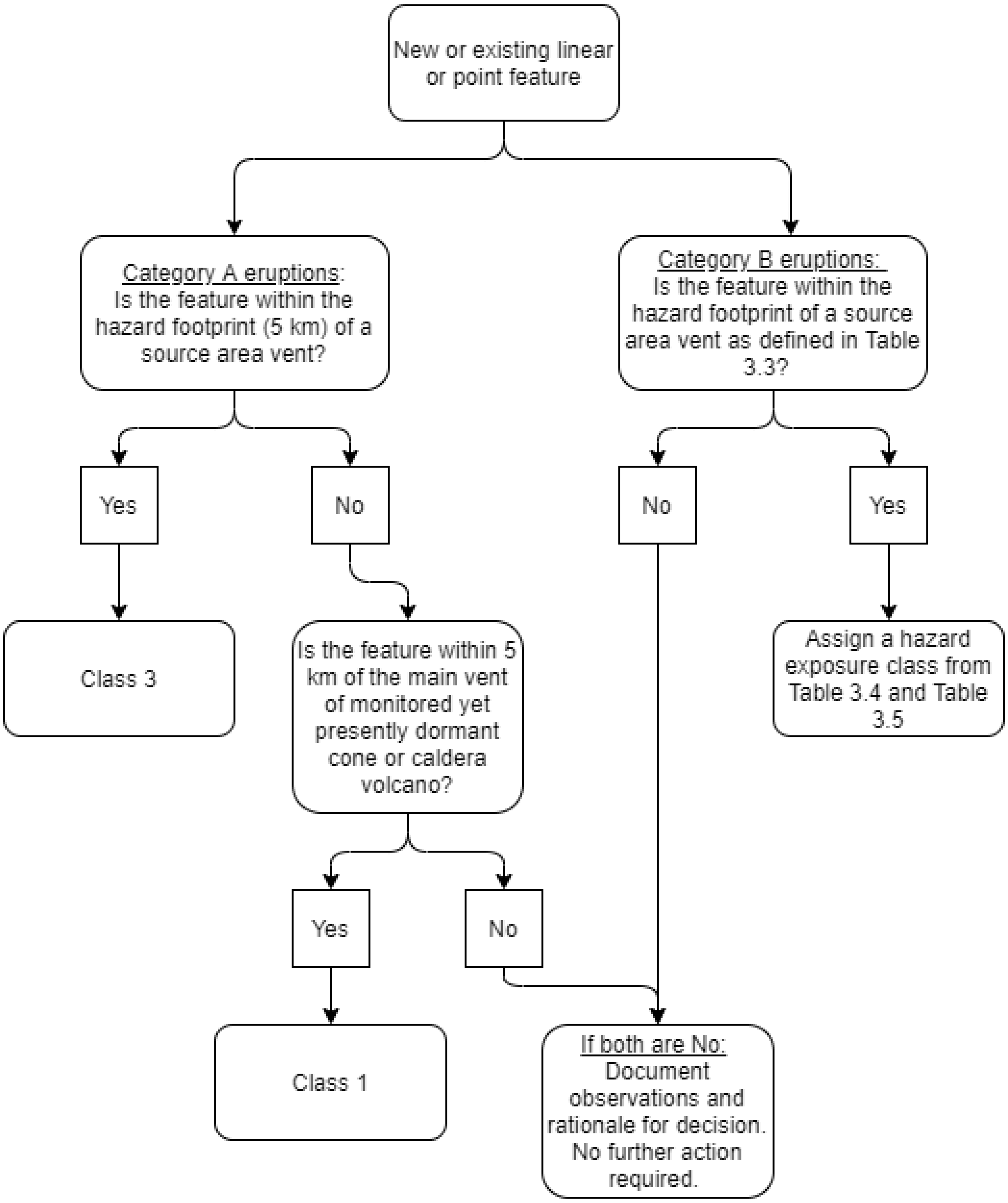

Figure 3.1 Flowchart of the preliminary screening tool method.

3.2 Categories of Volcanic and Geothermal Eruptions

Two categories of volcanic and geothermal eruptions are considered:

- **Category A:** Eruptions with no useful precursory activity indicating an eruption is imminent. These are a concern at geothermal areas and volcanoes with shallow magma near the surface (within the upper 2 km). These are sometimes called 'unheralded' or 'blue-sky' eruptions. As described in Appendix 2, these steam-driven eruptions fall under the category of hydrothermal eruption, phreatic eruption and phreatomagmatic eruption. Category A eruptions are unlikely to be recorded in the geologic record but are in the historic record when observed and noted. Geothermal hazards are included in consideration of Category A eruptions.
- **Category B:** Eruptions preceded by escalating volcanic unrest, providing advance insight on the likely location and size of volcanic activity. These can include all eruption types described in Appendix 2. Category B eruptions are often captured in both the geologic and historic records.

Lahars and sector collapse are not considered by this screening tool, as they are covered by the landslide hazard and risk analysis reports (Parts 2, 3 and 4). It is important to note that neither require an eruption or even unrest. Triggers are an eruption, failure of a crater lake wall (can be a portion), rainfall in the hours to decades following an eruption and structural instability.

3.3 Preliminary Analysis for Category A Eruptions

At the time of writing (May 2020), Category A eruptions are a concern from sources (e.g. vents) identified in an accompanying shapefile (to be supplied by DOC). However, in the future, other sites may become potential Category A source areas. The screening tool for Category A eruptions is based solely on distance from the source areas.

Process for evaluating hazard and exposure class for Category A eruptions:

1. Is the site within 5 km of one or more identified source areas in an accompanying shapefile? If yes, then assign hazard and exposure Class 3.
2. If the answer to the first question is no, is the site within 5 km of the main vent of a monitored yet presently dormant cone or caldera volcano? If yes, then assign hazard and exposure Class 1.

3.4 Preliminary Analysis for Category B Eruptions

The screening tool for Category B eruptions is based on eruption frequency (Table 3.1) and distance from vent source area.

3.4.1 Hazard Level

Use Table 3.3 to assign a hazard level given the site's distance from the source area. If the site is located beyond the distanced specified, no further action is required.

Table 3.3 Designated hazard level for Category B eruptive hazards for sites within a specified distance of given volcano, for use in exposure matrices.

	Very Low	Low	Medium	High	Distance
Offshore Island	-	Mayor Island	-	Raoul Whakaari / White Island	Entire island
Volcanic Field	Specific location in Auckland Volcanic Field (AVF) Northland volcanic fields	An eruption somewhere in AVF (if outside of eruptive episode)	An eruption somewhere in AVF (if within an eruptive episode)	-	Field extent + 5 km
Central TVZ Caldera Complex (CTVZC)	Rest of CTVZC	Specific location along one of: • Okataina Volcanic Centre (OVC): Haroharo lineament • OVC: Tarawera lineaments • Taupō Volcanic Centre (TVC) vent lineament 1	An eruption somewhere along any of: • OVC: Haroharo lineament • OVC: Tarawera lineament • TVC lineament vent 1	-	Identified lineaments + 10 km
Tongariro National Park [2]	-	-	Other Tongariro vents	Ruapehu, Ngauruhoe, historically active Tongariro vents	Within 10 km of vents
Tongariro National Park – valleys [2, 3]	Valleys and drainages directly connected to Ruapehu and Tongariro	-	-	-	Valleys and drainages within 20 km of vent with direct connection to edifice
Taranaki [3]	-	Taranaki: large eruptions	Taranaki: small to moderate size eruptions	-	Within 10 km of summit

[1] The Taupō Volcanic Centre vent lineament runs roughly from the area of Moutaiko Island to halfway between Te Kohaiakahu Point and Rangatira Point, near Taupō town.

[2] Lahars and sector collapse are addressed in the Part 2, 3 and 4 reports.

[3] A concern is lava flows, which can travel up to 20 km (e.g. Rangataua lava flow). There is no geological evidence of Tongariro National Park volcanoes producing pyroclastic density currents that travel further than 10 km.

3.4.2 Hazard and Exposure Class Identification

Two exposure metrics are used to assign hazard and exposure class:

- Individual spatio-temporal probability (Table 3.4): Estimated by combining the hazard frequency (Table 3.3) with the proportion of time over a 24-hour period that the individual most exposed spends at a given hazard level at the site. For the sake of comparison, the individual hazard and exposure class is approximately related to the Annual Individual Fatality Risk (AIFR), on the assumption that the activity was undertaken every day for a year. Details and assumptions are given in Appendix 6.
- Societal exposure (Table 3.5): Estimated by combining the hazard frequency (Table 3.3) with the number of people (N) likely to be exposed to the hazard.

Table 3.4 Hazard and exposure matrix for Category B eruption for the individual most exposed per trip. Class 3(a) identifies sites that would receive consideration for the highest priority of investigations and analysis.

Exposure			**Annual Temporal Hazard Probability (See Table 3.3)**			
Proportion of time spent at point location in 24 hours	Equivalent to:	Example activity	Very Low	Low	Medium	High
>0.1	More than 3 hours	Staying in a hut	Class 1	Class 2	Class 3	Class 3(a)
0.1–0.01	Half an hour to 3 hours	Picnic spot	Class 1	Class 2	Class 3	Class 3(a)
0.01–0.001	2 minutes to half an hour	Stopping at a viewing area	Class 1	Class 1	Class 2	Class 3
<0.001	Less than 2 minutes	Crossing a swing bridge	Class 1	Class 1	Class 2	Class 2

Table 3.5 Hazard and exposure matrix for Category B eruptions for societal exposure. Class 3(a) identifies sites that would receive consideration for the highest priority of investigations and analysis.

Exposure	**Annual Temporal Hazard Probability (See Table 3.3)**			
Number of people exposed to the hazard	Very Low	Low	Medium	High
>40	Class 1	Class 3	Class 3	Class 3(a)
5–40	Class 1	Class 2	Class 3	Class 3
2–4	Class 1	Class 2	Class 2	Class 3
1	Class 1	Class 1	Class 2	Class 2

3.5 Notes

- Class 3 does not require an actively erupting volcano, although all areas within at least 5 km of all volcanoes that have erupted within the last century are assigned Class 3.
- Areas that may be exposed to Category A eruptions are assigned Class 3, in part because dynamic risk mitigation options are severely limited. Eruptions with no useful precursory activity may be smaller than the Category B eruptions, but smaller does not mean benign for those in the path of lethal hazards.
- The distances in Table 3.3 capture the greatest known extent of lethal hazards from the volcano(es) in question.
- In Table 3.3, the Auckland Volcanic Field appears three times. The hazard posed by and indicative recurrence interval of an eruption in the Auckland Volcanic Field, which covers 360 km^2, requires several considerations:
  - Two-thirds of known Auckland Volcanic Field eruptions (over 30 eruptions of the known 53 eruptions) occurred within the last 60,000 years.
  - In the last 60,000 years, there have been periods of up to 10,000 years without an eruption and episodes with as many as five eruptions within 400 years. The majority of eruptions appear to be coupled, meaning two or more eruptions occurring within 1000 years of each other.
  - The penultimate eruption (Mt Wellington) was 10,000 years ago.
  - The most recent eruption (Rangitoto) was about 600 years ago; it was bigger than any previous eruption and erupted a new magma type – all of this combines to increase uncertainty.
  - The likelihood that a specific point within the Auckland Volcanic Field is affected by lethal hazards is classified as *Very Low*, yet the likelihood of an eruption within the Auckland Volcanic Field is classified as *Low* or *Medium,* depending on whether we are in or out of an episode, respectively – of which there is no scientific consensus.
  - The reference for considerations 1–3 is Leonard et al. (2017), while consideration 4 is from Hopkins et al. (2018).
- Using Tables 3.4 and 3.5, a specific location within the Auckland Volcanic Field would be assigned Class 1 or 2, yet the Auckland Volcanic Field as a whole would be assigned Class 3 (over 1 million people live within the Auckland Volcanic Field). Thus, resulting actions are to consider regional-level measures given Class 3, but a specific site would require lower-level actions.
- In Table 3.3, lineaments within the Okataina Volcanic Centre and the Taupō Volcanic Centre appear twice. This is because the likelihood from a specific point along one of these lineaments is classified as *Low*, yet the likelihood of an eruption along one of the lineaments is classified as *Medium*.

4.0 REPORT REQUIREMENTS

The information derived for each site, as set out in Section 3, should be summarised by the consultant in a short letter report. This report should document the data gathered, the logic applied and the conclusion reached so that the decisions that determined the Hazard Class can be defended.

The general data to be presented, with reference to the study area boundary, include:

a. List of data sources used.

b. Description, if the site is affected by Category A and/or Category B eruptions.

c. A map showing distance from source area vent(s) to the site for Category A and B eruptions.

d. Assessed hazard and exposure classes for both Category A and Category B eruptions hazards identified.

e. Recommendations for future analysis / risk mitigation.

Where any of the above is not or cannot be completed, the report should document the missing elements and include an explanation as to why.

5.0 DYNAMIC RISK AND VOLCANIC RISK MANAGEMENT PLANS

The life-safety risk to workers and visitors can rapidly change during volcanic unrest and/or eruption. Conversely, at a volcano with little change in volcanic activity (either at Volcanic Alert Level 0, in unrest, or during a long-lived eruption), there may be little change to life-safety risk for a long period of time. The Volcano Alert Level (VAL) system describes the current status of a volcano in New Zealand, as set by the GeoNet volcanic monitoring team in GNS Science. For more information regarding the VAL system, refer to Potter et al. (2014). Furthermore, a volcano does not need to be in unrest or eruption to cause life-threatening injury: volcanic 'environment' hazards, such as hydrothermal activity, earthquakes, landslides, volcanic gases and/or lahars (mudflows), can also kill. Volcanic environment hazards are more likely to occur at volcanoes with historical volcanic activity or in geothermal areas. Geothermal areas are not generally covered by the VAL system.

Prior to unrest/eruption and/or increase of volcanic/geothermal environmental hazards, it is critical that a risk management plan is developed and regularly exercised in an ongoing way. **The plan needs to lay out how risk will be assessed based on the current and probable and/or credible future activity and at what risk thresholds additional risk mitigation measures will be triggered.**

For many volcanic hazards, the best mitigation strategy for life-safety risk is removal of the person or infrastructure, thus reducing the exposure (e.g. risk avoidance, engineering protection or evacuation). However, at volcanoes and geothermal areas in relative low unrest / geothermal activity or in an eruptive steady-state, avoidance may be too conservative an approach when compared to other hazards posed on the public conservation lands and waters. In such areas, having a risk management plan in the case of escalating activity is invaluable.

Table 5.1 provides a list of prompts to consider for dynamic risk management during unrest / geothermal activity and/or eruption at time when risk may be rapidly changing. Regardless of risk evaluation approach, short timeframes are generally more appropriate in a rapidly evolving situation, particularly when there is high uncertainty. Table 5.1 assumes there is a risk management plan as described above. A change in VAL can be treated as a prompt to re-evaluate options, but it is ill-suited as a prescriptive tool. GNS Science strongly discourages tying access to areas to a given VAL.

Table 5.1 Proposed prompts to consider for dynamic risk management during volcanic unrest and/or eruption or increase of volcanic/geothermal environmental hazard activity. These prompts may require a detailed assessment.

Number	Prompt	Comments
1	Has the change in activity at the volcano(es) or geothermal area(s) changed the life-safety risk to visitors and workers near the volcano?	A change in activity could be reflected in a change in VAL. However, the risk may change without a change in VAL in geothermal areas, or without a change in VAL at the volcanoes (e.g. there is no change in VAL if the volcano goes from moderate to heightened unrest – both are encapsulated in VAL 2). A change in VAL could be a useful prompt to re-evaluate, but it is strongly not recommended that it be the only prompt. At this stage, refer to the risk management plan for mitigation measures to implement during a crisis.
2	Given the current status of the volcano(es) and/or geothermal area(s), what types of unrest and eruptive activity, or environmental hazards in the case of geothermal areas, are likely to occur in relevant time frames (e.g. next day, week, month, season)?	Data sources include current Volcano Alert Bulletins and expert advice. It can be helpful to consider various scenarios, such as the most likely case, worst case and unlikely case. There is likely to be high uncertainty, particularly for longer timeframes.
3	Given activity assessed in Prompt 2, what, if any, sites/trails could be directly impacted by concerning hazards?	Data sources include detailed maps of point and/or linear sites, geological and historical records and modelling, current Volcano Alert Bulletins and/or expert advice.
4	What is the level of life-safety risk at the sites identified in Prompt 3?	Data sources include work done as part of Prompt 2 and 3 and/or expert advice. The methodology presented in Deligne et al. (2018), adapted for the current volcano and situation, can support this analysis.
5	Given kaitiaki decisions and the level of risk identified in Prompt 4, what mitigative measures are appropriate?	Mitigative measures may include, but are not limited to, rāhui, access restriction(s), detection systems, warning systems and effective public and worker communication.
6	Given assessment in Prompt 5, do new mitigative measures need to be implemented and/or are current mitigative measures no longer required?	Considerations are likely to differ depending on whether the volcanic situation is escalating, de-escalating or stable, as well as other factors.

6.0 CONCLUSIONS

This report provides a methodology for a preliminary screening tool to identify volcanic and geothermal risks to the life safety for visitors and workers within the public conservation lands and waters. The hazards of concerns include volcanic unrest and eruptive hazards and geothermal hazards. While the approach could be applied to anywhere within the public conservation lands and waters, the focus is life-safety considerations at point sites (e.g. huts, carparks, viewpoints) and linear sites (e.g. trails, roads) within the public conservation lands and waters.

Volcanoes, their hazards and eruptions are complex and diverse, and can pose considerable threat to the life safety of visitors and workers. Numerous volcanic unrest and eruption hazards can occur concurrently and more than once, with varying severity. Furthermore, volcanoes can often display a variety of eruption styles and eruptive styles. For most volcanic hazards, avoidance of exposure is critical for life safety.

In light of this complexity and hazard and eruption diversity, the preliminary screening tool determines qualitative hazards levels that accounts for volcano type, volcano-specific eruptive histories and distance from source area.

It is important to note that the screening process considers background risk. As volcanic life-safety risk can rapidly change during a volcanic crisis, it is critical to have robust and exercised dynamic risk management plans that can be rapidly implemented to manage exposure. It is strongly recommended that risk management plans – options and implementation requirements – are considered at the planning stage.

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APPENDICES

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APPENDIX 1 VOLCANO MONITORING IN NEW ZEALAND AND GEONET PRODUCTS

Volcano monitoring for New Zealand volcanoes is led by GNS Science through the GeoNet programme [3]. For further details on volcano monitoring refer to the GeoNet website (https://www.geonet.org.nz/volcano) and to Miller and Jolly (2014). The GeoNet programme undertakes extremely limited monitoring of geothermal areas.

GeoNet has two standard products to communication information regarding volcanic activity: the New Zealand Volcano Alert Level System (Appendix A1.1) and Volcano Alert Bulletins (Appendix A1.2).

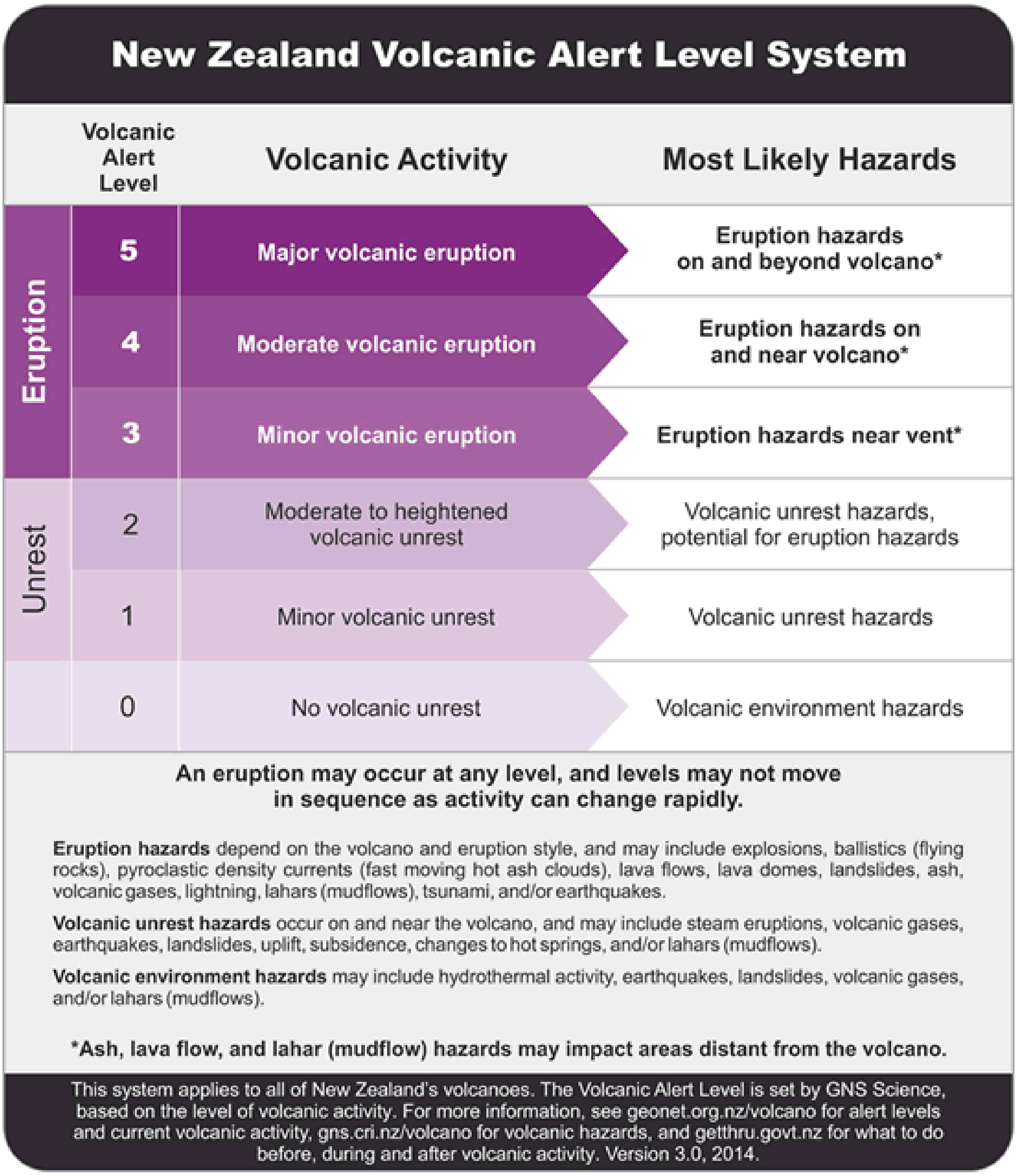
There are no equivalent products for geothermal areas that are not directly associated with one of the 12 monitored volcanoes [4] and, at volcanoes, a change in geothermal activity will not necessarily led to the issuance of a Volcano Alert Bulletin.

A1.1 New Zealand Volcano Alert Level System

In New Zealand, the current status of a volcano is described using the New Zealand Volcanic Alert Level System (VAL; Figure A1.1), set by the GNS Science GeoNet volcanic monitoring team. For further information, refer to Potter et al. (2014).

3 MetService, through the Wellington Volcanic Ash Advisory Centre (VAAC), monitors and models volcanic ash for aviation hazard, but is not responsible for ground-based hazards. GeoNet and the Wellington VAAC work closely together.

4 GeoNet monitors the Auckland Volcanic Field, Kermadec Islands (including Raoul Island), Mayor Island, Ngauruhoe, the Northland Volcanic Fields, Okataina Volcanic Centre, Rotorua, Ruapehu, Taranaki, Taupō Volcanic Centre, Tongariro and Whakaari / White Island.



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 A1.1 New Zealand Volcano Alert Level System. For further information, refer to Potter et al. (2014).

While detectable unrest (VAL 1, 2) almost always precedes an eruption (VAL 3, 4, 5), unrest does not always lead to an eruption. It can also be difficult to definitively determine that an eruptive episode is over.

A1.2 Volcano Alert Bulletins

A more detailed explanation of current activity, with forecasts of future activity when appropriate, is provided in a Volcano Alert Bulletin (VAB) issued by GeoNet (see Figure A1.2 for an example). VABs are emailed to a subscription list, published on the GeoNet webpage and social media accounts and pushed on the GeoNet app.

Mt Ruapehu: Minor seismic activity recorded

VOLCANIC ALERT BULLETIN: **RUA – 2020/02**

2020-02-24 15:55 NZ time; Ruapehu Volcano
Volcanic Alert Level remains at Level 1
Aviation Colour Code remains at Green

GNS SCIENCE TE PŪ AO

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199
www.gns.cri.nz

A short-lived episode of volcanic earthquakes occurred beneath Mt Ruapehu last Saturday 22 – Sunday 23 February. The earthquake episode has ended.

On Saturday 22 and Sunday 23 February, GeoNet seismographs detected a sequence of seismic events beneath Mt Ruapehu. GNS Science volcanologists have categorised them as volcanic earthquakes. The larger events at the start of the episode are approximately magnitude 1.5 and later, smaller events are too small to be located by GeoNet's earthquake detection-location system.

The seismic recordings indicate a source beneath the summit area, which is normal for volcanic earthquakes and volcanic tremor at Ruapehu. The sequence now appears to be over.

The Crater Lake (Te Wai ā-moe) temperature has been around 24-25 ºC for the last few months.

GeoNet monitors Mt Ruapehu via a network of seismic and acoustic sensors, GPS receivers, sensors in the lake and visits to the lake area. These include gas flights over Ruapehu for measuring gas emission and a monitoring visit to Te Wai ā-moe to collect water and gas samples as weather allows.

It is not unusual to observe volcanic earthquakes on Ruapehu and other episodes of increased seismic activity were observed during March 2018, April 2016 and September 2017. None of these resulted in a sustained increase in volcanic unrest.

The **Volcanic Alert Level**, therefore, **remains at Level 1**. The Volcanic Alert Level reflects the current level of volcanic activity and is not a forecast of future activity. **There is no change in the Aviation Colour Code from Green**.

GNS Science and the National Geohazards Monitoring Centre continues to closely monitor Mt Ruapehu for further signs of activity.

Agnes Mazot
Duty Volcanologist

Media Contact: 021 574 541 or media@gns.cri.nz

Institute of Geological and Nuclear Sciences Limited

Figure A1.2 Sample Volcano Alert Bulletin (VAB).

APPENDIX 2 TYPES AND SIZES OF VOLCANIC AND GEOTHERMAL ERUPTIONS

A2.1 Types of Volcanic and Geothermal Eruptions

Table A2.1 provides an overview of types of volcanic eruptions that can happen at New Zealand volcanoes. Steam-driven eruptions can also happen at geothermal fields.

Table A2.1 Types of volcanic eruptions, adapted from the GNS Science website [5], New Zealand volcanoes types they can occur at and past New Zealand examples.

	Description	New Zealand Volcanoes	Examples
Hydrothermal Eruption	A type of steam-driven eruption. An eruption driven by the heat in a hydrothermal system. Hydrothermal eruptions pulverise surrounding rocks and can produce ash, but do not include magma [1]. These are typically very small eruptions.	Cone volcanoes, caldera volcanos, geothermal areas	2000 Kuirau Park, Rotorua 2001 Kuirau Park, Rotorua 2016 Lake Rotorua
Phreatic Eruption	A type of steam-driven eruption. An eruption driven by the heat from magma interacting with water. The water can be from groundwater, hydrothermal systems, surface runoff, a lake or the sea. Phreatic eruptions pulverise surrounding rocks and can produce ash, but do not include new magma.	All	2006 Ruapehu 2012 Te Maari (both eruptions)
Phreatomagmatic Eruption	A type of steam-driven eruption. An eruption resulting from the interaction of new magma or lava with water and can be very explosive. The water can be from groundwater, hydrothermal systems, surface runoff, a lake or the sea.	All	Maungataketake, Auckland Volcanic Field
Lava Flows	Effusive (non-explosive) outpourings of lava [1] that usually flow slower than walking pace. Lava flow types include ʻaʻā, blocky and pāhoehoe.	All, but most likely at volcanic fields	Three Kings, Auckland Volcanic Field

5 https://www.gns.cri.nz/Home/Learning/Science-Topics/Volcanoes/Types-of-Volcanoes-Eruptions, accessed 26 March 2020.

	Description	New Zealand Volcanoes	Examples
Lava Fountains	Fountain of runny lava fragments from a vent or line of vents (a fissure). They can form spatter piles and, if the fragments accumulate fast enough, form lava flows.	Volcanic fields, calderas	Likely the vents that fed the lavas of Rangitoto (~600 years ago)
Lava Domes	Mounds that form when viscous lava is erupted slowly and piles up over the vent, rather than moving away as a lava flow. They are generally caused by viscous, thick, sticky lava that has lost most of its gas. They can range in volume from a few cubic metres to cubic kilometres.	Cone volcanoes, caldera volcanoes	Summit peaks of Tarawera (~700 years ago)
Strombolian and Hawaiian Eruptions	These are the least violent types of explosive eruptions. Hawaiian eruptions have fire fountains and lava flows, whereas Strombolian eruptions have explosions causing a shower of lava fragments.	Volcanic fields, cone volcanoes	1954–1955 Ngauruhoe
Vulcanian Eruptions	Small to moderate explosive eruptions, lasting seconds to minutes. Ash columns can be up to 20 km in height, and lava blocks and bombs may be ejected from the vent.	Cone volcanoes	1974 Ngauruhoe
Subplinian and Plinian Eruptions	Eruptions with a high rate of magma discharge, sustained for minutes to hours. They form a tall, convective eruption column of a mixture of gas and rock particles and can cause wide dispersion of ash. Subplinian eruption columns are up to 20 km high and are relatively unsteady, whereas Plinian eruptions have 20–35 km tall columns which may collapse to form pyroclastic density currents (PDCs). Very rare Ultraplinian eruptions are even larger and have a higher magma discharge rate than Plinian eruptions.	Cone volcanoes, caldera volcanoes	1886 Tarawera 1945 Ruapehu 1969 Ruapehu 1975 Ruapehu

[1] Lava is molten rock erupted at the ground surface. When molten rock is beneath the ground, it is called magma.

A2.2 Size of Volcanic Eruptions

The size of the volcanic eruption is often described using the Volcanic Explosivity Index (VEI; Newhall and Self 1982; Figure A2.1) or in terms of parameters that contribute to the VEI (e.g. column height, erupted volume). Note that there is no relation between VEI (describes size of a volcanic eruption) and the New Zealand Volcano Alert Level System (VAL), which describes the current status of volcano (see Appendix 1). We note that, in New Zealand, Ruapehu volcano has a customised eruption size scale developed by Scott (2013) to characterise historic activity (Table A2.2); this scale has no relation to neither VEI nor VAL.

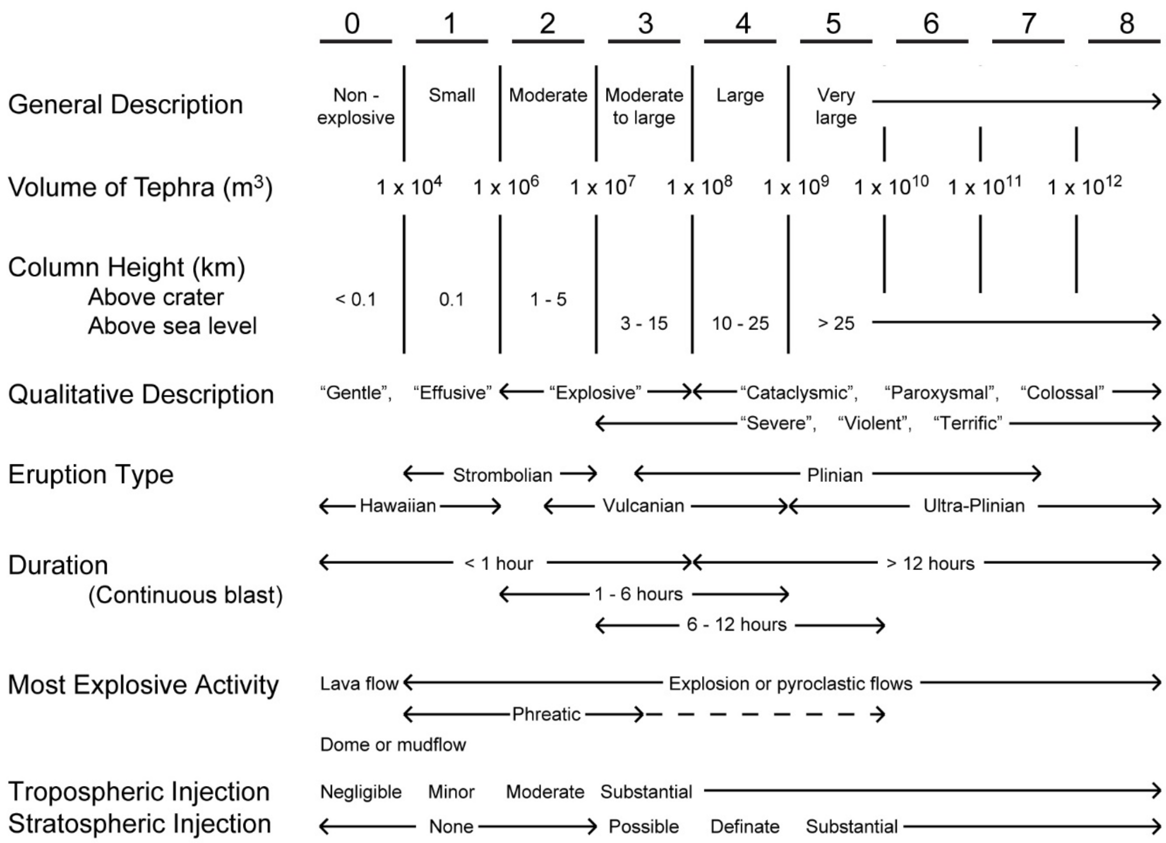


Figure A2.1 Volcanic Explosivity Index (VEI), developed by Newhall and Self (1982). Figure is Figure 1 from Deligne et al. (2010).

Table A2.2 Ruapehu-specific eruption scale, adapted using most recent example of such an eruption from Scott (2013).

	Observed Effects	Most Recent Example in Scott (2013)
Ruapehu Eruption Scale 0	Te Wai ā-moe / Crater Lake steaming and hotter than normal (i.e. above 30–35°C), creating additional interest, but no observations (or confirmation) of activity in Te Wai ā-moe / Crater Lake.	19 June 1950
Ruapehu Eruption Scale 1	Small phreatic eruptions (see Table A2.1) confined to Te Wai ā-moe / Crater Lake.	13 September 2005
Ruapehu Eruption Scale 2	Phreatic or phreatomagmatic eruption (Table A2.1) accompanied by surges; material deposited outside to Te Wai ā-moe / Crater Lake but still confined to the crater basin. May produce larger flows/floods in Whangaehu Valley.	13 July 2009
Ruapehu Eruption Scale 3	Deposition of material outside the crater basin; possible re-mobilisation/lahars in upper catchments and Whangaehu valley OR small-scale explosive eruptions / intermittent ash emission when no lake is present.	7 November 1997
Ruapehu Eruption Scale 4	Material deposited well outside the crater basin onto the summit plateau and outer flanks. Lahars possible in several catchments OR explosive ash eruptions when no lake is present, producing columns up to 10,000 ft.	25 September 2007
Ruapehu Eruption Scale 5	Large-scale explosive eruption displacing moderate volumes of the lake, lahars in all/most major valleys. Summit and slopes covered, with ashfall off the cone; OR explosive eruptions when no lake is present, producing tall (10,000 ft) eruption columns and ashfall off the cone.	27 July 1996
Ruapehu Eruption Scale DB	Te Wai ā-moe / Crater Lake Dam Breaks, post-eruption floods, landslides and glacier failures. In the historical chronology, these are assigned to events that occurred without an eruption.	18 March 2007

APPENDIX 3 VOLCANIC HAZARDS

Every volcanic eruption will have a unique combination and sequence of volcanic hazards. Fortunately, volcanoes often repeat their past behaviour, affording clues as to the likely nature of future activity.

The exact hazards produced depends on volcano type, eruption style and the specific volcanic system. Often several hazards can occur concurrently, and a hazard may manifest multiple times over the course of an eruption, which can last from minutes to decades. The expected hazards associated with a specific volcano and their extent and severity is generally assessed on the basis of past eruptive activity (historical record and geologic mapping) and behaviour of similar volcanoes. Table A3.1 describes and provides definitions of the main lethal volcanic hazards, including hazards that are out of scope for this report. The approximate range of each hazard is also provided; the spatial footprint during an eruption will depend on eruption style and size.

The many volcanic hazards impact, damage and destruct in a variety of ways (Table A3.2). Generally, hazards are mapped and/or modelled to describe their spatial extent and the intensity of specific hazard characteristics (e.g. size of ballistics), referred to here as hazard intensity metrics (HIMs). The most useful HIMs are most strongly correlated to (or causes) damage and are relatively straightforward to measure and/or model. Adequate characterisation of hazard intensity is important for understanding eruption consequences. To give an example of familiar HIMs, commonly used earthquake HIMs are Modified Mercalli intensity (MMI) or peak ground acceleration. In this example, while the earthquake magnitude describes the physical processes of the hazard (how much energy is released), the HIM describes the intensity of the hazard experienced at a location(s) of interest.

We note that in the case of volcanic eruptions, in particular, close to the vent area, there are often multiple hazards occurring at the same time, and a hazard can occur several times over the course of an eruption, which can last anywhere from minutes to decades. Depending on the hazards, it may be adequate to focus on the most lethal one or two in the area of interest. From an eruption management perspective, it is important to appreciate that if a hazard has happened, so long as the eruption is ongoing (or even after, in the case of lahars), it could happen again.

Table A3.1 Volcanic hazards, including description, alternate words used to describe hazard, how it kills, general range and at which New Zealand volcanoes these hazards occur. All apart from edifice / vent formation have documented fatalities globally. Unless otherwise indicated, descriptions are adapted from GNS website glossary. [6]

	Description	Kills By:	Range	New Zealand Volcanoes
Ballistic	Ballistic projectiles are pieces of rock thrown from a volcanic vent in an eruption. *Can also be called:* ballistic projectile, tephra	Trauma (Brown et al. 2017)	Near vent to several kilometres	All
Edifice / Vent Formation	Formation of new cone, fissure, tuff ring and/or maar (Deligne et al. 2017).	Explosive forces, trauma, thermal injury	Very localised	All
Gas – Eruption and Quiescent	Magmatic gases discharged through vents, fumaroles and the soil. There are many types of volcanic gases, with the most common being water vapour (H_2O); sulphur as sulphur dioxide (SO_2) or hydrogen sulfide (H_2S); nitrogen, argon, helium, methane, carbon monoxide and hydrogen.	Asphyxiation, toxicity	Downwind (eruption), edifice or geothermal area (quiescent)	All, although quiescent hazards are more likely in geothermal areas and at volcanoes in long-lived unrest.
Lava Flows	Magma that has reached the surface during a volcanic eruption and flows effusively away from the vent.	Escape routes cut off or explosions as lava flows over water, vegetation or fuel (Brown et al. 2017)	Near vent to several kilometres; in rare instances tens of kilometres	All
Pyroclastic Density Currents (PDCs)	Fast-moving and lethal hot clouds of ash, rocks and gas, caused by a volcanic eruption. They are controlled by gravity, move laterally and usually down topographical lows at high speeds (usually between 40–100 km per hour). *Can also be called:* pyroclastic flow, block and ash flow, pyroclastic surge, base surge	Thermal injury, asphyxiation, impact or blast trauma (Baxter et al. 1990)	Near vent to tens of kilometres	All

6 https://www.gns.cri.nz/Home/Learning/Glossary, accessed 28 November 2019.

	Description	Kills By:	Range	New Zealand Volcanoes
Tephra	Solid material of all types and sizes that are erupted from a volcanic vent and travel through the air. *Can also be called:* ash (if less than 2 mm in diameter), ballistics (if projectile)	Roof collapse, asphyxiation and burial (Spence et al. 2005)	Near vent to hundreds of kilometres downwind	All
Out of Scope for this Report – Refer to the Part 2, 3 and 4 reports				
Sector Collapse	Large-scale collapse of the top or flank of a volcano, which produces a debris avalanche. *Can also be called:* rock avalanche, debris avalanche, landslide	Burial, tsunami generation (in which case, deaths attributed to tsunami)	Tens of kilometres from vent	Geologic studies indicate five sector collapses at Taranaki in the past ~30,000 years, (Zernack et al. 2009) and more prior to that, and one sector collapse at Ruapehu ~10,500 years ago (Conway et al. 2016). We are unaware of sector collapses associated with other New Zealand volcanoes.
Lahar – Primary and Secondary	A flow of water-saturated, typically dense, volcanic material that resembles a flow of wet concrete. A primary lahar may be caused by the rapid melting of ice/snow by an eruption or from an eruption ejecting crater lake water. A secondary lahar is unaccompanied by an eruption, and can be caused by the collapse of a crater lake wall or through re-mobilisation of volcanic material due to heavy rain. *Can also be called:* debris flow, mudflows	Trauma, asphyxiation (drowning) (Baxter 1990)	Tens of kilometres downstream	All, but more likely at cone volcanoes and/or volcanoes with a crater lake. Requires a water source (e.g. crater lake, glacier/snow, precipitation).

	Description	Kills By:	Range	New Zealand Volcanoes
Out of Scope for this Report				
Indirect	Accidents, disease, famine (Brown et al. 2017).	Various	Regional	All
Lightning	An electrostatic discharge that is often seen in volcanic ash plumes. The lightning can be cloud-to-cloud (intracloud) or cloud-to-ground, which can be hazardous.	Electrocution	Local to eruption plume	All
Jökulhlaup	Floods released from glaciers, regardless of how they originate. The term comes from Icelandic, and no distinction is made between water flows and lahars of high sediment concentration (Gudmundsson 2015).	Asphyxiation (drowning), trauma	Tens of kilometres downstream	Unlikely – requires large glaciers absent from New Zealand volcanic zones.
Seismicity	Seismic activity; earthquakes and other shaking (tremors).	Building collapse	Areas under and near volcanic edifice	All
Tsunami	A surge of water with a long wavelength produced by the displacement of a body of water. Causes of tsunami include a volcanic eruption or a large landslide (including sector collapse). The height of a tsunami is influenced by the morphology of the coastline that it travels towards. The speed of a tsunami ranges between 10–100 km/hr in shallow areas and up to 800 km/hr when crossing deeper waters.	Asphyxiation (drowning), trauma	Can be a considerable distance from the volcano	Requires a large body of water at or next to volcano (e.g. island volcanoes).

Table A3.2 Damaging characteristics of volcanic hazards and associated hazard intensity metrics (HIMs) for hazards considered in this report and in the Part 2, 3 and 4 reports (primary and secondary lahars); these are bolded if relevant for life-safety considerations. Entries for tephra, pyroclastic density currents (PDCs), lava flows and lahar are adapted from Table 2 in Wilson et al. (2014).

	Damaging Characteristics	Hazard Intensity Metrics (HIMs)
Ballistic	• **Direct impact** • **Shrapnel** • **Impact crater formation** • Temperature	• **Impact zone** • **Ballistic size and concentration** • **Impact crater size** • **Impact energy** (common unit: J) • **Ballistic impact velocity** (common unit: m/s)
Edifice / Vent Formation	• **Explosion / total destruction**	• **Presence/absence**
Gas – Eruption and Quiescent	• **Toxicity** • **Lack of oxygen**	• **Species, concentration**
Lahar – Primary and Secondary	• **Dynamic pressure / velocity** • **Depth** • Channel erosion	• **Presence/absence** • **Dynamic pressure** (common unit: kPa): the kinetic energy per unit volume of the flow, which changes with flow density and velocity. Velocity (common unit: m/s) is often used as a proxy. • **Depth of flow** (common unit: m). Depth of flow can be greater than deposit thickness. • **Thickness of final deposit** (common unit: m)
Lava Flows	• **Presence**: emplacement of molten rock material. • **Temperature**: between 800–1200°C during eruption, can remain above ambient temperature from months to decades after emplacement.	• **Presence/absence** • **Temperature** (common unit: °C) • **Velocity** (common unit: m/s) • Depth of flow (common unit: mm, cm, or m) • Dynamic pressure (common unit: kPa) • Cooling duration (common units: days, weeks, months, years)
Pyroclastic Density Currents (PDCs)	• **Dynamic pressure** • **Temperature**: may reach 1100°C • Abrasiveness	• **Presence/absence** • **Dynamic pressure** (common unit: kPa). Velocity (common unit: m/s) sometimes used as a proxy. • **Temperature** (common unit: °C) • Thickness of final deposit (common unit: mm, cm, or m)

	Damaging Characteristics	Hazard Intensity Metrics (HIMs)
Tephra	• **Loading:** controlled by tephra thickness, bulk density and moisture content. • **Thickness:** can lead to burial. • Grainsize: smaller particles are dispersed further from the vent and can penetrate smaller openings than larger particles. • Surface chemistry: tephra particles have surface coatings of soluble salts as a result of scavenging in volcanic plumes. Salts may be released upon contact with water, resulting in water contamination. Acidic coatings may cause corrosion of metals. • Abrasiveness	• **Static load** (common units: kg/m^2, kPa): mass of tephra per unit area on a surface. • **Thickness** (common unit: mm, cm, or m) • Particle density (common unit: kg/m^3): the density of individual particles influences their mobility and settling rate in liquids. • Surface chemistry (common unit: mg/kg dry weight for individual elements): concentration of soluble salt layer on the surface of tephra particles. • Grainsize: particle size distribution of tephra at a particular site. • Moisture content (common unit: vol. %): water content of tephra deposit. • Hardness: particle hardness influences abrasiveness of tephra deposits. • Atmospheric concentration (common unit: $\mu g/m^3$): concentration of tephra particles suspended in air.

APPENDIX 4 HUMAN CONSEQUENCES OF VOLCANIC ERUPTIONS

The consequences of a volcanic eruption depend on the extent and severity of its hazard(s). Eruptions can result in casualties and fatalities, damage the built environment and disrupt critical services. Most of our understanding of eruption consequences is based on historical observations, supplemented with experimental work and testing.

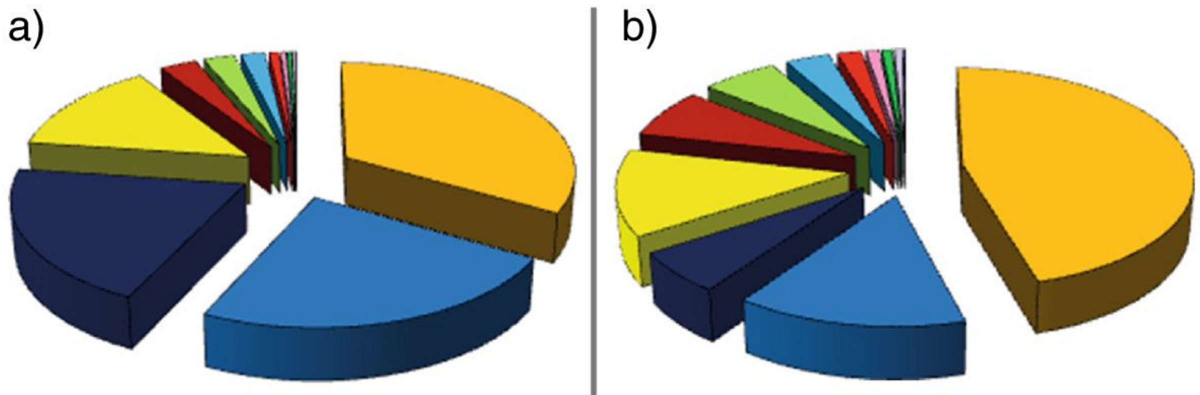
Note that the figures in this Appendix do not include information on edifice formation (see Appendix 3), but this also poses a hazard to life safety.

A4.1 Fatalities

Volcanoes kill people through a variety of hazards (Appendix 3; Figure A4.1), both during an eruption and days through to decades after an eruption, and at distances ranging from at the vent to over 100 km away from the vent (Appendix 3; Figure A4.2). Eruptions of all sizes kill, although bigger eruptions are more likely to result in a fatal incident (Figures A4.3 and A4.4).

Fatalities from smaller eruptions tend to be closer to the vent (Figure A4.3), and, while the data could be interpreted to suggest that larger eruptions are less lethal close to the vent, the data in fact reflects evacuations that are often called in the lead up to a large eruption. Most volcanic hazards are more lethal closer to the vent and with increased eruption size, but some volcanic hazards, in particular lahar and tsunami, have caused mass fatalities at considerable distances from the vent, in some cases from a small eruption (Figure A4.4).

With global databases, generalisations can help identify which volcanic hazards are of greatest concern at various distances from the vent, both in terms of fatal incidents and total fatalities (Figure A4.5). Such generalisations need to be paired with knowledge of the specific volcano, in particular, volcanic type and likely eruptive activity. This can be used to focus risk analysis and develop mitigative measures.



All Fatal Incidents			Largest 5 Disasters Removed	
Fatalities	%	Hazard	Fatalities	%
91,484	33	Pyroclastic Density Currents	50,994	46
65,024	24	Indirect	15,724	14
55,277	20	Waves (Tsunami)	6,813	6
37,451	14	Lahars (Primary)	14,054	13
8,126	3	Tephra	8,126	7
6,801	3	Lahars (Secondary)	6,801	6
5,230	2	Avalanches	3,953	3
2,151	0.78	Gas	2,151	2
1,163	0.42	Floods (Jökulhlaups)	1,163	1
887	0.32	Lava Flows	887	0.79
765	0.28	Seismicity	765	0.69
142	0.05	Lightning	142	0.13

Figure A4.1 Pie charts and table showing distribution of documented global fatalities by volcanic hazards from 1600 to 2010 AD. (A) Distribution for all fatalities. (B) Distribution for all fatalities apart from the five largest fatal incidents (Tambora 1815, Indonesia, most fatalities from tsunami; Krakatau, 1883, Indonesia, most fatalities from tsunami; Pelee 1902, Martinique, most fatalities from PDC, Nevada del Ruiz 1985, Colombia, most fatalities from lahar; Unzen 1792, Japan, most fatalities from landslide and tsunami). Note that here 'tephra' encompasses both tephra and ballistics and 'avalanches' refers to debris avalanches and landslides (in other literature these are referred to as landslides and/or sector collapse). Figure is Figure 10 from Auker et al. (2013).

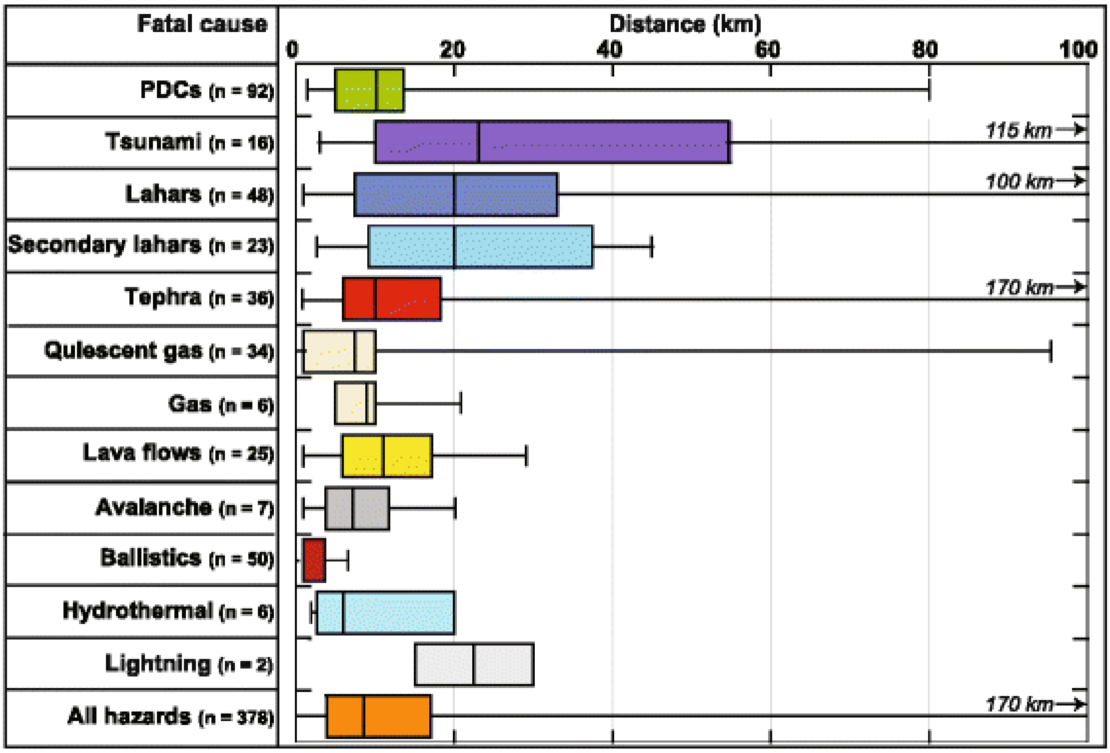


Figure A4.2 Box and whisker plot showing the distance recorded for fatal volcanic incidences by attributed volcanic hazard for incidents with distance information for 1500 to 2017 AD. The whiskers show the full range, the box shows the 25th and 75th percentiles and the black vertical line shows the median (50th percentile). The number of fatal incidents is indicated after each hazard (n = number). The figure does not show data for non-eruptive (apart from secondary lahar), seismic or indirect hazards. Note that here 'avalanches' refers to debris avalanches and landslides (in other literature these are referred to as landslides and/or sector collapse). Figure is Figure 3 from Brown et al. (2017).

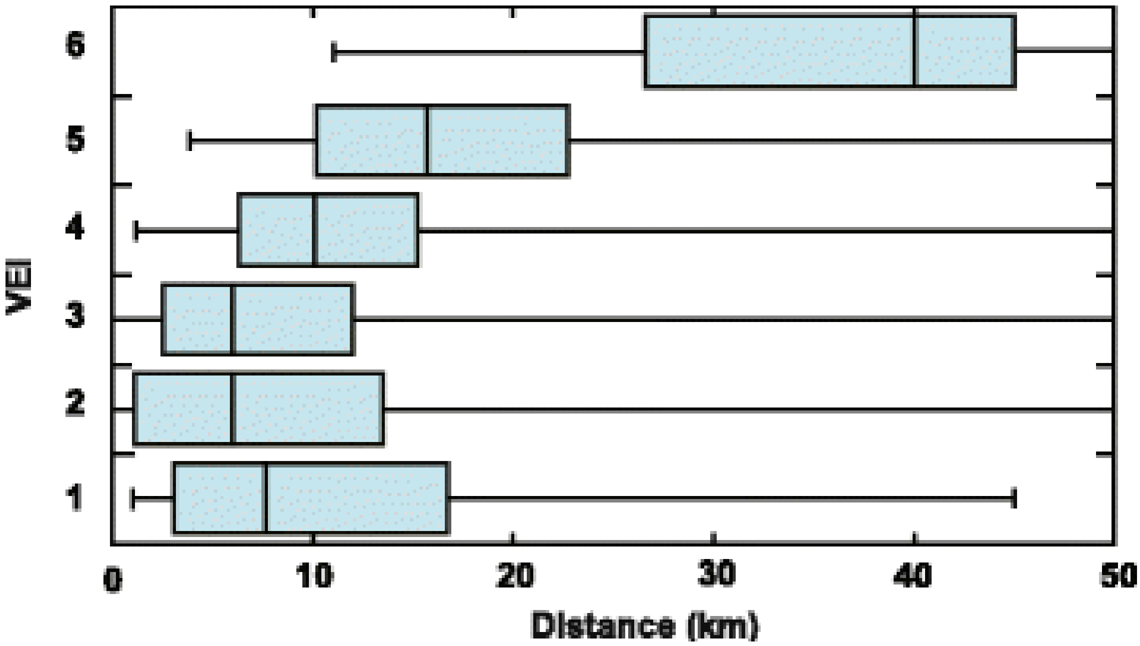


Figure A4.3 Relationship between Volcano Explosivity Index (VEI) and distance of fatal instances from all fatal hazards, excluding non-eruptive, seismic or indirect hazards. Data comes from available data from 1500 to 2017 AD. In the absence of information, the default eruption size for an eruption is VEI 2. Evacuations efforts are more likely to have occurred prior to / during larger eruptions. Figure is Figure 6 from Brown et al. (2017).

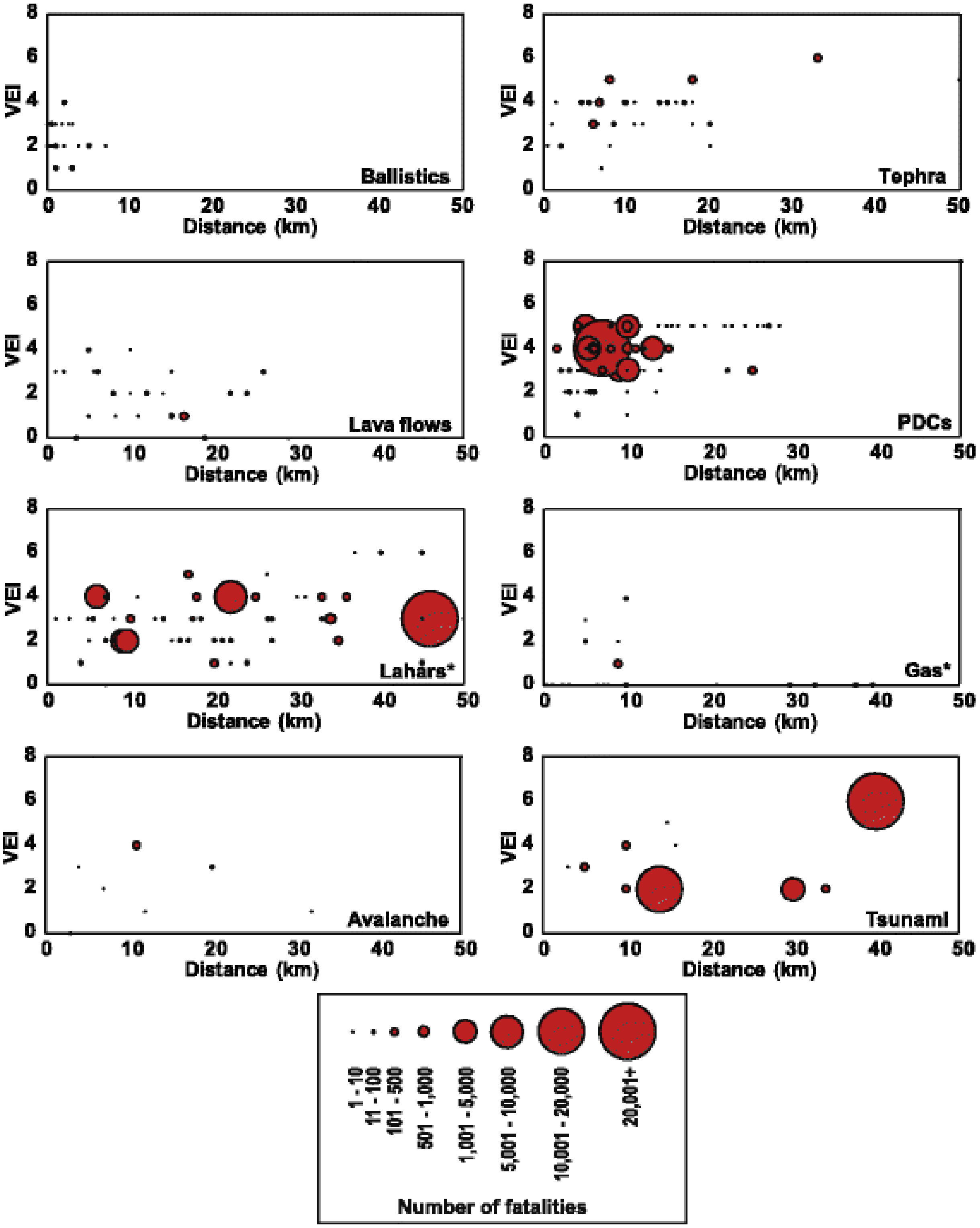


Figure A4.4 Relationship between Volcano Explosivity Index (VEI) for each hazard type and distance of fatal instances from all fatal hazards, excluding non-eruptive, seismic or indirect hazards. Data comes from available data from 1500 to 2017 AD. In the absence of information, the default eruption size for an eruption is VEI 2. Evacuations efforts are more likely to have occurred prior to / during larger eruptions. Figure is Figure 6 from Brown et al. (2017).

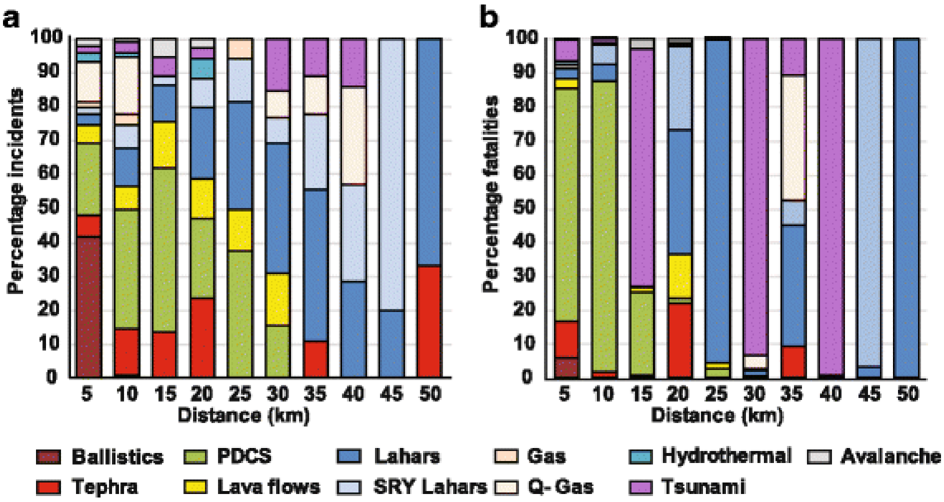


Figure A4.5 Normalised percentage of fatalities by attributed volcanic hazard for incidents with distance information for 1500 to 2017 AD. (A) Percent distribution of incidents. (B) Percent distribution of total number of fatalities. An incident has at least one fatality, and an eruption can have more than one incident (e.g. an eruption could kill some people by PDC and others by lahar; this would be recorded as two incidents here). 'Q-gas' is quiescent gas, 'SRY Lahars' is secondary lahars and 'avalanche' includes debris avalanches and landslides (in other literature these are referred to as landslides and/or sector collapse). Figure is Figure 4 from Brown et al. (2017).

A4.2 Non-Lethal Exposure to Volcanic Hazards

Figures A4.1–A4.5 concern fatalities caused by volcanic eruption. However, not all exposure to volcanic hazards leads to fatality. Unfortunately, there is no rigorous research on the lethality of various hazards (i.e. personal vulnerability); expert judgement based on scientific knowledge is recommended.

A4.2.1 Injuries

Volcanic eruptions can cause serious and/or life-changing injuries that require immediate medical attention. Although there is no authoritative database of volcanic injuries, there are case studies of individuals who have survived exposure to volcanic hazards; in many cases, they required prompt medical attention (e.g. Baxter et al. 1997; Kilgour et al. 2010; Jenkins et al. 2013; Shiroko 2018). There are examples of people who survived fatal incidents (e.g. the 2019 Whakaari eruption – at time of writing in May 2020, slightly more than half of those who were on the island at the time of the eruption survived the fatal eruption). Consideration of injuries is out of scope for this report.

A4.2.2 Exacerbation of Chronic Health Conditions

Exposure to volcanic gases and ash can worsen existing respiratory and skin conditions, and chronic exposure could lead to health problems. Consideration of chronic health concerns is out of scope for this report.

A4.2.3 Tephra

Although Figures A4.1–A4.5 record fatal incidents and fatalities resulting from tephra (we note that, in Figure A4.1, ballistics are grouped under 'tephra'), exposure to tephra is not usually an acute life-safety concern, although it can with time contribute to indirect hazards. If tephra is thick enough to lead to death from burial, asphyxiation and/or roof collapse, it is likely the location is close enough to the vent for there to be other lethal volcanic hazards to contend with and/or the population will have self-evacuated.

A4.3 People and Buildings

Buildings can be damaged or destroyed by volcanic hazards. While the material cost and risk to buildings is out of scope for this report, here we briefly discuss buildings through the lens of a shelter.

Although the best mitigation strategy for life safety is generally avoidance of volcanic hazards (e.g. evacuation), building or shelters have on occasion appeared to provide protection from ballistics and/or pyroclastic density currents.

A4.3.1 Ballistics

In the fatal 2014 Ontake and 2018 Kusatsu-Shirane eruptions in Japan, there were no fatalities among those who sheltered in nearby buildings, despite these buildings being struck by ballistics (Yamada et al. 2018; Yoshimoto et al. 2018). However, Williams et al. (2019) suggest that part of the successful performance of buildings in these events are related to pre-existing armouring of the roof and syn-eruptive tephra deposition providing a cushion during the ballistic phase of the short-lived eruptions.

There is a growing body of research on actions that contribute to survival if exposed to ballistics (e.g. Figure A4.6). However, this is best treated as a 'what to do in a terrible situation to increase chance of survival'.

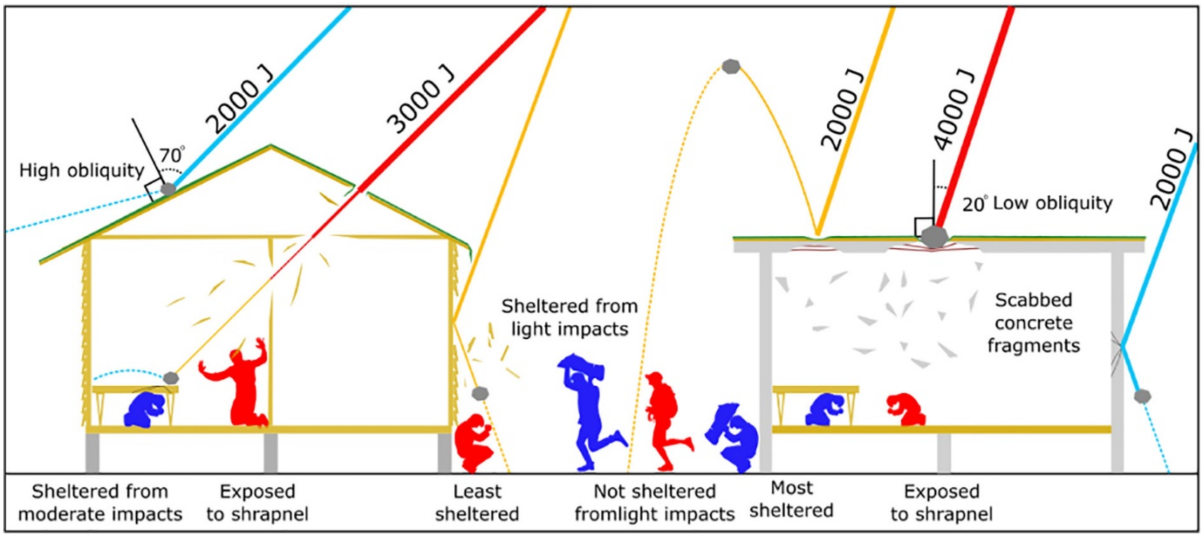


Figure A4.6 Cartoon illustrating likely building damage for ballistic impacts to timber and reinforced concrete buildings. The line colour of ballistic trajectories indicate likely damage severity, with blue being the least severe and red the highest. Blue figures are taking actions that may increase their chance of survival given their location, while red figures are not taking actions that benefit their chance of survival. Figure is Figure 13 from Williams et al. (2017).

A4.3.2 Pyroclastic Density Currents

There are rare examples of people surviving pyroclastic density currents inside of buildings (e.g. Jenkins et al. 2013), although the mortality rates appear to be high regardless of whether one has sought shelter from a pyroclastic density current (e.g. Spence et al. 2007; Jenkins et al. 2013). Theoretical research has suggested there may be some mitigative measures that lessen the likelihood of fatality from PDC if one is in a building (Spence et al. 2007), such as having a well-sealed internal room as a refuge, but these are empirically untested, not necessarily practical and require building users who take appropriate measures immediately before and during imminent exposure.

APPENDIX 5 ERUPTIVE HISTORIES OF NEW ZEALAND VOLCANOES

In Appendix 5, we briefly provide available chronologies and references for volcanoes monitored by GeoNet. This is by no means exhaustive and should not be the sole basis for hazard analysis work. Volcanoes are presented in alphabetical order, with the exception of Tongariro National Park volcanoes (Ruapehu, Tongariro, Ngauruhoe), which are grouped together in that order.

In general, smaller eruptions (which are often not preserved in the geological record) occur more often than larger eruptions. The types of volcanic hazards that occur in small and large eruptions can also be different. While most New Zealand volcanoes have reasonably detailed eruption chronologies (particularly for larger eruptions preserved in the geologic record), there are limited quantitative published magnitude–frequency relationships.

We provide some data from the Global Volcanism Program (2013). This is a global database, maintained by the Smithsonian Institution, USA. The database covers the last 10,000 years (the Holocene). The Global Volcanism Program considers events to be part of the same eruption if they happened within three months of each other and describes eruption size using the Volcano Explosivity Index (VEI; see Appendix 2). While the Global Volcanism Program is a valuable resource, it may not necessarily reflect the current agreed interpretation of eruptive activity in New Zealand.

A5.1 Auckland Volcanic Field

The Auckland Volcanic Field has 53 known eruptive centres. In the past decade, research efforts have greatly improved the eruption chronology and eruptive volume estimates (Figure A5.1). For further information, see Hopkins et al. (2020), Leonard et al. (2017) and Kereszturi et al. (2014b). There have been many recent investigations of Auckland volcanism, and several studies are in progress through the DEVORA research programme (http://www.devora.org.nz/).

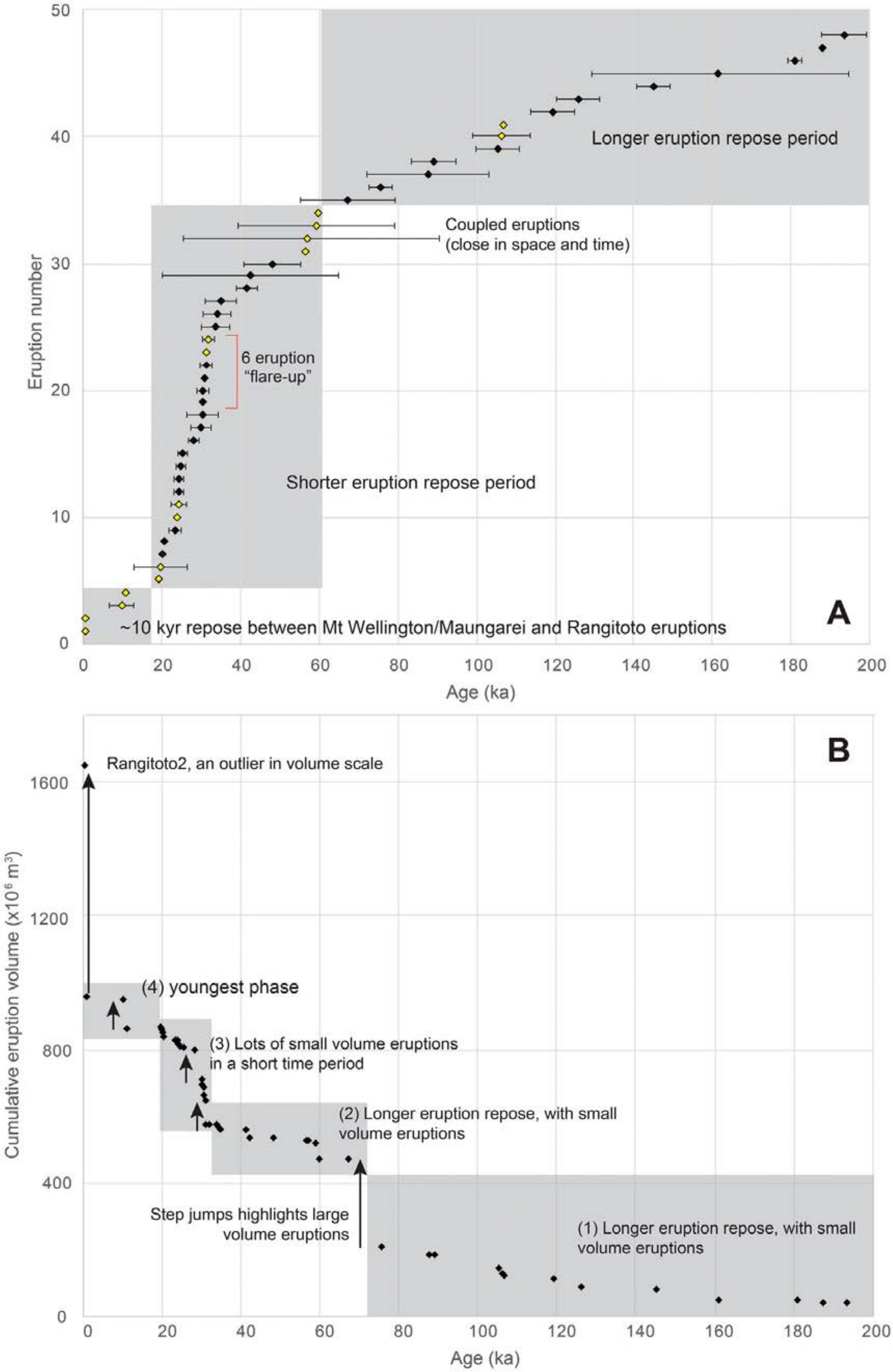


Figure A5.1 Eruption chronology and eruptive volume estimates of Auckland Volcanic Field. (A) Auckland Volcanic Field eruption chronology (error bars show 2 standard deviations), with grey shading delineating different temporal eruption periods. Yellow dots correspond to potentially coupled eruptions, and a flare-up is bracketed in red. (B) Minimum cumulative volume (shown as dense rock equivalent, which is equivalent to the volume of magma that was erupted) as a function of time. Volume data from Kereszturi et al. (2014a). Figure is Figure 11 from Hopkins et al. (2020) and is adapted from Leonard et al. 2017.

A5.2 Mayor Island

Mayor Island has two documented eruptions in the last 10,000 years, around 7000 to 8000 years ago. [7] The more recent eruption was a VEI 5.

A5.3 Northland Volcanic Fields

The literature has conflicting information regarding the timing of eruptions in Northland, which includes both the Kaihohe–Bay of Islands volcanic field and the Whangarei volcanic field. Further work is required to establish a definite and accepted chronology.

A5.4 Okataina Volcanic Centre

The Okataina Volcanic Centre covers a large area and has experienced diverse styles of volcanic activity. There have been many geologic investigations of Okataina volcanism, and several studies are in progress through the ECLIPSE research programme.[8] In the last 10,000 years, there have been six eruptions of VEI 4 or greater [9], including the 1886 AD Tarawera eruption.

A5.5 Raoul Island

Raoul Island is the largest island of the Kermadec Arc. It has several historically active vents and is immediately adjacent to Denham caldera. The Global Volcanism Program reports 13 eruptions of VEI 3 or greater in the last 4000 years, including the VEI 6 Fleetwood eruption from Denham caldera. The tragic eruption in 2006 is considered a VEI 1 eruption.

A5.6 Rotorua

Rotorua has not had a magmatic volcanic eruption in tens of thousands of years but has regular hydrothermal activity, including hydrothermal eruptions. Furthermore, in historic times, there have been numerous instances of fatalities from gas exposure (Brown et al. 2017).

A5.7 Taranaki

There are currently numerous research efforts underway to better understand the hazard and risks posed by Taranaki volcano, and the understanding of eruptive activity at Taranaki is rapidly being enhanced and refined. Figure A5.2 provides an example of a recent study.

7 https://volcano.si.edu/volcano.cfm?vn=241021, accessed 30 March 2020.
8 https://sites.google.com/view/eclipse-supervolcanoes/, accessed 30 March 2020.
9 https://volcano.si.edu/volcano.cfm?vn=241050, accessed 30 March 2020.

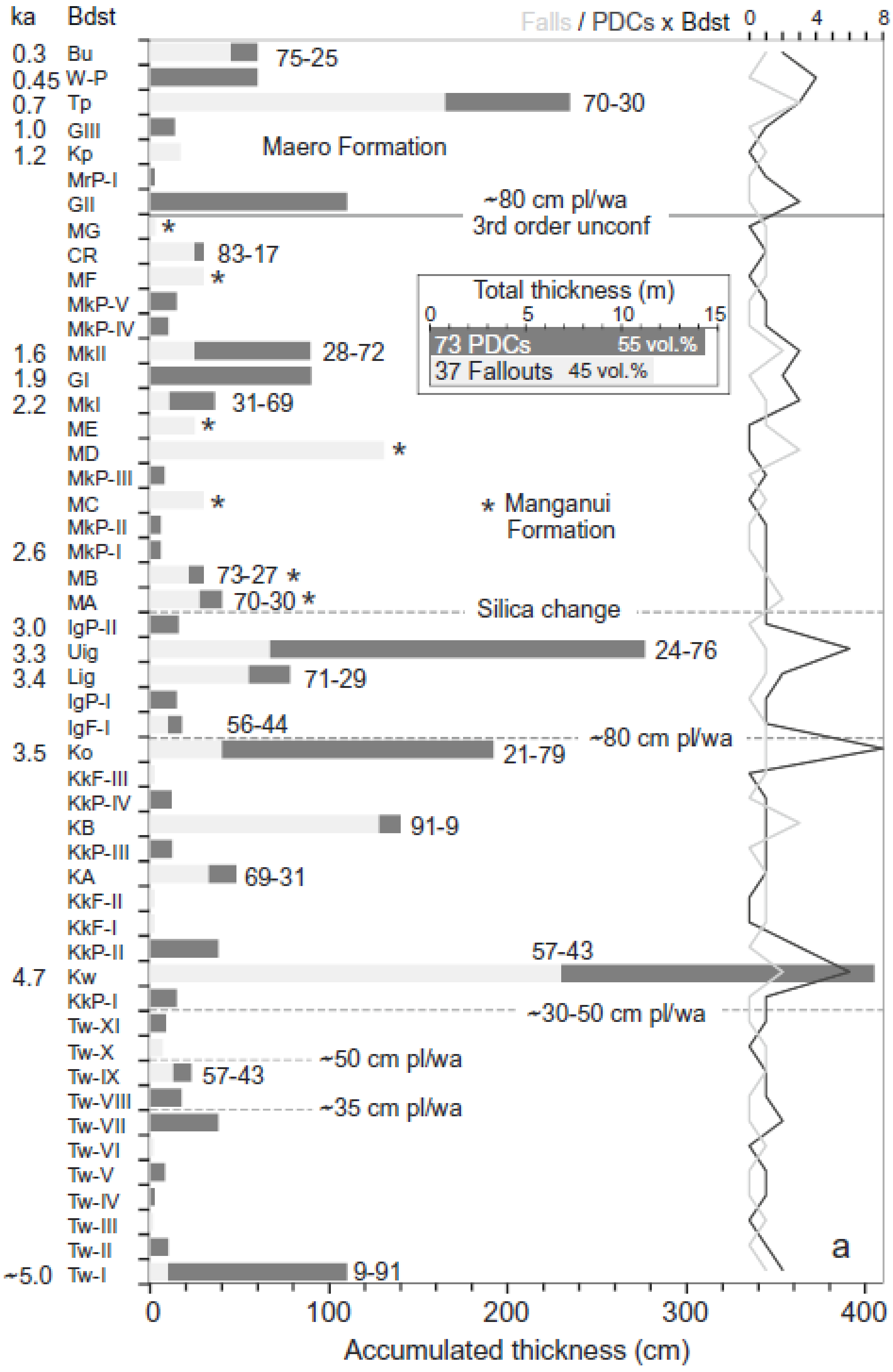


Figure A5.2 PDC (dark grey) and ashfall (light grey) deposit thicknesses from last 5000 years of explosive activity at Mt Taranaki. Figure is a portion of Figure 5 in Torres-Orozco et al. (2016).

A5.8 Taupō Volcanic Centre

The Taupō Volcanic Centre covers a large area and has experienced diverse styles of volcanic activity. There have been many geologic investigations of Taupō volcanism, and several studies are in progress through the ECLIPSE research programme.[10] Figure A5.3 provides the estimated probability of at least one eruption of a specified size using different models.

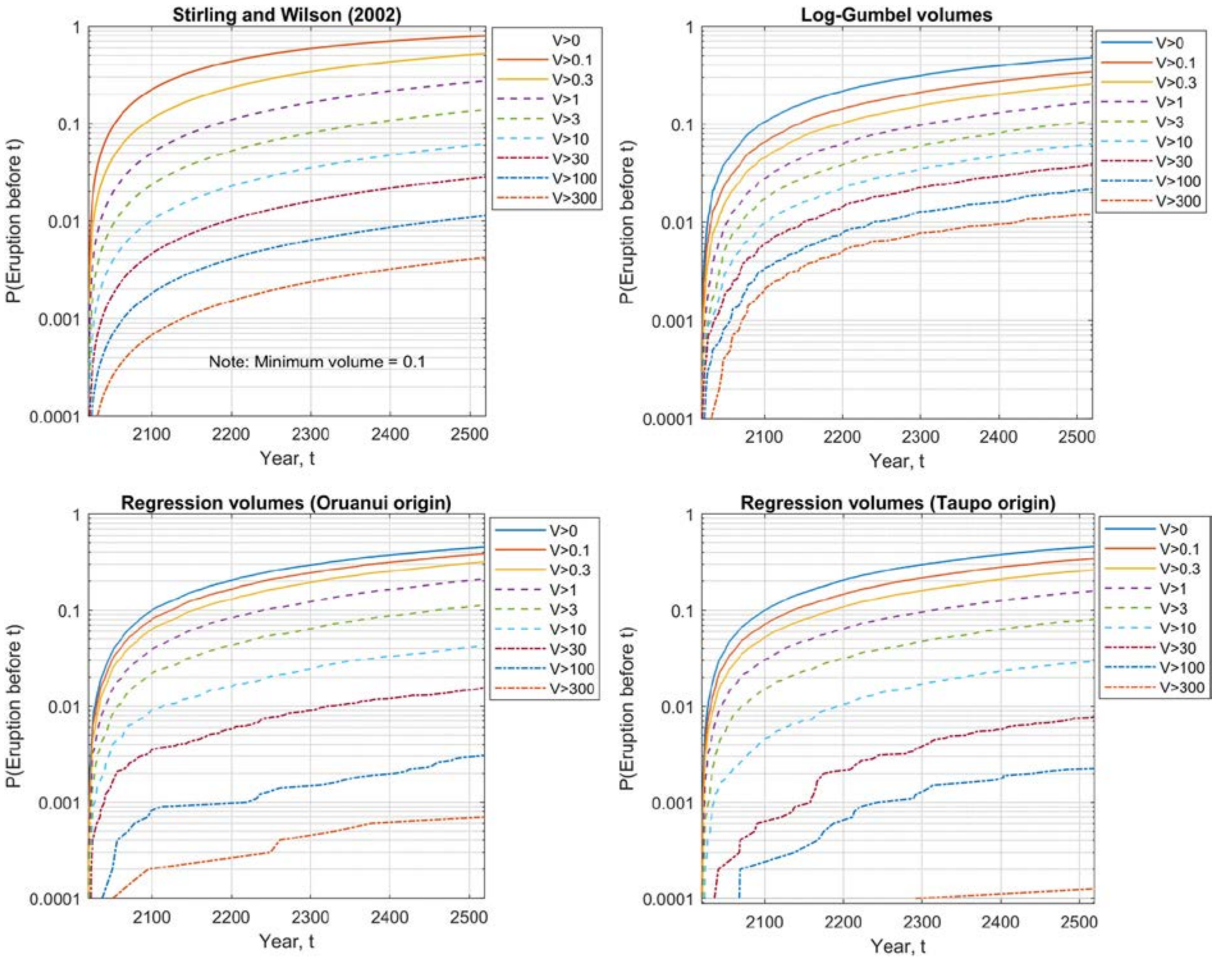


Figure A5.3 Estimated probability of at least one eruption from the Taupō Volcanic Centre exceeding the specified volume (each coloured line is a different volume) using four different models. Figure is Figure 5 from Bebbington (2020).

A5.9 Tongariro National Park volcanoes

A5.9.1 Ruapehu

Scott (2013) provides the authoritative historic eruption chronology for Ruapehu and, at the daily level, provides the eruption size per a customised scale (see Appendix 2). Figure A5.4A shows provides the historical record, and Figure A5.4B provides the historic magnitude–frequency plot for all historic data. We note that there was considerable activity in 1945 and 1995–96; Scott (2013) also provides magnitude–frequency data excluding these periods of heightened activity. Larger eruptions have been documented in the geologic record.

10 https://sites.google.com/view/eclipse-supervolcanoes/, accessed 30 March 2020.

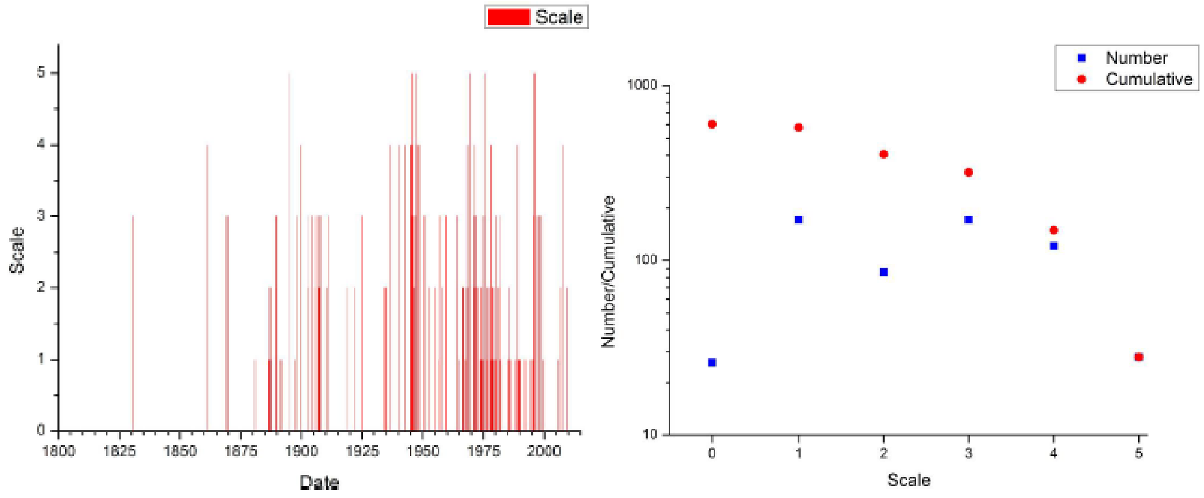


Figure A5.4 Eruptive record and scale of Ruapehu. (A) Historic eruptive record of Ruapehu, using the eruption scale described in Appendix 2. (B) Number of eruptions of each scale (see Appendix 2) in the historic record (red) and cumulative number of eruptions at each scale (blue). A is Figure 7.1 in Scott (2013) and B is Figure 4.1 in Scott (2013).

A5.9.2 Tongariro

Scott and Potter (2014) provide a detailed historical record for Tongariro, summarised in Figure A5.5. There are confirmed historic eruptions from Ketetahi, Red Crater and Upper Te Maari. Hobden et al. (1999) provide a longer-term big-picture view of eruptive activity and eruption rates, shown in Figure A5.6. We note that there are ongoing studies to improve the understanding of the Tongariro Volcanic Complex and its eruptions.

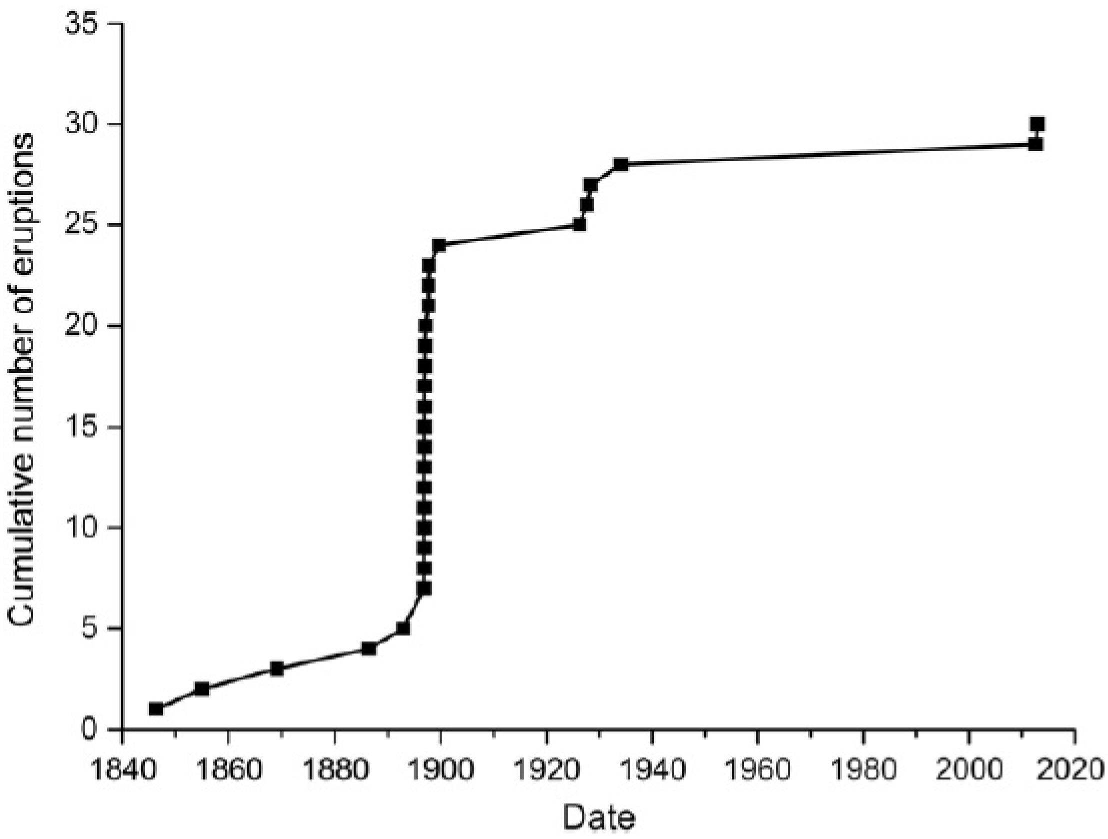


Figure A5.5 Cumulative historical eruptions at Tongariro volcano, including eruptions at Ketetahi, Red Crater and Upper Te Maari. Figure is Figure 6 from Scott and Potter (2014).

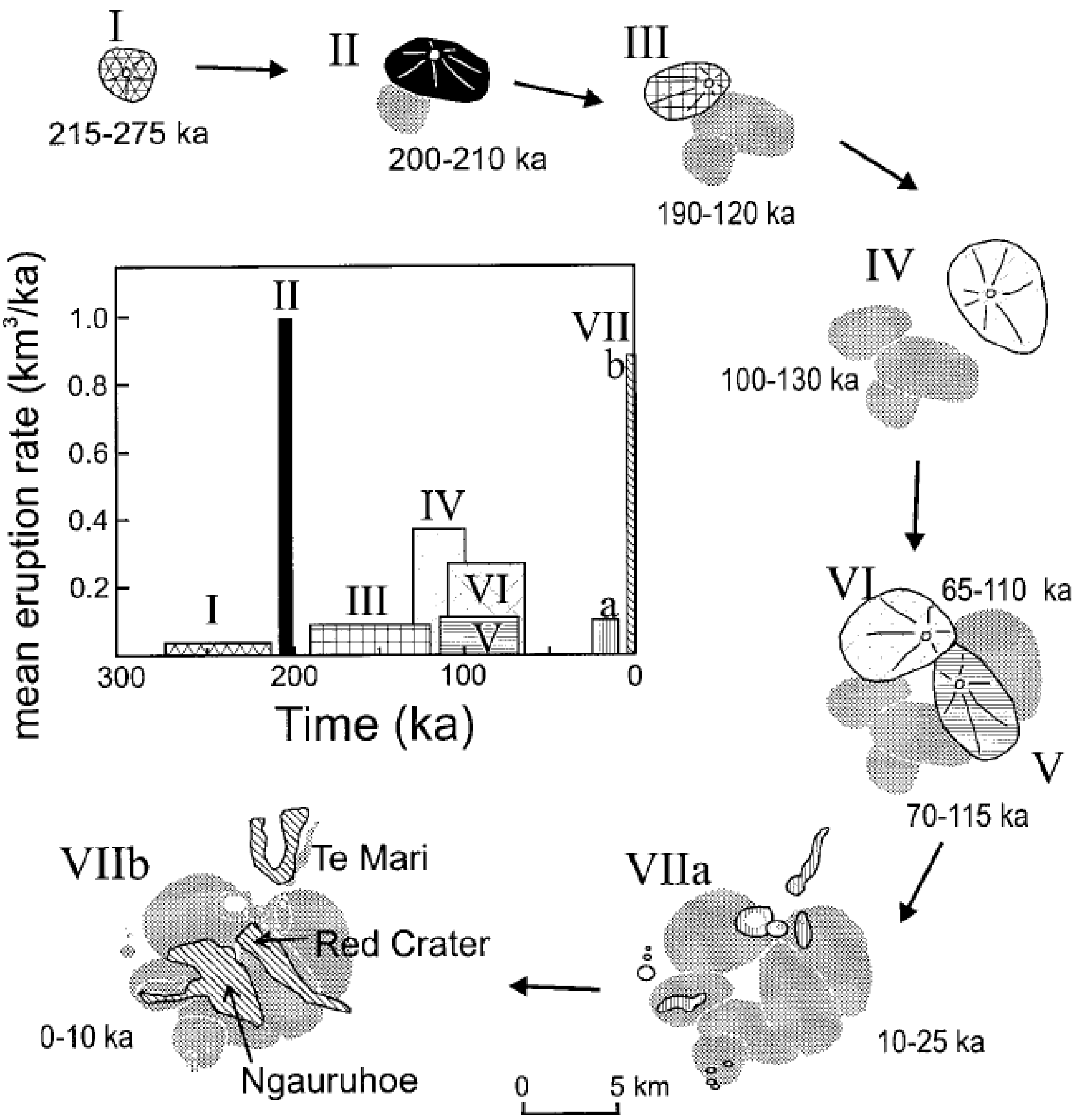


Figure A5.6 Cumulative historical eruptions at Tongariro volcano, including eruptions at Ketetahi, Red Crater and Upper Te Maari. Figure is Figure 6 from Scott and Potter (2014).

A5.9.3 Ngauruhoe

Ngauruhoe is technically a sub-feature of the Tongariro volcanic complex. However, as GeoNet sets a separate VAL for Ngauruhoe, we provide Ngauruhoe-specific information here. Hobden et al. (2002), and references therein, provide a detailed historical eruption chronology for Ngauruhoe, summarised in Figure A5.7; this paper also provides some volume and discharge rate data for select historical eruptions. There are also studies that have examined the geologic record through primarily airfall (tephra) deposits, illustrated in Figure A5.8, where the purple layers represent Ngauruhoe eruptions.

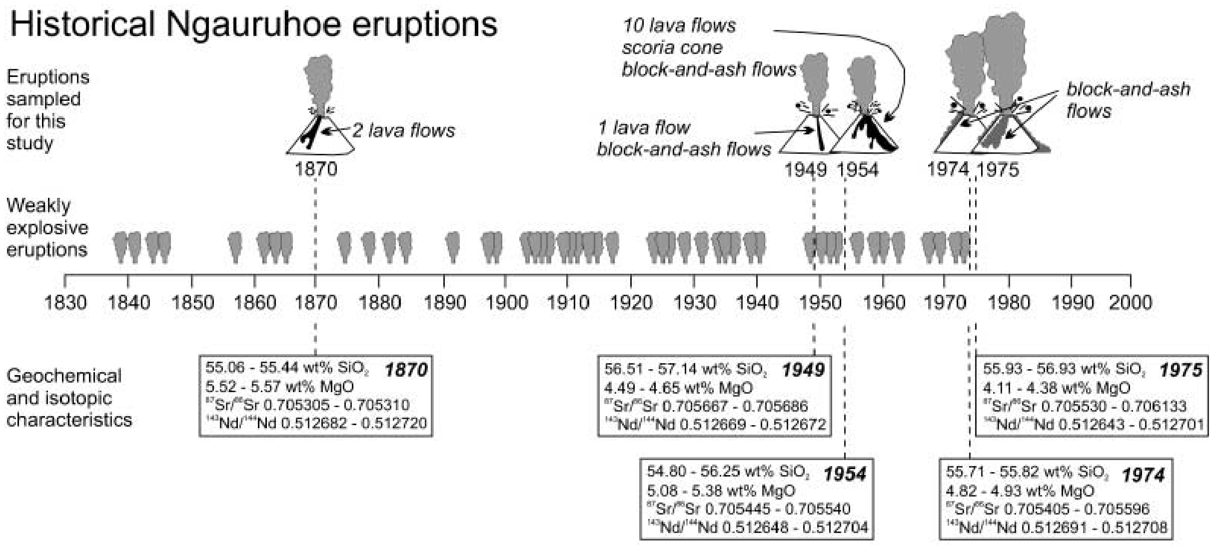


Figure A5.7 Historic activity at Ngauruhoe. Figure is Figure 4 from Hobden et al. (2002).

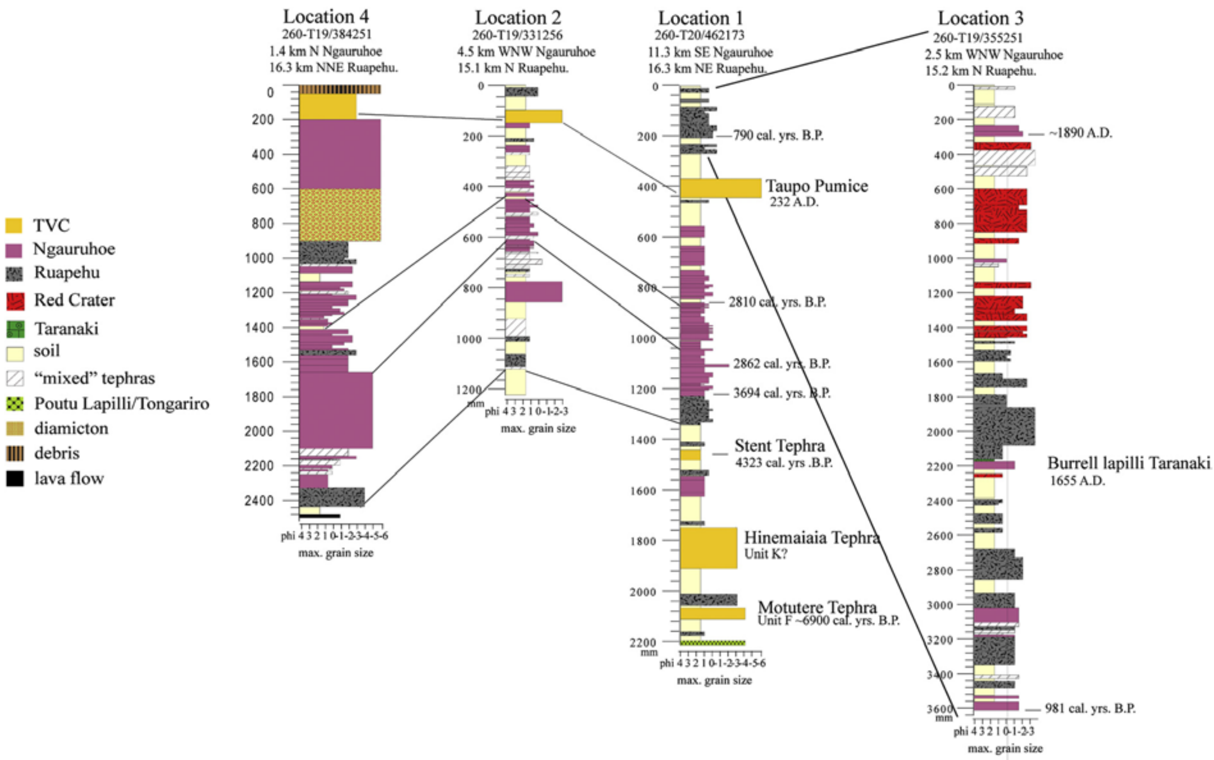


Figure A5.8 Stratigraphic columns from four sites in Tongariro National Park; see Moebis et al. (2011) for further details. Figure is Figure 8 from Moebis et al. (2011).

A5.10 Whakaari / White Island

There is work underway to construct a detailed historic eruption chronology for Whakaari. The Global Volcanism Program does not report any prehistoric eruptive activity.[11]

11 https://volcano.si.edu/volcano.cfm?vn=241040, accessed 30 March 2020.

APPENDIX 6 EQUIVALENT ANNUAL INDIVIDUAL FATALITY RATES

For the sake of comparison, we may approximately relate the individual hazard and exposure class (Table A6.1) to the Annual Individual Fatality Risk (AIFR) on the assumption that the activity was undertaken every day for a year.

Table A6.1 Matrix for calculating the individual hazard and exposure class using the temporal probability and spatio-temporal probability of the individual as inputs.

Spatio-Temporal Probability of the Individual			Temporal Probability			
Proportion of time spent at point location in 24 hours	Equivalent to:	Example activity	Very Low	Low	Medium	High
>0.1	More than three hours	Staying in a hut	Class 2	Class 2	Class 3	Class 3(a)
0.1–0.01	Half an hour to three hours	Picnic spot	Class 1	Class 2	Class 2	Class 3
0.01–0.001	Two minutes to half an hour	Stopping at viewing area	Class 1	Class 1	Class 2	Class 3
<0.001	Less than two minutes	Crossing a swing bridge	Class 1	Class 1	Class 1	Class 2

This relationship assumes that the vulnerability of a person exposed to a volcanic or geothermal hazard is 1.

The relationship can be illustrated by example. Consider a picnic site at the medium temporal probability (100–1000-year return period) that is visited for between half-an-hour and three hours (0.1–0.01 proportion of a 24-hour period). The annual probability of the hazard occurring at the site is therefore 10^{-2}–10^{-3}. If the individual were to visit the site for a picnic every day of a year, then the probability of being exposed to the hazard, should it occur in a particular year, is 10^{-1}–10^{-2}. The annual probability of exposure to the hazard is then obtained by multiplication to be 10^{-3}–10^{-5}. As vulnerability is assumed to be 1, the AIFR is of the order of 10^{-3}–10^{-5}. Taking the lower value of this range on a logarithmic scale, the AIFR is derived to be of the order of 10^{-5}.

Table A6.2 shows the resulting relationship between the hazard and exposure class and AIFR.

Table A6.2 Approximate AIFR equivalent in terms of order of magnitude for different hazard and exposure classes.

Hazard and Exposure Class	Approximate AIFR Equivalent Order of Magnitude
3(a)	10^{-3} or greater
3	10^{-4}
2	10^{-6}
1	Less than 10^{-6}

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Principal Location

1 Fairway Drive, Avalon
Lower Hutt 5010
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin 9054
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Private Bag 2000
Taupo 3352
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4657