Bay of Plenty Regional Volcanic Hazards

Scoping Study

Bay of Plenty Regional Council

Mt Tarawera in Eruption, June 10, 1886. View from the Māori village of Waitangi. Lithograph by A. D. Willis, based on a painting by C. Blomfield. (Alexander Turnbull Library, C-033-002).

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ACRONYMS/ABBREVIATIONS

Acronyms / Abbreviations	Definition
BoP	Bay of Plenty
BoPRC	Bay of Plenty Regional Council
RPS	Bay of Plenty Regional Policy Statement
TCC	Tauranga City Council
WBOPDC	Western Bay of Plenty District Council
RLC	Rotorua Lakes Council
WDC	Whakatāne District Council
KDC	Kawerau District Council
ODC	Ōpōtiki District Council
TDC	Taupō District Council
ka	Kiloanni (thousands of years)

VOLCANIC GLOSSARY

Volcanic Term	Definition
Andesite/Andesitic	Volcanic material with 52 to 63 weight percent silica (SiO2). Typically produce low to medium scale explosive eruptions from stratovolcanoes.
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.
Basalt/Basaltic	Volcanic rock (or lava) containing less silica than andesite. Typically produce low-explosive eruptions or effusive flows.
Block and ash flow	An avalanche of ash, hot gas and large blocks from oversteepening of a lava dome or flow front. They can be hundreds of degrees in temperature and travel at tens of kilometres per hour, covering distances of several kilometres.
Caldera	A volcanic depression with a diameter many times larger than the size of the individual vents, usually formed during large volcanic eruptions. May exceed up to 50 km across.
Crater	A depression formed by either explosion or collapse at a volcanic vent, from which volcanic material is ejected.
Dacite/Dacitic	Fine-grained rock intermediate in composition between andesite and rhyolite. Dacitic lavas are viscous and often form domes or erupt explosively.
Debris Avalanche	A rapid and sudden sliding or flow of unsorted rock and other material (fragmented cold and hot volcanic rock, water, snow/ice and trees).
Dome/Lava Dome	A steep-sided mass of viscous and often blocky lava extruded from a vent.
Effusive Eruption	An eruption dominated by the outpouring of lava onto the ground (opposed to the violent fragmentation of magma by explosive eruptions).
Ejecta	Material that is thrown out by a volcano, including tephra.
Eruption Column	A rising cloud of gases, steam and tephra rising from a crater or other vent, driven by thermal convection and gas pressure.

Eruptive Vent	The opening through which volcanic material is emitted.
Explosive Eruption	Explosive eruptions occur when the erupting magma is violently ejected as fragments into the air (opposed to effusive eruptions producing lava flows).
Hydrothermal eruption	Explosion driven by the transformation of hot groundwater to steam.
Ignimbrite	Material (rock) formed by deposition and consolidation of hot pyroclastic flows. Applies to densely welded and non-welded deposits.
Lahar	a discrete, rapid, gravity-driven flow of saturated, high-concentration mixtures containing water and solid particles of rock, ice, wood, and other debris that originate from volcanoes.
Lava	Magma which has reached the surface through a volcanic eruption. May be flowing rock from a crater or fissure, or cooled and solidified rock.
Magma	Molten rock beneath the surface of the earth. Magma that reaches the surface erupts as lava or pyroclasts.
Magmatic eruption	Eruption of lava or tephra from a magma source. A significant range exists in the intensity, magnitude, explosivity, eruption rate, and amount of magma erupted.
Phreatic eruption	An explosion of steam/water and other material caused by an underlying heat source.
Phreatomagmatic eruption	Volcanic eruptions resulting from interaction between magma and water.
Plinian Eruption	A large explosive eruption that produces a sustained convecting plume of pyroclasts and gas rising >25 km above sea level.
Pyroclastic Flow	A hot (>800 °C) chaotic mixture of rock fragments, gas, and ash that travels rapidly (10s m/s) away from a volcanic vent.
Pyroclastic/Pyroclasts	Material formed by aerial expulsion from a volcanic vent.
Rhyolite/Rhyolitic	Volcanic rock, light coloured, with a high silica content. Rhyolitic lavas are very viscous and often produce highly-explosive eruptions.
Stratovolcano	Steep, conical volcanoes built by the eruption of lava flows, tephra, and pyroclastic flows.
Strombolian eruption	A volcanic eruption characterised by frequent, discrete events of jetting and fountaining of lava fragments from a volcanic vent.
Subplinian	Lower magnitude and intensity versions of a Plinian eruption.
Tephra	A collective term for all clastic materials ejected from a volcano and transported through the air.
Tsunami	A great sea wave produced by a submarine earthquake, volcanic eruption, or large landslide.
Viscosity	A measure of resistance to flow in a liquid.
Volcanic Explosivity Index (VEI)	A relative measure of the explosiveness of volcanic eruptions. Based primarily on volume of erected products. Ranges from 0 (very small) to 8 (mega-colossal, e.g., Taupō Oruanui).
Volcanogenic	A process attributed to a volcano or volcanic activity.

1. INTRODUCTION

1.1 BACKGROUND

The Bay of Plenty Regional Council (BoPRC) engaged Tetra Tech Coffey (NZ) Ltd (Tera Tech Coffey) to develop a scoping document for a future volcanic hazard mapping and risk assessment project.

The BoPRC is obligated to fulfill the BoP Regional Policy Statement (RPS) Policy NH 13C requirements to conduct hazard mapping and risk assessment across the Bay of Plenty (BoP) area. The focus of this document is to address aspects related to RPS Policy NH 7A(a), Volcanic Activity. Specifically, NH 7A lists the following volcanic hazards:

- Pyroclastic and lava flow.
- Landslip, debris flow and lahar.
- Ashfall.
- Geothermal hazard.
- Caldera unrest.

Volcanic hazards are often widespread and not confined by regional boundaries, therefore, to meet the RPS requirements, volcanic sources beyond the BoP area are also to be considered.

Tetra Tech Coffey understands that the current scoping stage - stage one, is the first of up to three stages of work for the volcanic hazards mapping and risk assessment. Stage one is a scoping study with the indicated aim of understanding and outlining the information that is currently available, and to identify and assess any gaps in knowledge or resources that may need to be filled. Future stages of volcanic work will include mapping and assessment of hazards and risk assessments to support risk management strategies.

1.2 SCOPE

The following list outlines the aims and scope of this report:

1. A literature review of information that is readily available and relevant to volcanic hazards susceptibility mapping and risk assessment, including identification of information gaps. This includes information beyond the boundaries of the BoP.
2. Development of methods to fill information gaps, including a priority list of the volcanic hazards covered under RPS Policy NH 7A (that excludes hazards not applicable to the BoP).
3. Summary of risk assessment methodologies for volcanic hazards.
4. Target level of detail for the volcanic hazard susceptibility mapping, and recommendations for improving how volcanic hazard mapping is displayed and shared.
5. Recommendations for the inclusion of Mātauranga Māori in both the future susceptibility mapping and risk assessment.

1.3 STRUCTURE OF REPORT

This report is structured as follows:

Section 1. – Provides background information that is relevant to this scoping study including definition of the scope and study area.

Section 2 – Provides a summary of the key findings of the literature review (scope items 1 and 2). Includes a high-level method/approach for filling in missing information or gaps in knowledge. Includes a priority list of volcanic hazards.

Section 3 – Provides a summary of methodologies, and resources for hazard and risk assessments (scope item 3).

Section 4 – Outlines the target level of detail for the volcanic hazard susceptibility mapping and provides recommendations and resources for improving how volcanic hazard maps are produced, displayed, and shared with the public (scope item 4).

Section 5 – Provides recommendations for the inclusion of Mātauranga Māori in both the future susceptibility mapping and risk assessment (scope item 5).

Section 6 – Summary of findings and recommendations.

Section 7 – References.

Section 8 – Appendices.

1.4 STUDY AREA

The BoP area (the Study Area) is shown in Figure 1 and comprises the land area within the Bay of Plenty regional boundary as well as several active offshore volcanic islands.

The Study Area includes the entirety of the district and city councils of: Tauranga City Council (TCC), Western Bay of Plenty District Council (WBOPDC), Whakatāne District Council (WDC), Kawerau District Council (KDC) and Ōpōtiki District Council (ODC). Most of the Rotorua Lakes Council (RLC) and a partial area of Taupō District Council (TDC) also lie within the BoPRC boundaries.

1.5 PLANNING GUIDANCE FOR AREAS WITH THE POTENTIAL TO BE IMPACTED BY VOLCANIC HAZARDS

There is currently little comprehensive land use planning for reducing volcanic risk in New Zealand (Becker et al., 2010). This is likely due to only limited guidance being available to planners to show them what options are available. Becker et al., 2010 make mention of very brief volcano land use planning advice existing in a 2008 Ministry for the Environment Natural Hazard Guidance Note.

The limited application of land use planning for reducing volcanic risk is due in part to a number of barriers, which include (Becker et al. 2010):

- The sporadic nature of volcanic activity.
- Uncertainty over the timing, magnitude and impact of potential eruptions.
- Limited guidance on volcanic hazards planning.
- The difficulties of incorporating information about volcanic hazards into land use plans.
- The variable quality of local authority plans.
- Problems with giving effect to plan intentions.
- The lack of integration between the emergency management and land use planning professions.
- Land ownership.
- The development potential of land subject to volcanic risk often overshadows concerns about any hazards present.

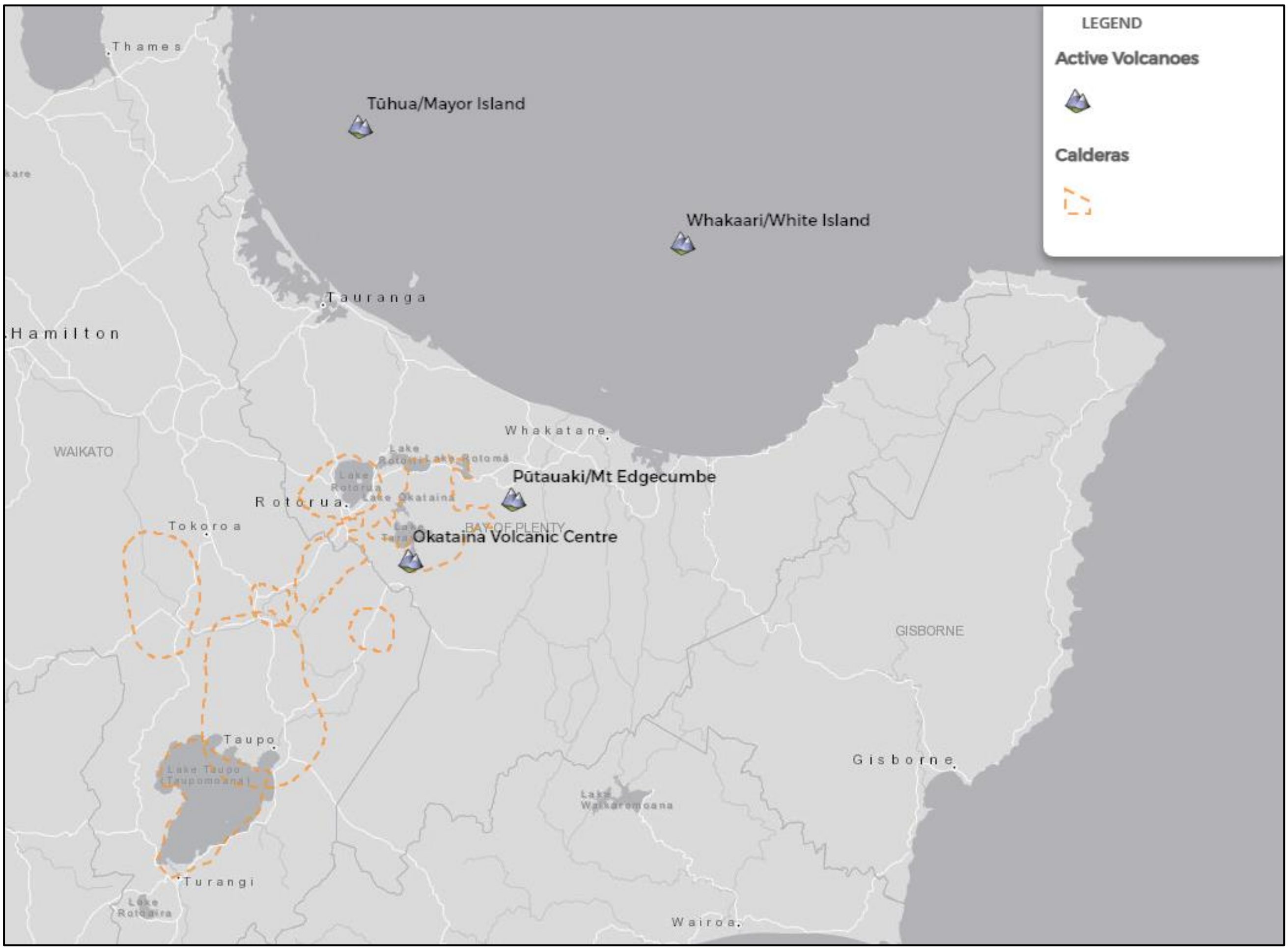

Figure 1. Map Showing the Bay of Plenty Region with Active Volcanoes and Caldera Margins. Source: BoPRC BayHazards Viewer.

2. LITERATURE REVIEW

2.1 LITERATURE FINDINGS

2.1.1 Regional Volcanic Overview

The geology of the Bay of Plenty region is dominated by the volcanically active Taupō Volcanic Zone (TVZ) (Figure 1). The TVZ marks the southern end of the Tonga–Kermadec–New Zealand active volcanic arc, stretching 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., 1995). Forming part of the Pacific Ring of Fire, the TVZ is associated with the subduction of the Pacific–Australian plate boundary that passes through New Zealand. It is the most frequently active and productive silicic system on Earth (Wilson et al., 2009).

Volcanic activity within the TVZ is characterised by an enormous range of eruption magnitudes, as evident by the volumes of erupted material (ash, lava etc.). The larger events have ejected 200-700 km^3 of pyroclastic material, while the smallest produced less than 0.001 km^3 (Wilson and Rowland, 2016). The duration of eruptive episodes is also highly variable, ranging from a few hours to months, through to sustained, intermittent activity that may last several centuries. Magma type (chemical composition) and vent location typically determine the variety of eruption styles, which range from relatively gentle extrusions of lava to violent explosive discharges

(Scott, 2010). The TVZ also accommodates a large number of fractures and faults including the active Taupō Fault Belt.

The TVZ is divided into three distinct sectors: the northern and southern sectors, which comprises andesitic volcanoes and the central sector (Rotorua–Taupō), made up of mainly rhyolitic caldera volcanoes. Composite cones of andesitic composition like Ruapehu, White Island and Ngauruhoe erupt relatively small volumes with minor to moderate impacts on a geologically regular basis (5-20 years), while the major caldera volcanoes are typically silicic in composition and generally erupt much less frequently (1,000-5,000 years), producing much greater eruptive volumes. The eruptions of either have the potential to produce regionally damaging impacts.

The TVZ is also world famous for the abundance and intensity of geothermal fields and their features (Figure 2). Many geothermal systems are expressed at the surface as areas of warm to hot ground, hot springs and steam vents. The geothermal systems are typically the by-product of volcanism and are long lived geological features with economic and intrinsic values (Fitzgerald et al., 2022). Within a geothermal system, a variety of features can be present, ranging from hot crater lakes to boiling springs and geysers, small springs, hot and warm pools, steam vents (fumaroles) and mud pots and streams. Harmful gasses can also be discharged.

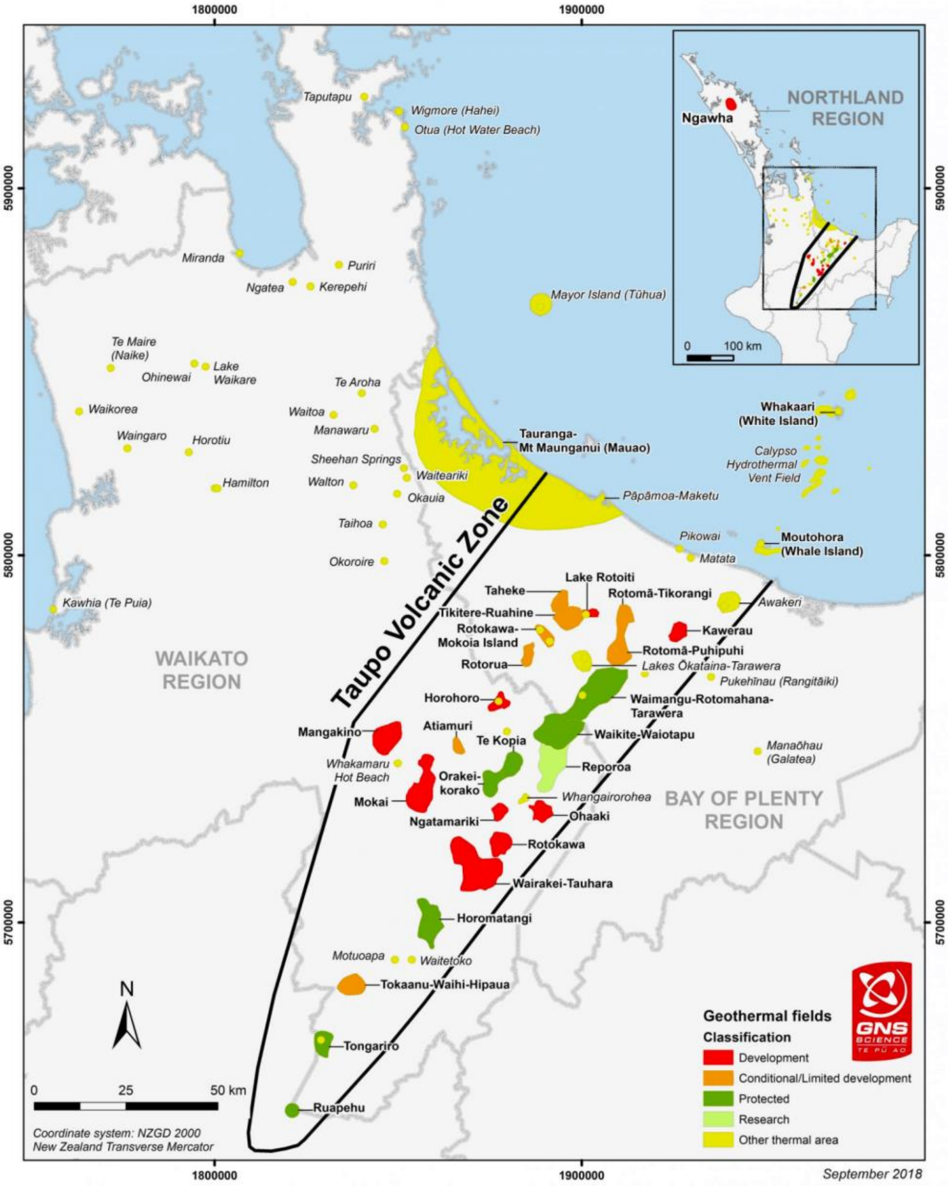

Figure 2. A Map of Geothermal Fields Within The North Island of New Zealand. Bay of Plenty Regional Boundaries Are Included. Source: GNS.

2.1.2 Types of Volcanic and Geothermal Hazards

Volcanic Hazards

Volcanoes vary remarkably in how often they erupt, the sizes and types of eruptions, and the composition of the magma produced. They operate over complex and often unpredictable timescales, and their impacts can be important at local, regional and/or global scales (Sparks et al., 2013). Volcanic eruptions are excellent examples of multi-risk cascading threats in which a variety of volcanic and associated hazards interact or impact sequentially. Within a single eruptive event multiple phases and pulses may occur (Figure 3) (Sparks et al., 2013). Within each phase and pulse of an eruption a variety of products are generated which have different dynamics and emplacement modes, and therefore will also generate different potential hazards. For example, tephra (ash) falls, pyroclastic flows, lava flows and lahars can occur simultaneously or sequentially and over differing spatial and temporal scales (Wilson et al., 2014).

The nature and timing of eruptions varies depending on the specific volcano. In New Zealand, it is generally the case that smaller eruptions occur more frequently (e.g., geothermal eruptions occur every few years; small ash eruptions every decade or so) while larger eruptions occur less frequently (every few millennia to tens or hundreds of thousands of years). The range in eruption sizes, frequency and locations can make forecasting and planning for volcanic activity difficult.

Hazards can also be produced long after an eruption ends, for example, material deposited by an eruption (e.g., ash) may be affected by other geological processes (erosion, reworking, and redeposition) and form secondary volcanic deposits (e.g., lahars post-Pinatubo in 1991). These processes can occur for years after a volcanic event. It is important to consider the multi-hazard nature of volcanic events and the possibility that such hazards may become cascading events with similarly cascading consequences.

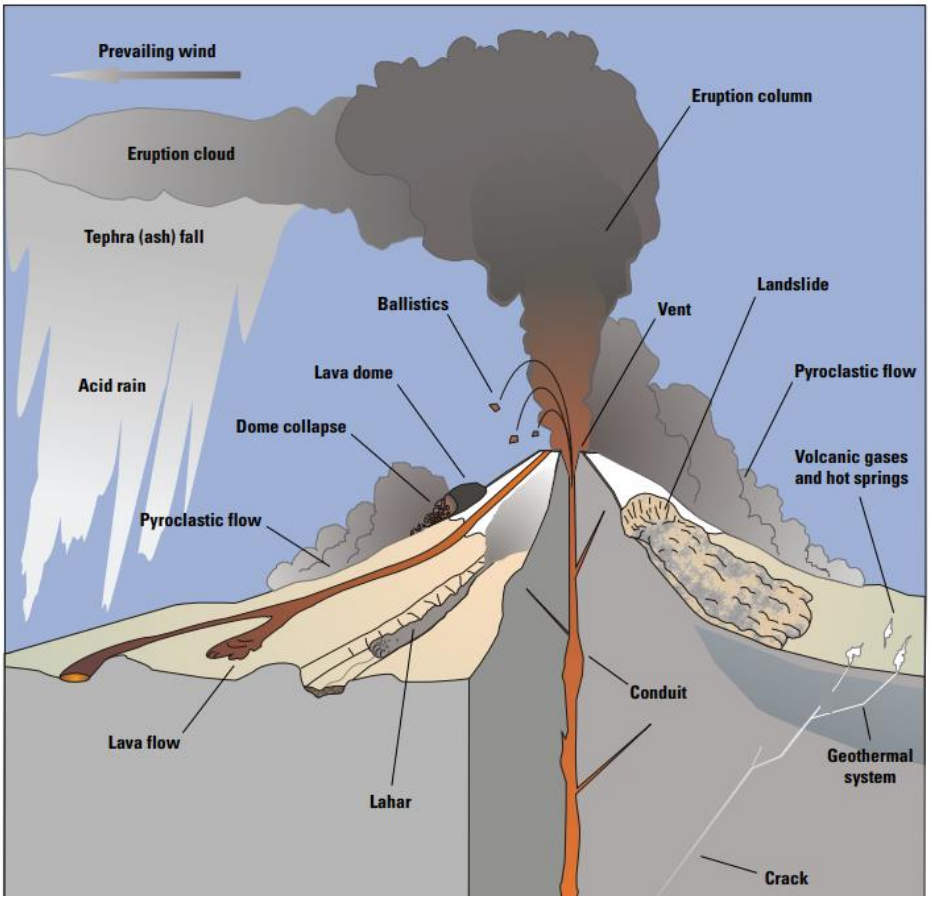

Figure 3. Idealised Illustration of Common Volcanic Hazards. Source: USGS.

Geothermal Hazards

Geothermal hazards have typically received less attention than volcanic hazards despite numerous lives being lost in New Zealand from geothermal activity. For example, about 14 people have been killed by gas poisoning in the past century, and a number of deaths have occurred from people (mainly children) falling into boiling mud pools and hot springs (Scott, 2010; Brown et al., 2017; Fitzgerald et al., 2022). Geothermal systems of varying scales can manifest at both active and inactive cone volcanoes and calderas, however, the hazards produced are typically smaller and impact smaller areas compared to their volcanic counterparts (Browne and Lawless 2001; Christiansen et al., 2007). Hazards may be enhanced or have new hazards created by renewed volcanic activity or major earthquakes that occur near-by (Fitzgerald et al., 2022).

To effectively plan for and reduce the risks from geothermal activity, it is important to understand all aspects of potential hazards, including the areas that may be impacted, the intensity and severity of the hazard within these extents, and how frequently hazards occur (Wilson et al., 2014).

Multiple hazards can originate from geothermal surface features – both eruptive and non-eruptive (e.g., Figure 4). These include: geothermal gases; weak and unstable ground; heated ground; hot water, mud and steam within existing surface features; ground collapse; mild explosive activity such as jetting, splashing and bubbling; shallow earthquakes; infrastructure failures, wells that cause artificial eruptions; hydrothermal eruptions (small to large); and phreatic (steam-driven) eruptions (Scott 2010, 2012a; Fitzgerald et al., 2022). Hazards can impact different-sized areas, from being contained within surface features to large hydrothermal eruptions that eject material up to 4 km from the vent area (Fitzgerald et al., 2022). The frequency at which hazards are produced is important, and events typically occur much more frequently than they are observed or reported (Fitzgerald et al., 2022). Hydrothermal eruption deposits have been observed at Tahunaatara and Horohoro (near Kapenga), and at the Ongaroto, Ngatamariki, Rotokawa and Kawerau geothermal fields (Leonard et al., 2010; Scott, 2010).

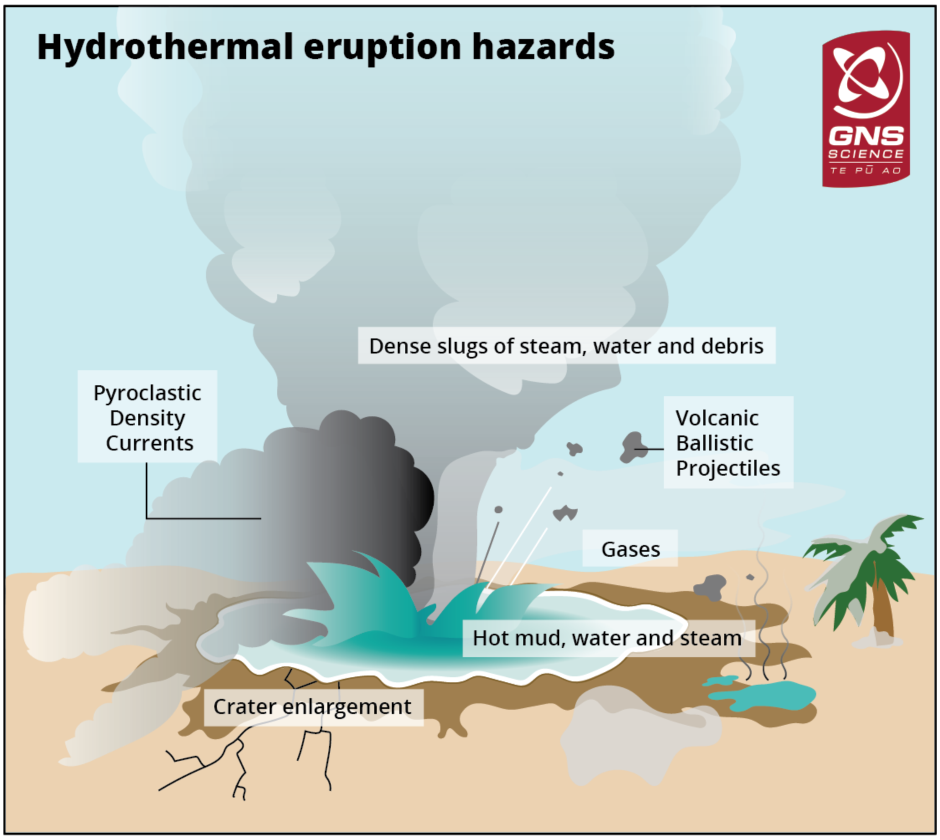

Figure 4. Illustration Of Common Hazards Associated with Geothermal Eruptions. Source: GNS.

2.1.3 Hazard Types within the BoP RPS

Table 1 summarises the hazards outlined in the BoPRC RPS Policy NH 7A and provides a brief description of them within a New Zealand context. Further information for each volcanic hazard is provided in Appendix A.

Other Volcanic Hazards

Volcanic and geothermal activity can create a range of other hazards outside of those listed in RPS Policy NH 7A. These include toxic and/or acidic volcanic gasses, volcanogenic tsunamis and seiches (in lakes), flooding, proximal ballistic projectiles (e.g., lava blocks and bombs), volcanogenic earthquakes, lightning, and a number of downstream secondary hazards such as climate variation and famine.

Within this report lake breakout floods are discussed in conjunction with lahars because the sources and trigger mechanisms within the volcanological/geological history of the BoP region are closely linked. Volcanogenic tsunamis also discussed, although only briefly. Other hazards outside of the those in the RPS Policy NH 7A are not discussed in this report. The BoPRC should consider the need to include these in future hazard mapping and susceptibility assessments.

2.1.4 Active Volcanic Centres within the Study Area

This section summarises the active volcanic centres (volcanoes) capable of producing hazards that will impact the Study Area (effectively the BoPRC area). It places them in geological context, describes their known eruption history and catalogues significant hazards relevant to the BoP region and RPS NH 7A. Volcanic centres are presented in North to South geographical order. References for each volcanic centre are presented in Section 7 – References. Appendix B includes more detailed supplementary information about the main volcanoes discussed. The Study Area may also be impacted from volcanoes outside of the region e.g., Taupō. These are discussed in Section 2.1.5.

Table 1. Summary of Hazard Types from RPS Policy NH 7A. Adapted from Wilson et al., (2014).

Hazard	Pyroclastic Flows	Lava Flows	Landslides, Debris Flows and Avalanches (Volcanogenic Only)	Lahars and Lake Break-out Floods	Ashfall	Caldera Unrest	Geothermal Hazards	Volcanogenic Tsunamis (not listed in NH 7A)
Origin	Eruption column collapse; lava dome collapse; directed blast.	Outpourings of molten rock.	Collapse of volcanic features or flanks; can be co-eruptive or during inactivity.	Rainfall remobilised tephra; eruptions through lakes; collapse of dam structures.	Explosive volcanic or steam eruptions.	Background volcano processes; pre-eruption unrest.	Interaction and circulation of water with geological heat sources at depth.	Volcanic source: under-water explosions; caldera collapse; pyroclastic flows; atmospheric pressure waves.
Composition	Mixtures of generally hot volcanic ejecta and gas.	Majority basaltic-andesitic magma, rarer silicic flows tend to have reduced velocity and distances.	A mix of volcaniclastic material from small to very large clast (grain) size.	Slurry of volcaniclastic material and water in varying concentrations.	Fine volcanic tephra (ash and lapilli) and lithic (rock) particles.	Multiple manifestations; steam eruptions; earthquakes; subsidence; hot or toxic gasses.	Multiple manifestations, see Section 2.1.6.	Ocean water; mixed with eroded and ripped up material and debris.
Transport	Primarily gravity-driven (higher columns create more energetic flows); up to 300 km/s velocity; up to 10s of km travel.	Gravity-driven downslope; ~10 km/s velocity; up to 10s of km travel (although typically <10 km).	Gravity-driven downslope; up to 10s of km travel.	Velocities of 10s of m/s; travel a few to >10's km.	Eruption plumes; 5 to >50 km vertical travel and up to 1000s of km laterally.	Typically manifest within the caldera boundaries.	Multiple manifestations.	Oceanographic.
Hazard/Damaging Characteristics	High velocities; dynamic pressure, run-out distance; temperature; abrasiveness; inundation; burial; fire.	Travel along confined paths; impact and inundate objects in path; temperatures of 800-1200 C; fires.	Dynamic pressure; run-out distance; abrasiveness; inundation; burial; transport of large blocks (boulders).	High velocities; erosion; long run-out distances; burial; inundation.	Dispersal area; thickness; loading on structures; chemical contamination and damage; abrasiveness.	Multiple manifestations depending on hazard type.	Multiple manifestations.	High velocities; dynamic pressures; onshore runout distances; impact and inundate objects in path.
External Factors and Controls	Topography (in part), can also mount topographic obstacles.	Topography.	Topography; rainfall.	Rainfall; topography and river morphology	Atmospheric and meteorological conditions.	Dependent on hazard type.	Spatial extent of field; aquifer and groundwater properties; adjacent volcanic systems; regional tectonics.	Source distance; trigger mechanism; magnitude; bathymetry and topography.
Spatial Extent	Local to district.	Typically only local.	Typically only local.	Local to district depending on magnitude and rivers impacted.	District to regional.	Local.	Local.	District to Regional (mostly restricted to coastlines; limited inland inundation).

2.1.4.1 Tūhua/Mayor Island

Tūhua/Mayor Island represents the peak of a 700 m high, 15 km wide shield volcano with a 3 km wide caldera at its peak (Wilson, 2007; Kósik et al., 2022). It has erupted on average once every 3,000 years for the past 130 thousand years (ka) (Buck, 1981). Almost every style of volcanic eruption has occurred at some stage in its history (Houghton et al., 1992). Around 7.2 ka the largest known eruption occurred, producing a widespread air-fall deposit called the Tūhua Tephra with numerous pyroclastic flows that entered the sea, possibly causing tsunamis, followed by caldera collapse. (Kennedy and Froggatt, 1984; Manighetti et al., 2003). This event is probably the only recorded instance of rock and ash flow entering the sea within the New Zealand region (Berryman, 2005). A substantial amount of fall material fell on the North Island and is found up to 100 km from source (Manighetti et al., 2003). The most recent eruption may have occurred less than 1,000 years ago (Buck, 1985; Kósik et al., 2022). Since human arrival to New Zealand, no activity or unrest is known to have occurred and our understanding of the volcano is limited to what we can see on the island (Potter et al., 2012).

The maximum credible event described by BoPCDEM (2014) is a small to moderate phreatomagmatic eruption which may extend beyond the summit caldera. Proximal areas (2-5 km) would be significantly impacted, and BoP coastal areas may receive ashfalls between 1-20 mm. The probability of an eruption in the next 50 years is calculated at about 2.0% BoPCDEM (2014), classifying it as a rare event (after Wright et al., 2010). Other possible eruptions include extrusion of lava domes within the caldera, or a repeat of a large Tūhua Tephra-style eruption. The consequence of a large volcanic eruption would be catastrophic on the island but much reduced on the mainland (BoP region). Damage to infrastructure and properties as well as societal impact caused by distal ashfall would be minor as only small areas would likely be impacted onshore. Numerical modelling of a Tūhua Tephra-style eruption (7.2 ka) with flows entering the sea suggests a 0.5 m high tsunami on coast around Whakatāne could be produced (de Lange and Healy 1986; de Lange 1997).

Table 2. Tūhua/Mayor Island Literature Summary.

Last Eruption	Possibly as little as <1 ka.
Significant Eruptions	Tūhua Eruption at about 6.3-7.2 ka – the largest known eruption.
Eruption Frequency	Every 2,500 to 3,000 years on average for the past 120 thousand years.
Eruption Styles	(Sub)-Plinian ashfalls; pyroclastic flows and surges; lava flows; domes; caldera collapse; phreatic eruptions.
Volcano Type & Composition	Peralkaline-rhyolitic complex shield volcano, caldera.
Historic Unrest	No activity or unrest known to have occurred since human arrival to NZ.
Main BoP Hazards	Ashfall onto mainland; pyroclastic flows and possible generation of tsunamis.
Available Resources and Gaps	
Volcanic History and Processes	Weakly constrained. Limited research conducted, most of which is several decades old.
Maps	Some maps dating from 1980s to recent, mostly within research literature.
Hazard Assessments	Limited.
Knowledge Gaps	• Wide range of eruption sizes and styles – current, limited knowledge of the volcanic system makes it difficult to forecast future events. • Unknown how many eruptions have occurred since 6.3 ka. • Uncertainty about most recent eruption history (i.e., 1,000-500 years ago). • The impact of potential pyroclastic flows affecting onshore areas in the event of a large eruption. • Limited tsunami assessments (although risk assessed as low).
Current or Future Research Programmes	Beneath the Waves (GNS).

2.1.4.2 Whakaari/White Island

Whakaari/White Island is New Zealand’s most active volcano, and the northernmost volcano within the TVZ (Kilgour et al., 2021a). Explosions at Whakaari are historically small and weak, with activity primarily comprising phreatic (steam-driven) and phreatomagmatic (magma and steam-driven) eruptions interspersed by occasional magmatic strombolian activity (small discrete explosive events) (Houghton and Nairn, 1991; Kilgour et al., 2021b). These relatively small eruptions typically occur several times per year during an eruptive episode (a prolonged period of increased unrest and activity). A small collapse of the main crater in 1914 formed a debris avalanche which killed 11 sulphur miners and may have entered the sea (Berryman, 2005). An eruption occurred on 9 December 2019 during a tourist visit to the island, killing 22 and injuring 25.

The maximum credible event as defined by BoPCDEM (2014) has a return period of less than 10 years. The consequence of which is assessed as moderate to major on the island if visitors are present. Very light ashfall could occur on the mainland. The impact to the North Island is considered to be negligible in the event of eruption (BoPCDEM, 2014). The generation of significant tsunamis sourced from White Island is considered low (de Lange and Healy 1986; de Lange and Prasetya, 1997; Berryman, 2005).

Table 3. Whakaari/White Island Literature Summary.

Last Eruption	2019, but considered near-continuously active.
Significant Eruptions	2019 eruption; 1914 collapse and debris avalanche.
Eruption Frequency	<10 years for small eruptions; >1000-2000 years for larger.
Eruption Styles	Phreatic and phreatomagmatic; Strombolian; Sub-Plinian
Volcano Type & Composition	Stratovolcano, dominantly andesite in composition.
Historic Unrest	Near-continuous unrest.
BoP Hazards	Minor ashfall on mainland BoP, tsunami; proximal hazards for visitors (on the volcano only) include ash, small pyroclastic flows, ballistic ejecta.
Resources	
Volcanic History and Processes	Recent eruption history is well constrained.
Hazard Maps	Limited. Some are specific to the 2019 event.
Hazard Assessments	Hazards are assessed as mostly limited to near-vent areas on the island.
Knowledge Gaps	• A mis-match exists between current (generally small) eruptive episodes and the significantly larger episodes recorded for the last 15 ka in sea-bed cores. • Limited tsunami assessments (although risk assessed as very low).
Current Research Programmes	Beneath the Waves (GNS).

2.1.4.3 Pūtauaki/Edgecumbe

Pūtauaki/Edgecumbe (~800 m elevation) is a young, multiple vent, dacitic cone complex located 50 km east of Rotorua and 3 km east of Kawerau. The main cone forms the largest part of the complex and was created from a series of lava flows and volcanic breccias deposited as hot block-and-ash flows and cold debris avalanches (Carroll et al., 1997). A lava plug and two small craters occupy the summit. Evidence suggests that the cone has grown mostly over the last 5 thousand years, with recent eruptions dated around 2.3-3.1 ka (Carroll et al., 1997). Explosive activity appears to have been very minor (Nairn, 1999). Debris avalanche deposits to north of the mountain, indicate that some cold avalanching has occurred since 1,850 years ago, and was possibly seismically-triggered (Nairn, 1999). The proximity of Pūtauaki to Ōkataina has led some researchers to speculate that it may be linked to the Ōkataina Volcanic Centre and represents its easternmost part (Potter et al., 2012). Steep angles on the flanks of the main cone have led to concerns over flank stability, particularly under earthquake shaking and water table elevations (Hewitt, 2007).

Geological evidence suggests that no widespread impacts from eruptions have occurred, however future eruptions may differ. The most likely scenarios for eruptions are assessed to include small pyroclastic flows, including block and ash flows off the cone, and light ashfalls (BoPCDEM, 2014). Hydrothermal eruptions may also be triggered in the nearby Kawerau geothermal system, either by an eruption or during an unrest period. The probability of an eruption in the next 50 years is assessed at about 2-5% (BoPCDEM, 2014) (unlikely to rare following Wright et al., 2010).

Table 4. Pūtauaki/Edgecumbe Literature Summary.

Last Activity	Debris avalanche ~1850 years ago.
Significant Eruptions	2.3 to 3.1 ka lava flows and block and ash (pyroclastic) flows.
Eruption Frequency	Unknown in detail.
Eruption Styles	Lava flows, dome growth and collapse.
Volcano Type & Composition	Stratovolcano, andesite to dacite composition.
Historic Unrest	None recorded. Active Kawerau geothermal system nearby.
BoP Hazards	Localised pyroclastic flows (block and ash flows); lava; debris avalanche.
Resources	
Volcanic History and Processes	Poorly constrained.
Hazard Maps	Limited.
Hazard Assessments	Limited.
Knowledge Gaps	• Poor eruption history and generally low amount of research conducted. • Connection to the Kawerau Geothermal system is poorly understood.
Current Research Programmes	None known.

2.1.4.4 Ōkataina Volcanic Centre (OVC)

The Ōkataina Volcanic Centre (OVC) occupies the northern extent of the central zone of the TVZ and is located near the city of Rotorua and the township of Kawerau. Many eruptions at Ōkataina have produced large volumes of rhyolite lava, which have piled up over the vent areas to produce two large massifs, Haroharo and Tarawera (Nairn, 1984, 2002). The OVC has produced at least three very large caldera-forming rhyolitic eruptions, with the last of these being the 45 ka Rotoiti Eruption (Nairn et al., 2001). Nine rhyolitic Plinian eruptions have occurred in the last 26 ka, focused along two Linear Volcanic Zones (LVZs) within the Haroharo and Tarawera massifs. The Kahoroa eruption is the most recent rhyolitic eruption, occurring in 1314 AD from the Tarawera LVZ (Lowe et al., 1998; Leonard et al., 2010; Sahetapy-Engel et al., 2014). Two basaltic eruptions have also occurred. The first, the Rotokawau eruption (3.7 ka), comprised a small basaltic fissure eruption that generated localised tephra fall and formed an east-west alignment of four shallow maars (Walker et al., 1984; Beanland and Houghton 1991). The second, the Tarawera Eruption (1886 AD), was New Zealand’s largest and most destructive historical eruption, producing an unusual basaltic Plinian eruption that manifested as multiple vents across 17 km of the Tarawera LVZ (see Appendix B for further information).

Future eruptions are assessed as either of two types, 1) caldera-forming (of which there have been 3 over the last 500 ka), and 2) post-caldera eruptions (akin to the 9 that have occurred since 26 ka). BoPCDEM (2014) only considered post-caldera eruptions in their assessments because of the very long return periods of the caldera-forming eruptions (10s of thousands of yeas). The probability of a post-caldera eruption in the next 50 years is about 2-4% - a rare to unlikely event (BoPCDEM, 2014). The consequence of a post-caldera-type event would be major to catastrophic. Near vent areas (within 5-10 km) could be totally destroyed and distal portions of the BoP region may receive significant ashfalls (0.1-1 m). The topography may be heavily modified and existing lakes may be impacted, leading to large scale floods and lahars. Remobilisation of ashfall deposits could create erosional issues for many years after the eruption.

Future activity at OVC will be preceded by caldera unrest that may or may not culminate in an eruption. A period of volcanic unrest lasting weeks to years is possible, with damaging earthquakes, ground deformation and changes in hydrothermal systems (Potter et al., 2012). Caldera unrest could occur as often as once every 50-100 years and is considered as a possible event by BoPCDEM (2014). Unrest has the potential to affect the local and national economies, the tourism industry, infrastructure of national importance, and the psychological and physical health of nearby residents (Potter et al., 2012).

Table 5. Ōkataina Volcanic Centre Literature Summary.

Last Eruption	1886 AD Tarawera Eruption.
Significant Eruptions	1886 AD Tarawera; 1314 AD Kaharoa; ~45 ka Rotoiti.
Eruption Frequency	1 per 3,000 years since 60 ka, 1 per 2,000 years since 22 ka.
Eruption Styles	Plinian; caldera-forming or post-caldera; dome growth and lava flows.
Volcano Type & Composition	Caldera complex; dominantly rhyolitic.
Historic Unrest	Short-term unrest prior to the Tarawera Eruption; only minor unrest periods recorded since instrumented monitoring has begun.
BoP Hazards	Ashfall; pyroclastic flows; lake modification and break-out floods; lahars and remobilisation of ash; caldera unrest periods.
Resources	
Volcanic History and Processes	Generally well-constrained, although the oldest eruptive history is poor due to overprinting of new material.
Hazard Maps	Several official hazard maps produced. Many studies provide geological maps of units and their extents. Many studies have applied modelling techniques to the major hazards, particularly ashfall.
Hazard Assessments	Include ashfall, pyroclastic flows lake break-out floods.
Knowledge Gaps	• Connection to Rotorua Caldera and geothermal fields is possible but unknown to what extent, or how an eruption my influence either. • Unknown future eruption style(s) and vent location(s). E.g., rhyolite, basaltic, caldera-forming, rift eruption, steam explosion.
Current Research Programmes	CALDERA (GNS); ECLIPSE (GNS)

2.1.4.5 Rotorua Caldera

Rotorua Caldera is the youngest caldera of the TVZ, with activity beginning at 240 ka. The caldera was formed during the very large (145 km^3) Mamaku Plateau forming eruption in 240 ka (Milner, 2001; Gravley et al., 2007). After the Mamaku Plateau eruption, rhyolitic lava was extruded forming a number of small domes including those at 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 (Leonard et al., 2010). Rotorua Caldera contains the Rotorua and Eastern Rotorua geothermal fields. It is unknown if future eruptive activity or caldera unrest is possible.

Table 6. Rotorua Caldera Literature Summary.

Last Eruption	Unknown, at least 20 ka.
Significant Eruptions	240 ka Mamaku Plateau formation eruption.
Eruption Frequency	Undetermined.
Eruption Styles	Plinian; caldera-forming or post-caldera eruptions; dome growth.
Volcano Type + Composition	Caldera complex; rhyolitic.
Historic Unrest	Continuous geothermal activity within the Rotorua and Eastern Rotorua geothermal fields; small seismic swarms approximately every 2 to 10 years.
BoP Hazards	Ashfall, pyroclastic flows, caldera unrest and increased geothermal field activity.
Resources	
Volcanic History and Eruption	Possibly poorly constrained. Major eruptions are well documented.
Hazard Maps	None found. Geological maps catalogue dispersal of ignimbrite material.
Hazard Assessments	Kaye, 2008.
Knowledge Gaps	• Unknown if future eruptive activity or caldera unrest is possible. • Connection with nearby geothermal fields, particularly in response to unrest, is unknown. • Connection with OVC has been suggested but not fully understood.
Current Research Programmes	None known.

2.1.5 Distal Volcanic Centres Capable of Impacting the Study Area

These volcanic centres lie outside of the BoPRC boundaries but are located close enough or are capable of producing large enough eruptions that the BoP region could be impacted. These volcanoes typically only represent distal hazards for the BoP, with the major hazard being ashfall.

2.1.5.1 Taupō Volcanic Centre (TVC)

The Taupō Volcanic Centre (TVC) is the southernmost caldera of the TVZ. It is considered the most productive individual rhyolitic volcano in the world (Barker et al., 2019). Activity began in ~330 ka and since then it has had a complex history of both very large and very small eruptions, most of which were rhyolitic in composition (Wilson et al.,1986, 2009; Barker et al., 2019). The caldera was mostly formed during the largest eruption, the cataclysmic Oruanui Eruption dated ~27 ka (530 km^3 of material erupted over a period of several months). 28 eruptions have been documented since the Oruanui that range in size from about 0.5 km^3 to over 45 km^3 (Wilson et al., 2009). The most recent, the Taupō/Hatepe Eruption (232 AD) was uncharacteristically large and destructive compared to other post-Oruanui events (Wilson, 2001). Smaller events are typically more frequent. See Appendix B for a more detailed eruption history.

The TVC is typically upwind of the Study Area and very capable of producing eruptions that disperse ashfall greater than a few mm thick within the BoP region. Maximum expected ashfall from a small event (<1 km^3) is considered by BoPCDEM (2014) as being about 1-2 cm (dependant on location within the region and factors such as eruption column height and wind direction). The probability of this kind of eruption in the next 50 years is about 5% (based on the last 28,000 years) and classed as an unlikely event (BoPCDEM 2014). Larger events are rarer, likely less than 2% in the next 50% years however the consequences are much greater - minor to moderate. Societal impact would be moderate as large numbers of people would be affected. Minor to moderate damage to infrastructure and properties might be expected, with the local to national economy also impacted. There would also be serious environmental impacts with large areas affected. The TVC frequently undergoes periods of unrest, however impacts are typically restricted to the confines of the caldera system and are not considered capable of impacting the BoP region.

Table 7. Taupō Caldera Literature Summary.

Last Eruption	282 AD.
Significant Eruptions	282 AD Taupō/Hatepe; 26 ka Oruanui.
Eruption Frequency	1 every ~1,000 years since ~28 ka.
Eruption Styles	(Sub)-Plinian to Ultra-Plinian (very large Plinian-style eruption).
Volcano Type + Composition	Caldera; rhyolite.
Historic Unrest	Frequent unrest periods including in 2022-2023.
BoP Hazards	Ashfall and pyroclastic flows possibly affecting southern BoP Region.
Resources	
Volcanic History and Eruption	Generally well constrained.
Hazard Maps	Some hazard maps available. Many studies provide geological maps of units and their extents. Studies exist that have applied modelling techniques to the major hazards, particularly ashfall.
Hazard Assessments	Include ashfall, pyroclastic flows, lake break-out floods.
Knowledge Gaps	• High consequence but low likelihood events such as 282 AD eruption are difficult to forecast. • Even larger, less frequent events such as the Oruanui eruption are very difficult to account for.
Current Research Programmes	ECLIPSE (GNS)

2.1.5.2 Other Volcanic Centres

North Island Volcanoes

There are other volcanoes within the North Island capable of producing eruption events that could affect the BoP region (Table 8). These include the southern TVZ cone volcanoes of Tongariro, Ngauruhoe and Ruapehu, as well as Taranaki in the western North Island. Typically, only the largest eruptions from these volcanoes are capable of impacting the Study Area, and this is primarily comprised of an ashfall hazard (Scott, 2010).

Other active volcanic systems in New Zealand also exist, however these are far enough outside of the Study Area that any activity is highly unlikely to affect it. These volcanoes include the Kermadec's (Raoul Island and many submarine volcanoes), the Auckland Volcanic Field, and the Northland volcanic fields. They are not discussed further in this report.

Table 8. Literature Summary for Other North Island Volcanoes with Capability of Impacting the Study Area.

Volcano	BoP Hazards, Magnitude and Spatial Extent	Frequency (based on Neild, et al., 1998)	Useful Reference	Available Hazard Maps	Gaps
Tongariro and Ngauruhoe	Ashfall (mm to cm thickness). Most likely impacting the southern BoP region.	Small (<0.01 km^3) – 10 to 100 years. Medium (0.01-0.1 km^3) - 100 to 1,000 years. Large (0.1-1 km^3) – 10,000 years	Hitchcock and Cole, 2007; Hurst and Smith, 2010; Leonard et al., 2021.	Hitchcock and Cole, 2007; Hurst and Smith, 2010.	Limited modelling for ashfall dispersal, particularly for larger eruptions.
Ruapehu	Ashfall (mm to cm thickness). Most likely impacting the southern BoP region. 1995-96 activity deposited mm thicknesses of ash within the BoP region.	Small (0.01-0.1 km^3) - 20 years (e.g., 1995-96 activity). Medium (0.1-1.0 km^3) - 100 to 500 years. Large (>1 km^3) – 10,000 years.	Cronin et al., 1997; Hurst and Turner, 1999; Hurst and Smith, 2010; Leonard et al., 2021.	Cronin et al., 1997; Hurst and Turner, 1999.	Limited modelling for ashfall dispersal, particularly for larger eruptions.
Taranaki	Minor ashfall (mm to cm thickness). Most likely impacting the western BoP region.	Only large deemed likely to impact the BoP (<0.1 km^3) every 10,000 years	Wier et al., 2022; Cronin et al., 2019; Hurst and Smith, 2010.	Hurst and Smith, 2010.	Limited models for distal impacts of ash. Most models terminate at the Taranaki region boundaries.

Potentially Active Calderas within the TVZ

A number of caldera volcanoes in addition to those discussed above are present within the central TVZ, including two calderas within the Rotorua district (Kapenga and Reporoa) (Figure 1). These calderas are generally considered inactive or unlikely to erupt in the near future, however, there is a possibility that future hazards from eruptions, unrest, and/or geothermal activity may be generated that could impact the Study Area. These calderas are briefly summarised in Table 9 below.

Table 9. Summary of Potentially Active (Eruption or Unrest) Calderas within the TVZ. (Summarised from Potter et al., 2012).

Volcanic Centre	Eruption History	Future Eruptions or Unrest?	Key Sources	Gaps
Kapenga Caldera	Active from 900 to 240 ka.	Long-term dormancy indicates future eruptions are unlikely but cannot be ruled out. No research on historical unrest has been conducted, therefore no unrest episodes are known to have occurred. Many shallow earthquakes are recorded in the area that are likely tectonic.	Leonard, 2003; Leonard et al., 2010; Potter et al., 2012.	Uncertainty around history of unrest and the exact nature of the seismicity.
Ohakuri Caldera and the Maroa Volcanic Centre	Large Ohakuri eruption (224 ka). 4 small (<0.2 km^3) eruptions since 61 ka, with most recent (16 ka) of 0.14 km^3 volume.	Leonard (2003) calculated the probability of future eruption at ~0.7% in 80-years and the most probable future eruption size at <0.1 km^3. No historical unrest has been documented except for regional earthquake activity and hydrothermal eruptions at Orakei Korako geothermal field.	Leonard, 2003; Gravley et al., 2007; Wilson et al., 2009.	Uncertain eruption and unrest history. Uncertain nature of seismicity.

Reporoa Caldera	230 ka Kaingaroa Ignimbrite. Lava domes (older and younger than Kaingaroa). Occasional small basalt eruptions.	Long-term dormancy indicates future eruptions are unlikely but cannot be ruled out. There is no research on historical unrest therefore no unrest episodes are known to have occurred. The area does experience regional earthquake activity and localised geothermal activity.	Leonard et al., 2010; Potter et al 2012.	Uncertain history of unrest.
Mangakino Caldera	Very large ignimbrite eruptions dated at 1.6 million years ago and 950 ka.	Long-term dormancy indicates future eruptions are unlikely but cannot be ruled out. There is no research on historical unrest therefore no unrest episodes are known to have occurred.	Leonard et al., 2010, Potter et al. 2012.	Uncertain history of unrest.
Whakamaru Caldera	350 ka - very large eruption (1,500 km^3). 340 ka - smaller (500 km^3) eruption.	Long-term dormancy indicates future eruptions are unlikely but cannot be ruled out. There is no research on historical unrest therefore no unrest episodes are known to have occurred. The caldera boundary includes multiple geothermal fields and active fault lines.	Leonard et al., 2010; Wilson et al., 2009; Potter et al., 2012.	Uncertain history of unrest.

2.1.6 Geothermal Hazards within the Study Area

The Bay of Plenty region hosts several large, and many smaller high-temperature geothermal systems (Figure 2). Most of these are located within the Rotorua district, of which there are 20 geothermal systems recognized (Scott, 2010). The size of the surface and sub-surface expressions of the geothermal systems are variable, as are the styles of activity and features produced. Some fields have undergone exploitation, modifying their structure, properties and activity. A review of the Rotorua geothermal fields and their hazards can be found in Scott (2010). Geothermal fields do not generally present large or significant hazards. The greatest hazards are hydrothermal eruptions and collapse of unstable hot ground (Scott, 2010). Hydrothermal explosions occur roughly every 2-10 years in the Rotorua area (Table 10) (Fitzgerald et al., 2022).

A number of geothermal systems are present within the southern TVZ, however most of these are outside of the BoPRC boundaries, and due to the limited spatial extent of their hazards are unlikely to affect the BoP region.

BoPCDEM (2014) describe the maximum credible geothermal event as a large-scale explosion occurring at either Kawerau or Waimangu fields, possibly following a post-caldera eruption nearby. Everything nearby to one of these will be significantly impacted or destroyed, with extensive damage occurring up to about 1 km from the source. These large eruptions have a return period of about 2,000 years, with BoPCDEM (2014) assigning a probability of occurrence of 2.4% within 50 years (unlikely to rare). Smaller scale geothermal eruptions occur in all high temperature geothermal systems and appear to be more common in some exploited systems. These occur on about an annual basis and only significantly affect areas near to the source (5 to 50 m) (BoPCDEM, 2014).

Table 10. Summary of Geothermal Hazard Types Adapted from Fitzgerald et al., (2022) (see for more detailed information on specific hazards and processes).

Hazard	Hazard Feature Description	Spatial Extent of Hazard (m)	Average Recurrence Interval (years)
Phreatic eruption	Range from small-scale individual steam-driven bubble explosions through medium-scale eruptions with slugs of sediment-laden debris to large-scale eruptions creating craters and ejecting ballistic projectiles, pyroclastic density currents, ash, gas and jets of water and steam.	<3200	95
Large hydrothermal eruption	Larger-scale explosive activity forming new vents and craters; debris entrainment, surges, and ballistics	>100	10
Moderate hydrothermal eruption	Vigorous overflows and geysering; possible minor vent enlargement, debris entrainment.	10-100	4.3
Small hydrothermal eruption	Irregular geysering of hot water; minor vent clearing debris; re-activation or new activity.	5 to 10	2.5
Mild explosive activity (EHSF)	Explosive splashing, spattering and jetting reaching outside feature	<5	6
Ground collapse	Collapse of overlying surface into void, sometimes filled with hot steam and fluids	<30 (crater)	3.8
Key Geothermal Hazard Resources		**Spatial Extent**	**Author**
Fitzgerald et al., 2022	Compiles and reviews local and international peer-reviewed geothermal literature. Presents potential hazards and impacts associated with surface geothermal features. Suggestions for monitoring, categorising hazards, and completing hazard and risk assessments. Contains an appendix cataloging hazard data for use in analysing the frequency of various hazards within three geothermal systems (Rotorua, Waimangu and Yellowstone in the USA).	All active geothermal areas of NZ and some international examples.	GNS
Tonkin and Taylor, 2022	Focuses on geotechnical assessment of the geothermal hazards and risks to residential buildings and their occupants within Rotorua City. Includes geothermal hazard and risk identification and analysis. Some summary maps are provided.	Rotorua City	Tonkin and Taylor
Deligne et al., 2020	Considers aspects of volcanic and geothermal hazards with a focus placed on volcanic or geothermal eruptions as the mechanism for producing hazards. Provides guidelines for undertaking volcanic and geothermal hazard and exposure analysis.	All active geothermal areas of NZ	GNS
BoPRC, 2018	Management plan for the Kawerau Geothermal System.	Kawerau	BoPRC (with multiple collaborators)
Scott et al., 2012b	Provides guidelines for mapping and monitoring of geothermal features within Whakatāne.	Whakatāne, BoP	GNS
Scott, 2010	Provides a series of hazard studies to underpin recommendations for best practice in areas of management and planning for volcanic and geothermal hazards.	Rotorua district	GNS

2.1.7 Available Maps, Datasets and Software Relevant to Volcanic Hazard and Risk Assessments

Available Maps

Table 11. Available Geological, Volcanic and Hazard Model Maps Relevant to the BoP Region.

Title	Author(s)	Published Date	Scale	Comments
Future Taupō Volcanic Zone Map (official title unknown)	GNS Science	Yet to be published. Possibly 2023.	Indication: 1:60,000, 2 Sheets	Not currently officially published. Georeferenced. Geomorphological as well as geological. LiDAR based and high-resolution. All new geology polygons updated from QMap series.
Taupō Ash Dispersal Maps	Barker et al., 2019	2019	Multiple	Modelling ash dispersal from future eruptions of Taupō. Multiple eruption scenarios based on eruption magnitude and meteorological conditions.
Ōkataina Ashfall Hazard Maps	Thompson et al 2015a, 2017a	2015-2017	Multiple	Maps within a series of journal articles. Based on probabilistic tephra dispersal modelling of future OVC activity and impacts to agriculture.
Geology of the Rotorua Area (QMAP)	Leonard et al., 2010; GNS Science	2010	1:250,000	Georeferenced. Digital datasets available through GNS.
Ashfall Hazard Maps	Hurst and Smith, 2010.	2010	Multiple – regional scale	Probabilistic maps within a journal article.
Geology of the Ōkataina Volcanic Centre	Nairn, 2002 - GNS Science	2002	1:50,000	Adapted from 1998 map below.
Geology of the Raukumara Area (QMAP)	Mazengarb and Speden, 2000 - GNS Science	2000	1:250,000	Georeferenced. Digital datasets available through GNS.
Volcanic Hazard Map of Ōkataina Volcanic Centre	Scott and Nairn, 1998 – GNS Science	1998	1:50,000	Hazard Map of Ōkataina Volcanic Centre.

Available Geothermal Databases

Table 12. National and Regional Volcanic and Geothermal Databases.

Item	Description	Spatial Extent
Geothermal and Groundwater (GGW) Database	Stores a collection of hydrological, geochemical (sampling and chemistry), geological and geophysical data collected from over 1,500 sites within New Zealand for groundwater and geothermal research purposes.	NZ-wide.
BOPRC Geothermal Surface Features	Geothermal surface feature database (location, description, chemistry, observation, water levels)- public access data.	BoP region.
Natural Thermal Feature/Springs of New Zealand	Publically available data collated from a variety of sources on thermal and geothermal features of New Zealand. This includes features from both high-temperature and low-temperature geothermal systems.	NZ-wide.
Volcano Monitoring	Volcanic fluids (water/gaz/condensate) chemical analyses regularly collected for the purpose of Volcano Geochemical Monitoring.	NZ-wide.

Available Software and Analyses Packages

A suite of quantitative software packages that can model volcanic phenomena are available. These include software that models individual volcanic processes/hazards such as ashfall (e.g., Biass et al. 2016; Bonadonna et al. 2021). In recent years, a focus has been placed on building integrated packages that can provide hazard and risk assessments for multiple hazards over regional scales. Wild et al., (2020) provide a comprehensive and useful review of many of these individual and multi-hazard software packages. They supply decision-making flow charts to aid in determining the most appropriate methods to use. A summary of regional-scale, multi-hazard programmes are provided in Table 13 below.

Table 13. Available software packages for multi-hazard, regional-scale hazard and risk assessment.

Title	Authors	Date	Comments	Key References
RiskScape 2.0	GNS Science & NIWA	2004 to ongoing	Open-access risk modelling software jointly developed by NIWA and GNS Science.	Reese et al., 2007; Kaye, 2008; Deligne, 2017; Thomas et al., 2020.
BET_VH **BET UNREST**	INGV Italy	2008 to ongoing	Useful for long-term assessments that considers volcanic hazards across a spatial area. BET UNREST extends the BET_EF framework to consider non-magmatic unrest hazards.	Marzocchi et al. 2008; Marzocchi et al. 2010; Rouwet et al. 2014; Tonini et al. 2016.
ADVISE model *(integrAteD VolcanIc risk assessment)*	University of Geneva	2021	An attempt to capture the multi-dimensional and dynamic nature of volcanic risk. Applicable to short-term and long-term risk management. Allows qualitative, semi-quantitative and quantitative risk assessment depending on the final objective and on the available information.	Bonadonna et al., 2021.
MatHaz	D. Bertin (University of Auckland)	2019	Open source integrated probabilistic long-term spatio-temporal volcanic hazard assessment model written in Matlab. The outputs from the spatial, temporal and volcanic phenomena analysis can be merged to produce volcanic hazard maps.	Bertin et al. 2019.

Available Scientific Literature (Reports, Journal Articles etc.)

A large amount of literature is available for most aspects of a future volcanic hazard mapping and susceptibility study (source volcanoes, eruptive processes, volcanic hazards and their impacts). These are described throughout this report and categorised in Section 7 - References.

2.1.8 Current Scientific Research Programmes

Multiple large-scale natural hazards and volcanology projects are currently ongoing. These represent the state-of-the-art of New Zealand hazards and risks research. A summary is provided in Table 14.

Table 14. Summary of Current Research Programmes Relevant to Volcanic and Geothermal Hazards, Risk Assessments and Management within the BoP Region.

Project	Description	Dates	Key Contact(s)	Link
Beneath the Waves	Building preparedness and resilience to hazards from Tūhua/Mayor Island and Whakaari/White Island.	2021 to 2026	Craig Miller, GNS Science	https://www.gns.cri.nz/research-projects/beneath-the-waves/
CALDERA	A research project that explores the inner workings of the Ōkataina Volcanic Centre in the central North Island. Explores both volcanic and geothermal aspects.	Future, initial workshops have begun at the date of this report.	Cecile Massiot, GNS Science	https://www.gns.cri.nz/research-projects/caldera-connections-among-life-geo-dynamics-and-eruptions-in-a-rifting-arc-caldera/
Resilience to Natures Challenges (RNC)	Large multi-collaborative project with the mission of accelerating natural hazard resilience. Multiple themes including, Volcano, Built Environment, Urban, Rural, Multi-hazard risk, and Policy and Governance.	2015 to ongoing	See website for Theme Leaders.	https://resiliencechallenge.nz/ https://resiliencechallenge.nz/about-us/programme-leaders/
ECLIPSE (Eruption or Catastrophe: Learning to Implement Preparedness for future Supervolcano Eruptions)	Determining the geological cues that signal unrest versus those that signal eruption, the programme contributes to the global understanding of super-volcanic systems and the local development of hazard models and disaster preparedness plans.	2017 to 2023	Simons Barker, Victoria University of Wellington	https://sites.google.com/view/eclipse-supervolcanoes/
DEVORA (Determining Volcanic Risk in Auckland)	Assessments of volcanic hazard and risk in the Auckland metropolitan area, and strategies and rationale for appropriate risk mitigation approaches.	2008 to ongoing	Jan Lindsay, University of Auckland	https://www.devora.org.nz/
Taranaki Volcanic Futures	Focused on geological, engineering and socio-economic research for the New Zealand economy to transition through a Taranaki eruption.	2019 to 2024	Shane Cronin, University of Auckland	https://volcanicfutures.co.nz/
National Volcanic Hazard Model of New Zealand	*Not a formal project*. Multiple researchers have been in work to develop a national volcanic hazard model similar to the existing seismic model for NZ.	2002 to ongoing	Mark Stirling, Otago University	Key papers: Stirling et al., 2002; Stirling et al., 2017.

2.2 VOLCANIC HAZARDS PRIORITY LIST

A priority list of volcanic hazards for consideration for further assessment is presented in Table 15. This is a preliminary qualitative assessment based on likely impacts and spatial extents from the literature review, geological histories, and informed by past hazard assessments.

Table 15. Priority List of Volcanic Hazards within the BoP Region.

Priority	Hazard	Relative Likelihood (qualitative assessment)	Consequence (qualitative assessment)	Spatial Extent
1.	Ashfall	Moderate	Low-Moderate	High
2.	Geothermal Hazard	Very High	Low	Low, geothermal field boundaries.
3.	Caldera Unrest	High	Low-Moderate	Low to medium, caldera margin boundaries (can be large areas e.g., OVC)
4.	Pyroclastic Flow	Low	High	Low-Moderate
5.	Lahar and Break-out Floods	Low	Moderate-High	Low (limited to some rivers)
6.	Debris Flow and Avalanche	Low	Low to High	Very Low (typically only proximal)
7.	Lava Flow	Low	Low	Very Low (typically only proximal)
8. (Outside of NH 7A)	Volcanogenic Tsunami (from eruption or flank collapse)	Low	Moderate-High	Moderate (along coastline and short distances inland)

2.3 SUMMARY OF AVAILABLE INFORMATION, IDENTIFIED GAPS AND METHODS TO FILL GAPS

Table 16 summaries the state of understanding, key available information related to mapping of volcanic hazards in the Study Area. The table also includes identified gaps and provides recommendations for methods to fill them.

Table 16. A Summary of Available Information Relevant to RPS Policy NH 7A Volcanic Hazards. Identified Information and Mapping Gaps and Recommended Methods to Fill them are Included.

						Gaps and Methods to Fill Them	
Hazard (in Priority Order)	**Relevant Volcanic Centres**	**Literature Review (NZ and Global)**	**BoP Region (and NZ)**	**Key Hazard Assessment References**	**Maps**	**Information and Mapping Gaps**	**Sourcing Method/Work and Suggested Entity to Conduct.**
1. Ashfall	All BoP and listed distal volcanic sources.	Physical Processes and models well constrained. Hazards well constrained. Risk assessment methods well constrained.	Many studies on ashfall distribution, hazards and distribution models for NZ and within the TVZ. Many papers on OVC ash hazards (the most relevant volcano).	Nairn, 1999; Hurst and Smith, 2010; Wilson et al., 2012; Thompson et al., 2015a.	Nairn, 1999; Hurst and Smith, 2010 (North Island); Thompson et al., 2015a (Ōkataina); Barker et al., 2019 (Taupō).	No region-wide probabilistic ashfall assessments and isopach maps. (North Island assessment by Hurst and Smith, 2010).	**Sourcing Method:** Conduct assessment to update the work of Hurst and Smith, 2010. Key outputs required are ashfall thicknesses based on RPS annual exceedance probabilities. * **Who:** GNS or other qualified body.
2. Geothermal	All geothermal fields within the BoPRC boundaries.	Physical processes and models somewhat constrained. Hazards typically well constrained. Risk assessment methods recently becoming well constrained.	Many studies, particularly in recent years, with a focus on hazard assessments relating to BoP region and TVZ overall.	Scott, 2010; Deligne et al., 2020; Fitzgerald et al, 2022; Tonkin & Taylor, 2022.	TVZ geothermal fields mapped by GNS and others.	Difficult to account for all manifestations of hazards and their locations. **	Hazard mapping can use existing geothermal field spatial extents. Consider updates when new information becomes available.
3. Caldera Unrest	Ōkataina Volcanic Centre; Rotorua Caldera; Tūhua (on the island only)	Physical processes are well constrained (there are many types). Significant research exists for major active calderas globally.	Several papers exist that document the unrest within the TVZ, although mostly focused at TVC, with limited work on OVC.	Johnston et al., 2002; Scott, 2010; Potter et al., 2012; Potter et al., 2015a; Potter et al., 2015b.	Geological maps outlining caldera structural margins. By GNS and others.	Limited record of unrest at OVC – difficult to accurately forecast due to this lack of information. **	No further mapping required. Hazard mapping can use existing caldera spatial extents.

						Gaps and Methods to Fill Them	
Hazard (in Priority Order)	**Relevant Volcanic Centres**	**Literature Review (NZ and Global)**	**BoP Region (and NZ)**	**Key Hazard Assessment References**	**Maps**	**Information and Mapping Gaps**	**Sourcing Method/Work and Suggested Entity to Conduct.**
4. Pyroclastic Flows	Ōkataina Volcanic Centre; Pūtauaki; Tūhua (over-water); Rotorua Caldera.	Physical processes and models are reasonably well constrained. Hazards are well constrained. Risk assessments are less constrained.	Studies relating to BoP focused around OVC and Rotorua calderas. Mostly research on historic deposits. Most research focused on Taupō and Taranaki.	Nairn, 1999; Spence et al., 2004a, 2004b, 2007; Jenkins et al., 2013; Cole et al., 2015; Tierz et al., 2018.	Geological maps showing deposit (ignimbrite) extents (e.g., GNS). Maps within Nairn, 1999 (and possible GIS datasets).	Limited assessments for BoP volcanoes (OVC). Mapped deposits may not fully capture the spatial extent of hazards.	**Sourcing Method:** Determine if hazard can be adequately modelled and mapped. Conduct pyroclastic flow modelling. Key outputs required are runout distances and spatial extents. Maximum extent of flows. **Who:** GNS or other qualified body.
5. Lahars and Lake Break-out Floods	Ōkataina Volcanic Centre; Pūtauaki; Rotorua Caldera (unlikely).	Physical Processes and models are well constrained. Hazards well constrained. Risk assessment methods reasonably well constrained.	Lahar assessments are primarily focused on Ruapehu and other cone volcanoes (Tongariro, Ngauruhoe). Some research into break-out floods for OVC.	Neall, 1996; Hodgson and Nairn, 2004; Lecointre et al., 2004; Manville et al., 2007.	Nairn, 1999. Hodgson and Nairn, 2004; Manville et al., 2007.	Generally limited record of lahars within the BoP region. This may be a result of the limited research conducted.	**Sourcing Method:** Conduct lahar flow modelling. Key outputs required are the rivers and lakes that might be affected, maximum runout extents, and levels (thickness) of flows and their deposits. **Who:** GNS, NIWA or other qualified body.
6. Landslides, Debris Flows and Debris Avalanches	Ōkataina Volcanic Centre; Pūtauaki	Physical processes and models well constrained. Hazards well constrained. Risk assessment methods less constrained.	Assessments are primarily focused on the major cone volcanoes (Tongariro, Ngauruhoe, Ruapehu, Taranaki). Limited in the BoP region.	Voight and Elsworth, 1997; Tost et al., 2014; Harnett and Heap, 2021; Kereszturi et al., 2021.	Mapping of geological units. Some mention of units produced by debris and avalanche flows within Nairn, 1999.	Limited literature and/or assessments for BoP volcanoes (e.g. OVC, Pūtauaki).	**Sourcing Method:** Conduct landslide vulnerability assessments for volcanic flanks during non-eruptive periods. Key outputs required are maximum runout extents and the directionality of events. **Who:** GNS or other qualified body.

						Gaps and Methods to Fill Them	
Hazard (in Priority Order)	**Relevant Volcanic Centres**	**Literature Review (NZ and Global)**	**BoP Region (and NZ)**	**Key Hazard Assessment References**	**Maps**	**Information and Mapping Gaps**	**Sourcing Method/Work and Suggested Entity to Conduct.**
7. Lava Flow	Ōkataina Volcanic Centre; Pūtauaki	Physical processes and models well constrained. Hazards well constrained. Risk assessment methods well constrained.	Limited studies specific to the BoP. Most of the assessments in NZ are focused on the Auckland Volcanic Field. Many useful resources available for lava hazards and flow modelling.	Kereszturi et al., 2012; Dietterich et al., 2017; Tsang, 2020.	Mapping of geological units. Nairn, 2002.	Limited assessments for BoP volcanoes (e.g., Pūtauaki, OVC).	**Sourcing Method:** Conduct lava flow modelling. Key outputs required are locations of flows (i.e. identify lava flow paths) and maximum runout extents. **Who:** GNS or other qualified body.
8. Volcanogenic Tsunami	Tūhua; Whakaari Syn-eruptive or from flank collapse.	Physical processes and source mechanisms are well constrained. NZ source volcanoes generally well constrained.	Limited, typically older assessments. Distal volcanoes (e.g., Kermadec volcanoes) have had more research.	de Lange and Prasetya, 1997; Berryman, 2005.	No volcanogenic-source-specific maps found.	Historical record in NZ contains no local volcanic events. Limited by poor understanding of Tūhua and Whakaari eruption history.	**Sourcing Method:** Conduct tsunami modelling***. This could be based on eruption volumes related to AEPs (e.g., tsunami extent based on eruption volume attributed to a 0.2% AEP eruption). Key outputs required are maximum height of tsunami and areas of coastline affected. **Who:** NIWA, GNS or other qualified body.

Notes:

** It is noted that major eruptions within the TVZ often occur at rates of about one in every 1 to 3 thousand years. These intervals could be considered as alternative likelihood(s) (e.g., AEP) for the hazards that are typically associated with large eruptions (pyroclastic flows, lahars and break-out floods, and volcanogenic tsunamis).*

*** Methods should allow for updates based on future information changes.*

**** The Beneath the Waves Project (GNS) indicates that volcanogenic tsunami assessments and models may be produced by their research.*

3. SUMMARY OF RISK ASSESSMENT METHODS

The disruption, damage and economic loss from volcanic eruptions can be considerable, although they are often hard to quantify (Sparks et al., 2013). Volcanic hazard and risk assessments are used to evaluate the potential hazards and subsequent consequences that could result in injury and/or death to people, and damage and/or disruption to assets and services (Wilson et al., 2014). Risk assessments typically involve a combination of hazard, exposure and vulnerability assessments aimed at determining the nature and extent of risk to a site, area or region of interest and identifying, avoiding or minimising losses (Wilson et al., 2014). Evaluation of volcanic risk is extremely complex, since it can encompass multiple different hazardous natural phenomena occurring across various spatial boundaries.

Assessments can be qualitative or quantitative, or a combination of both depending on the nature of available data and the purpose of the assessment. More recently, quantitative assessments have been preferred due to higher precision in comparing between risks, however, the results of such assessments are often expressed using qualitative descriptions such as ‘high risk’, ‘medium risk’ or ‘low risk’ to allow more effective communication to non-scientific audiences.

A good comparison can be found with earthquake risk assessments, where there are well established quantitative studies that estimate damage, disruption and casualty impacts which have informed the establishment of robust seismic building codes. The field has well-established methods for post-earthquake building assessments and for deriving fragility functions to probabilistically estimate structural damage (Wilson et al., 2014). Other natural hazard fields have employed similar empirical approaches to earthquake assessments but are typically less well defined. As a field, volcanology trails behind earthquake risk assessments but may be on par with other fields such as landslide and tsunami risk assessment (Wilson et al., 2014).

International Organization for Standardization (ISO) has a published standard, ISO 31000:2018.

Risk management — Guidelines. It is noted that this standard has been utilised by the BoPRC RPS. This provides a detailed approach to manage any risk that organisations have and is an appropriate prompt to utilise as the foundation to the risk assessment method.

Hazard Assessment Methodologies

Hazard assessment approaches should incorporate hazardous volcanic phenomena probabilities and their spatial extents. This can be achieved using a number of different methodologies and analyses software. A regional volcanic hazards study should implement a “long-term” style assessment methodology and software that supports land use planning and community preparedness. Probabilistic hazard assessments should be considered as a preferential option (over deterministic or scenario-based) as they more fully capture the varied nature of eruptions and their uncertainties (e.g., the number of variables as inputs and the accounting for the limited understanding of volcanic systems). A suite of quantitative software models that can model individual volcanic phenomena are available (e.g. tephra fall, lava flows, lahars) as well as a smaller number of integrated hazard assessment models that consider multiple hazards across a large spatial region.

The reader is directed towards Wild et al., (2020) for an extended discussion and use of workflow methodologies for determining the most appropriate method depending on the exact purpose of the study and resources available.

Exposure Assessment Methodologies

Exposure assessments are an important part of risk assessments. They quantify the exposure of various elements (e.g., population, property and infrastructure) within a hazard zone which have the potential to be impacted (Wild et al., 2020). Exposure can be assessed at a range of scales from site-specific through to regional, although there is an inverse relationship between the level of detail and the size of the area being studied (Wilson et al., 2014), and considerations must be made in this regard. Assessments should make use of existing asset inventory data sets (e.g., asset databases held by local and regional authorities). These data sets may require supplementation through field investigations or remote sensing (Wilson et al. 2014; Wild et al., 2020).

Additional information can be added to datasets to better characterise asset vulnerability, for example, a building's construction material or occupancy numbers. If data is limited, exposure inventories could be bolstered by applying inferences, for example an unknown attribute such as building occupancy can be estimated based on known building size and use types (commercial, light industry etc.). Assessments should consider how multiple exposed elements interdepend on one another. For example, a complex suite of interdependencies can develop between different sectors such as healthcare, infrastructure, transportation and emergency response. Network models can be developed to represent these relationships and allow for the assessment of loss of service or impact to downstream elements due to damage or impact to upstream elements (Wilson et al., 2014; Wild et al., 2020).

Vulnerability Assessment Methodologies

Vulnerability assessments aim to determine the characteristic of an element (e.g., buildings, infrastructure) that makes it susceptible to the effects of a hazard (UNISDR, 2009). Vulnerability assessments of buildings are reasonably well established, and are used to identify buildings that may benefit from mitigation measures and support development of improved construction guidelines for new buildings (e.g., Jenkins et al., 2014). Vulnerability assessments for critical infrastructure systems and components, by comparison, are poorly established, with the majority of assessments only qualitative in nature (Wilson et al., 2012). Importantly, the interconnectedness of infrastructure systems means that the damage or disruption to them likely to have a greater impact on society than building damage (Wilson et al., 2012; Jenkins et al., 2014).

For further information regarding development of volcanic vulnerability methods and a discussion of recommendations and challenges, the reader is referred to Wilson et al. (2014).

Volcanic Hazard and Risk Assessment Resources

Key resources outlining various methodologies are outlined in Table 17 and some New Zealand experts (far from exhaustive) are mentioned in Table 18.

Table 17. Some Useful Hazard and Risk Resources, Guidance Documents.

Resource	Type	Comments
International Organization for Standardization, 2018	Standard	ISO 31000:2018 Risk management — Guidelines This is a high-level guideline on managing risk that can be utilised by any organisation and is not specific to a particular activity or item.
Wild et al., 2020	GNS Report	Frameworks to support the selection hazard, exposure and vulnerability for volcanic impact or risk assessments.
Wilson et al., 2014	Journal article	An in-depth review of the impacts of volcanic hazards to infrastructure. Many useful references within.
Wilson et al, 2012	Journal article	A summary of volcanic ash impacts on critical infrastructure.
Jenkins et al., 2014	Journal article	Methodologies for probabilistic assessments of regional ash fall hazard.
Weir et al., 2022	Journal article	Presents a framework for the development of multi-hazard, multi-phase volcanic eruption scenario suites.

Mead et al., 2022	Journal article	Present a probabilistic volcanic hazard assessment for Taranaki National Park infrastructure close to Taranaki Volcano.
Bebbington et al., 2018	Journal article	National-level long-term eruption forecasts by expert elicitation.
Wilson et al. 2017	Journal article	Infrastructure vulnerability for tephra fall.

Table 18. Useful Volcanic Hazard and Risk Assessment Contacts in New Zealand.

Contact	Organisation/Role
Thomas Wilson	Chief Science Advisor, National Emergency Management Agency (NEMA) and Professor of Disaster Risk and Resilience at University of Canterbury.
Alec Wild	AON, Risk Consultant.
Richard Woods	GNS, Principal Advisor Risk Reduction and Resilience. RiskScape.
Josh Hayes	GNS, University of Canterbury, Natural Hazard and Risk Scientist/Modeller.

4. VOLCANIC HAZARD MAPPING RECOMMENDATIONS

Hazard maps are essential for understanding what locations are subject to volcanic hazards and the risks posed. They combine many types of information into a concise, visually digestible graphic that can be shared across many types of media and are therefore often used in land-use planning and crisis communication.

Visual representation of hazard information on a map can influence the way that people engage with the information, as well as the messages that people take away, and decisions they make. (Thompson et al., 2017b). Mapping should help guide decisions about where to locate critical infrastructure and human settlement (e.g., avoid development in high-risk areas) and other mitigation measures that might be appropriate (Becker et al., 2010). Developing a volcanic hazard map is challenging, as it requires consideration and integration of a vast array of information into a single graphical image (or suite of GIS layers), including past eruptive activity, topography, weather patterns, any available modelling data, time frames for volcanic hazard analyses, quality of data, and associated uncertainties, as well audience-specific map elements and design features (e.g., Thompson et al., 2017b). This challenge is compounded when the systematic development of a suite of hazard maps across an entire region is called for, given that there is typically a wide range in quantity and quality of information available for each volcano (Lindsay and Robertson, 2018).

Table 19 below outlines the target level of detail required for mapping targeted towards the BoPRS RPS requirement to map areas susceptible to hazards (Policy NH7A). This includes mapping a set of likelihood scenarios as set out in Appendix L of the RPS (if possible). This mapping work can be stage-based on priority of need for risk reduction/management (for example, highest priority of mapping could be given to areas where the largest population centres overlap with a hazard).

Some useful resources, guidance documents and examples of long-term land-use focused maps are provided in Table 20. A short list of key contacts within New Zealand is provided in Table 21. Recommendations for creation methods and design elements for volcanic hazard maps are provided in Table 22.

Table 19. Recommended Hazard Mapping to be Undertaken, and Target Level of Detail Required.

Volcanic Hazard	Mapping Priority (High to Low) *	Existing Hazard Models and maps?	Hazard Map Gaps	Method to Use	Comments
Ashfall	High Priority	Probabilistic models for OVC, Taupo. Previous ashfall mapping.	Require region-based RPS scenarios for 0.1%, 0.2%, 0.005% AEP. There is no probabilistic ashfall for Tūhua, Whakaari, Pūtauaki.	Probabilistic ashfall zones based on RPS AEP scenarios.	This is the hazard that should be most prioritised. Mapping may consider informing ash load (to building roofs etc.) and other factors to assist in hazard mitigation.
Pyroclastic Flows	Low priority. Medium if historic flows overlap population centres.	None. Geological mapping of past deposits exists.	Future flows may not follow previous paths. Dependant on magnitude of eruption – to be determined by probabilistic methods.	Deterministic (scenario based on past activity) if probabilistic methods are unfeasible. N/A if geological maps will suffice.	Difficulty in predicting the extent of future events. If OVC could cause flows over towns – there may be a need for additional mapping above geological units.
Lava	Low priority. Medium if historic flows overlap population centres.	None. Geological mapping of past deposits exists.	Future flows may not follow previous paths. Uncertainty of vent location/lava source within OVC.	Deterministic (scenario-based) or N/A if geological maps will suffice.	If lava could flow through towns – there may be a need for additional mapping above geological units
Debris Flow and Avalanche	Low priority. Medium if historic flows overlap population centres.	None. Geological mapping of past deposits exists.		Deterministic (scenario-based) or N/A if geological maps will suffice.	Possible significant overlap with ‘non-volcanic’ landslip hazards within volcanic areas.
Lahar and Break-out Floods	Low priority.	Hodgson and Nairn, 2005; Manville et al., 2007	No probabilistic models/maps.	Deterministic (scenario-based) on mapped deposits (e.g. Tarawera River during Kaharoa Eruption) if probabilistic methods are unfeasible.	It may be that meteorological flooding hazard zones are able to capture the mappable lahar hazard areas.

**Mapping Priority informed by Table 15*

Note. Mapping of geothermal and caldera unrest hazards are not included as any mapping would utilise currently existing mapped geothermal field and caldera margin boundaries.

Table 20. Useful Mapping Resources, Guidance Documents and Mapping Examples. See References for Additional Material.

Resource	Type	Comments
IAVCEI Hazard Mapping Working Group	Website: Link	Many resources and examples. A guidance book is in production. Land-use specific map dataset: Link.
Auckland Council Hazard Viewer	Website: Link	Online map showing the extent of volcanoes around the Auckland region. Shows current vents, past volcanic deposits and buffer zones.
National Civil Protection Plan Campi Flegrei	Interactive online map.	Example of an online map. Website: Link.
California's Exposure to Volcanic Hazards, (Mangan et al., 2019)	Report.	Multiple maps illustrating multiple regional hazards and volcanoes. Infrastructure also mapped. Link to resource.
Lindsay and Robertson, 2018	Journal article.	Outlines regional hazard mapping in Lesser Antilles. Multiple mapping recommendations provided.
Thompson et al., 2017b	Book chapter.	Useful background and visual considerations for hazard maps.
Thompson et al., 2015b	Journal article.	Mapping of probabilistic hazards and engagement with users. Based on Ōkataina eruption ashfall models. Multiple mapping recommendations provided. A useful survey is included as a supplementary file.
Calder et al., 2015	Book chapter.	Useful background material.
Southern Peru (regional), Chile-Peru, Peru (Samaniego et al., 2003).	Print map.	Example of a regional volcanic hazard map. Website: Link.

Table 21. Useful volcanic hazard mapping contacts in New Zealand.

Contact	Organisation/Role
Danielle Charlton	GNS, Hazard and Risk Management Scientist.
Mary-Anne Clive (Thompson)	GNS, Team Leader - Hazard and Risk Social Science.
Graham Leonard	GNS, Principal Scientist.
Jan Lindsay	University of Auckland, Professor.

Table 22. Important items of consideration and recommendations relevant to volcanic hazard mapping and communication.

Mapping Aspect	Recommendations
Seek Expert Guidance	Prior to beginning any mapping, seek out expert guidance and advice. The contacts above are at the global forefront of volcanic hazard map creation and communication.
Intended Audience and Purpose	The primary users are councils and land-use planners, however, other potential users should be considered (e.g. emergency agencies and the general public). Print and/or digital/online formats should consider ways to cater to different audiences.
Audience Needs and Perspectives	Consider the audience needs and perspectives (how the information might be used, read, understood, and applied). Ensure the maps are understood by their target users and consider these needs when making design choices.
Audience and Community Engagement,	Engage with target users to explore how they understand and derive meaning from the map(s). Constructive multi-way dialogue to help that important information is communicated in a transparent and trusted way. Consider adopting participatory, or community-based/co-creation methods. These often include collaborative workshops between scientists and community members (including local Iwi).
Temporal Scales	Map developers should implement methods targeted towards long-term-style mapping. We note that these maps may be used in some capacity to inform short-term uses – and this should be considered in their development.
Spatial Scales	Regional-scale hazard maps often depict the hazards from many volcanoes and cannot display the same level of hazard detail as more local-scale maps. It is important to fully capture the extend of all of the hazards mapped, however this can be difficult because of the various spatial extents of hazards, e.g. ashfall (whole region) vs debris avalanche (local). A digital/online interactive map capable of displaying multiple spatial scales should be prioritised.
Types of, and Number of Hazards Displayed	Displaying multiple hazards may be difficult on printed maps but is much more feasible with a digital/online dataset (where layers can be turned on and off). Some hazard processes are more commonly described in text than displayed on a map as part of hazard zones e.g. fire, lightning, and geothermal hazards (particularly for secondary hazards). This could be considered.
Zonation of Hazards	Consideration of the zonation methodology is important (how different hazards are represented and what dividing lines are used). Thompson et al.,2015b discuss this in-depth for probabilistic data, and include useful results of a survey looking into different display options and their effectiveness.
Mapping Offshore/Marine Hazards	Most hazard maps only show hazard extents on-land. Eruptions may generate hazards that affect the marine environment to varying degrees (Tūhua and Whakaari especially). How to depict hazards as they extend beyond the shoreline should be explored.
Cartographic and Design Elements	Design elements such as colour, symbology, data classification map content (including borders, landmarks etc.), and use of gradational shading can significantly affect the way in which users interpret information on a map. A few points are provided here, and the reader is directed towards the references provided for further information. • Select colours that are easy to understand. Consider visual impairment and/or colour-blindness. • Use different colours or colour-combinations/themes across different types of hazard maps if multiple types are produced. • Consult potential map-readers when selecting the base map or choosing what to show. • Explore the effectiveness of showing hazard zones as gradational boundaries or as discrete lines.
Languages Displayed	Maps should implement English and Te Reo, with other languages also considered based on the intended audience (e.g. it is possible the maps may be used for tourism even if this was not their intended use). Additional languages could be easily supplemented in digital format, however on print versions spatial constraints make including multiple languages more difficult.

5. RECOMMENDATIONS FOR THE INCLUSION OF MĀTAURANGA MĀORI

Traditional knowledge or *Mātauranga Māori* can contribute to understanding volcanic hazards and risks, especially when the geological or written history of a volcano is limited (Cronin and Cashman, 2008). Indigenous communities often have their own understanding and ways of articulating a volcano's processes. They may also have traditional systems of land use planning and emergency management practices. Opportunities exist to better utilise traditional knowledge and practices to address volcanic risk (Becker et al., 2010).

Here in Aotearoa, the knowledge has become reasonably localised being held by those *iwi* and *hapū* who live in close proximity to active volcanic zones. Tuwharetoa and Te Arawa iwi in particular, whose *rohe* includes the Volcanic Plateau in the central North Island. But also, the coastal iwi of Whakatōhea and Ngāti Awa who have an ancestral relationship with Whakaari, White Island. However, on a different scale, other iwi have geothermal springs and other features of volcanic origin such as fumaroles within their rohe. The use of the waters for healing and washing – not to mention the use of geothermal steam and hot water for cooking - are well documented.

Mātauranga Māori refers to the body of knowledge originating from Māori ancestors, passed on via oral traditions, including the Māori worldview and perspectives, Māori creativity and cultural practices. It can be described as an expanding knowledge continuum containing both old and new Māori knowledge, building on a foundation of traditional wisdom and practices (MoRST, 2007).

Recommendations for Integrating Mātauranga Māori in Future Hazard and Risk Mapping

Seek historic knowledge or stories of volcanic activity and impacts

Consider investigating or surveying local Māori for history and stories about volcanic hazards. Any knowledge found could be a useful addition, leading to new information, infilling of existing knowledge gaps, or leading to new knowledge gaps being identified. Information could be integrated into a database (if one doesn't already exist) that could be added to over time. For example, if local oral traditions indicate an area should not be inhabited due to volcanic or geothermal danger, this may aid the hazard mapping knowledge base.

Foster meaningful, respectful, and mutually beneficial relationships with iwi, hapū, marae and other Māori stakeholders

This can be achieved by

- Engagement with relevant iwi and hapū from the onset.
- Participatory or co-creation/development of hazard maps and risk assessments.

Production of a Tikanga Document

Production of a Tikanga (such as RNC Urban Theme, 2020), akin to a mission statement that outlines the values and commitments of the study from the outset. This could be focused specifically on Mātauranga Māori but could also serve as a value guidance document for all aspects (scientific and social etc.) of conducing the next stages of the BoPRC volcanic hazards project.

Consider relevant Iwi and Hapu Management Plans (IHMPs)

Iwi and Hapū Management Plans (IHMPs) are legislated under the Resource Management Act 1991. They provide a desktop resource a researcher can use as a starting point to inform research and engagement with iwi and hapū. IHMPs are highly valuable documents for envisioning how specific research expertise may be of interest to iwi—they outline iwi or hapū priorities, they have environmental and resource-based objectives, methods, and actions. In addition, they often outline the preferred engagement process. Despite their availability, Keiser (et al., 2020) found that only 22% of natural hazard researchers surveyed used them in their research process, and subsequently provide some recommendations for improving engagement with IHMPs.

Table **23** outlines some relevant resources relating to integrating Māori knowledge into natural hazards. Only limited publications have been produced relating specifically to volcanic hazards – and these are included. Table 24 provides useful researchers and contacts currently working within this space.

Table 23. Resources, Guidance Documents and Examples of Mātauranga Māori Integration. See References for additional materials.

Resource	Type	Comments
Resilience to Nature's Challenges - Whanake te Kura i Tawhiti Nui Theme	National Science Challenge - Research Programme.	This is a theme of the RNC project with the aim of creating a new body of mātauranga that will inform frameworks, tools, models and strategies to provide resilience benefits for tangata whenua and wider Aotearoa New Zealand.
MoRST, 2007	Report	Large report on many aspects of Mātauranga Māori.
Saunders and Kaiser, 2019	GNS Report	Inclusion and use of natural hazard information in iwi and hapū management plans. Uses case studies from the Bay of Plenty.
Gabrielsen et al., 2018	Book chapter	A reflection on indigenous community volcanic event management, communications and resilience.
Pardo et al., 2015	Journal article	Bridging Māori indigenous knowledge and western geosciences in active volcanic regions.
Kaiser et al., 2020	GNS Report	Discusses the role of iwi and hapū management plans for natural hazard research design.
Kenney, 2018	Journal Article	Collaborative governance within indigenous disaster management settings in Aotearoa
Wilkinson et al., 2020	Journal article	Discusses existing frameworks, case studies, and provides recommendations for incorporating Mātauranga Māori.
Hikuroa et al., 2011	Journal article	Integration of indigenous knowledge and science
Tapuke, 2017	Thesis	This qualitative study maps two waiata koroua regarding the Tarawera Eruption, 1886. Demonstrates the use of waiata to communicate volcanic risk and readiness.

Table 24. Useful contacts for integration of Mātauranga Māori in New Zealand volcanic hazard studies.

Contact	Organisation/Role
Daniel Hikuroa	University of Auckland, Associate Professor, Faculty of Arts, Māori Studies, New Zealand
Jonathan Procter	Massey University, School of Agriculture and Environment, Professor in Natural Hazards
Lucy Kaiser	GNS, Māori Social Scientist
Wendy Saunders	EQC, Principal Advisor, Land use planning
Christine Kenny	Massey University, Joint Centre for Disaster Research, Māori disaster risk reduction and emergency management
Acushla Dee Sciascia	Massey University, School of Agriculture and Environment, Senior Research Officer

Kristie-Lee Thomas	University of Canterbury, PhD Researcher
Hautapu Baker	Tauranga City Council Kaitohutohu Hapori Māori (Māori Community Engagement Advisor).

6. SUMMARY

The Bay of Plenty region is one of the most volcanically and geothermally active areas in the world. A large number of features exist, each with the potential to generate a wide range of hazards that could negatively impact the region. This report serves as a scoping document with the purpose of collecting and aggregating the information relevant for use in future volcanic and geothermal hazard susceptibility mapping and risk assessments. The report provides a summary of the current state of scientific knowledge and data that are available, and assesses this information in consideration of the BoP Regional Council's statutory obligations.

A priority list of volcanic hazards has been created, and a number of information gaps have been identified (discussed throughout the document) with recommendations to fill them suggested. A summary of resources for hazard and risk assessments, and some recommendations have been provided. A target level of detail for future volcanic hazard susceptibility mapping is included, with recommendations for creating and visualising maps also provided. Additionally provided are recommendations for the inclusion of Mātauranga Māori in any future work.

A summary of key findings and recommendations are included below:

Key Findings:

- Tūhua/Mayor Island and Pūtauaki/Edgecumbe have relatively low amounts of available information. Their eruptive histories are, for the most part, poorly constrained and hazard assessments are the most limited within the region. In contrast, the Ōkataina Volcanic Centre and Whakaari/White Island are relatively well understood, with much more complete recent geological histories. In the case of Ōkataina, a number of varying hazard assessments have already been undertaken.
- The Ōkataina Volcanic Centre represents the greatest source of hazards for the region. This due to its proximity to Rotorua and Kawerau, its potential to produce a wide range of hazards, and it potential to generate large eruptions with regional impact. Whakaari/White Island and Tūhua/Mayor Island represent the lowest hazard, primarily because of their distance offshore.
- Volcanoes outside of the BoP region with the potential to generate hazards for the BoP include Taupō, Ruapehu, Tongariro, Ngauruhoe and Taranaki. The hazard is dominantly that of ashfall. Taupō represents the greatest hazard due to its closer proximity to the region and its potential to produce (very) large eruptions.
- Numerous inactive caldera systems are present throughout the centre of the TVZ. Two of these are located within the BoP region. These systems are unlikely to erupt in the future, however, hazards associated with geothermal activity or caldera unrest are more likely.
- Numerous geothermal fields exist throughout the BoP region, mostly centred around the Rotorua district. Hazards typically occur much more frequently, but are of much lower consequence than volcanic ones, and are primarily restricted to the boundaries of the geothermal fields.
- A number of national scientific research programmes focused on volcanic hazards are ongoing and are a useful source of information and resources. Two recently started programmes, *Beneath the Waves* and *CALDERA* are directly related to BoP volcanoes. Their outputs are likely to fill some of the gaps identified in this report and may provide new hazard maps and models.

Recommendations

- A volcanic hazards priority list is provided, with ashfall considered the most important due to its likelihood of occurrence and potential to impact on a region-wide scale. Geothermal and caldera unrest are considered the next most important, primarily due to their frequency of occurrence. Other RPS Policy NH 7A hazards are placed lower on the list due to their lower occurrence frequencies (typically related to only the larger eruptions) and generally lower spatial extents (local to district scale). It must be noted however, that these hazards (pyroclastic flow and lahar, for example) have the potential to be highly consequential in the areas that are affected.
- Ashfall should be mapped using probabilistic methodologies akin to those produced by Hurst and Smith, 2010. Common return periods used currently by the BoPRC RPS for volcanic hazards (i.e. primary and secondary likelihoods specified in RPS Appendix L) should be used. Consideration should be made to also implement return periods of between 1,000 and 3,000 years – representative of the general periodicity of large rhyolitic eruptions (e.g., post-caldera eruptions from Ōkataina). Models and maps produced should implement a scale appropriate to the BoP region (rather that the entire North Island in the case of Hurst and Smith, 2010).
- For mapping of other volcanic hazards, it may be that deterministic (scenario-based) models and maps are more appropriate. These could be based on previous events and the geological units that were deposited during them.
- Future hazard mapping studies of caldera unrest may be considered to demarcate the hazard susceptibility area and currently available information may be utilised to inform the mapping. Caldera boundary margins (geological and structural) can be used for caldera unrest. It is noted that there is a minor likelihood that hazards may extend beyond these spatial extents.
- Recommendations around stylistic and visual mapping choices are provided. See section 4 for a summary.
- A summary of hazard and risk assessment methodologies is proved. See Section 3 for details. Any future hazard or risk methods employed should be targeted towards long-term, regional-scale, multi-hazard assessments where possible. Several software suites designed to conduct these styles of assessment are discussed, with the reader directed to Wild et al., 2020 for a workflow to aid in selecting the most applicable.
- A number of recommendations for the inclusion of Mātauranga Māori in future mapping and assessment studies are provided. Key among these is to engage early with the relevant iwi and hapu groups (which may be different for each volcano) and to consider co-creation methods throughout any future projects.

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7. REFERENCES

This section serves two purposes. The first purpose is to provide a list of the citations used in this report. The second use is to provide additional resources that may not have been cited but are considered useful for future hazard and risk assessments within the BoP region. Some references are specific to the New Zealand context while others are international examples. The list is divided into sections following the format of the report (individual hazardous phenomenon and then volcanic centres, etc.) with the intention that this format is more useful to navigate to a specific set of references and/or resources.

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APPENDIX A: ADDITIONAL INFORMATION – VOLCANIC PROCESSES AND HAZARDS

Appendix A provides additional information for the volcanic hazards outlined in BoPRC RPS NH 7A.

Pyroclastic Flows/Pyroclastic Density Currents (PDC)

Pyroclastic Flows (or sometimes Pyroclastic Density Currents, PDCs) typically occur after the collapse of a large eruption column, from phreatomagmatic eruptions, or through the gravitational collapse of lava domes and flows (Cole et al., 2015). They travel away from the volcano at speed across the land in an outwardly expanding, thick cloud of ash, rock and volcanic gas (Branney and Kokelaar, 2002). They are potentially the most dangerous volcanic hazard due to their high emplacement velocities, great temperatures and transport capacity, and their overall destructive capacities (Burgisser and Bergantz, 2002). They travel at hundreds of kms per hour and can travel distances of over 100 kilometers. The deposits of pyroclastic flows are called ignimbrites. The material transported by a flow can be so hot (600-700 °C) and thick that the material welds together (a welded ignimbrite) (Cole et al., 2015).

Pyroclastic flows behave as suspension currents, and range from highly dilute to highly concentrated, and from highly turbulent to laminar. Their mobility and runout distances depend on the initial momentum of the flow, particle concentration, temperature, and the flow regime (Valentine and Fisher, 2000). Topography plays a large role. Flows are typically restricted to the main valleys and gullies around the volcano but may also cover larger areas depending on parameters such as the initial density, temperature, and velocity. Unlike lava flows, the main impact on objects is exerted by dynamic pressure which is directly dependent on their density and velocity (Spence et al., 2004a, 2004b). Pyroclastic flows can cause asphyxiation, burial, and incineration or, as occurs with lavas, may mix with surface water (or snow and ice melt) to form secondary explosions and/or destructive lahars and floods that affect valleys further downstream (Wilson and Houghton, 2000).

Some New Zealand settlements are located within pyroclastic flow or surge hazard areas, for example, some development around Lake Tarawera and Lake Okareka is located within a mapped pyroclastic flow zone (Johnston and Nairn, 1993).

Lava Flows

Lava flows are streams of molten rock (Kilburn, 2000). Flows come in many shapes and sizes and have a wide range of surface morphology (pahoehoe, aa, blocky, etc.), whose differences are mainly controlled by variations in magma viscosity and supply rates. The distance they travel also depends on the viscosity of the lava, output rates, volume, slope steepness, topography and obstructions in the flow path (Kilburn, 2000). The principal constraint on lava emplacement is topography and flows will tend to invade the lowest lying areas (Griffiths, 2000). Differences in viscosity, effusion rates and ground slopes will determine the initial thickness of a lava flow and the total distance it extends. When lava flows are emplaced at relatively low velocities they do not represent a significant hazard for people or animals, however, they are highly hazardous for property and infrastructures due to their highly destructive capacity—the bulldozer effect—and their high temperatures (Tsang et al., 2020).

The more viscous magmas (andesite, dacite, rhyolite) of the TVZ in New Zealand form lava flows which tend to be shorter and thicker than the typical Hawaiian-style basaltic lava flows (Leonard et al., 2010). Much lower effusion rates result in lava flows emplaced at much lower velocities (e.g., several hundreds of meters per hour). On occasions, the effusive emplacement of viscous magmas may give rise to the formation of lava domes over the vent area or even almost solidified spines or plugs extruding from eruption conduits (Leonard et al., 2010). These viscous flows are prone to failure and collapse, forming pyroclastic or debris flows (e.g. block and ash flows).

Landslides, Debris Flows and Avalanches

Debris flows (and volcanic landslides) form during the sudden collapse of an unstable portion of a volcano (Voight and Elsworth, 1997). This portion may be part of a growing dome (Harnett and Heap, 2021; Carr et al., 2022) or an older part of a flank of the volcano (Voight and Elsworth, 1997). Masses of rock and soil fall, slide or flow very rapidly down the slopes under the force of gravity. Collapses range in size from small rock falls to very large landslides, or debris avalanches when an entire volcanic flank collapses, e.g. Taranaki (Cronin et al., 2021). Typically generated on the steep slopes that characterise many large volcanoes, flows are often highly mobile and can run for several tens of kilometres (Lerner et al., 2019). Collapses most frequently occur during volcanic activity, but sometimes occur in non-eruption periods. They can be triggered by eruptions, earthquakes, or by long-term exposure to weathering of the material that make up the volcano. Large flows, such as debris avalanches are highly destructive and can often produce indirect hazards including lahars that threaten populated regions downstream. Steeper sided volcanoes such as Ruapehu (Kereszturi et al., 2021), Taranaki (Cronin et al., 2021) or Pūtauaki/Edgecumbe (Hewitt, 2007) have the potential to create significant debris flows.

Lahars and Lake Break-Out Floods

Lahars are discrete, rapid, gravity-driven flows of saturated, high-concentration mixtures containing water and solid particles of rock, ice, wood, and other debris that originate from volcanoes (Neall, 1996, Vallance, 2000). Flows can vary in terms of the amount of solid particles they transport and range from very dense (lahars) to very dilute (hyper-concentrated flows). Lahars may be sourced from a crater lake, a dam collapse, heavy rainfall washing remobilising ash, or even condensation from water vapor in a pyroclastic flow. Although most lahars are triggered during or shortly after volcanic eruptions, they can occur days, weeks or even years after an eruption has finished (Vallance, 2000; Tilling, 2005). These kinds of 'secondary' lahars can be initiated without warning, such as the gravitational collapse of structurally weakened volcanic edifices, large earthquakes, lake outbreaks, or extreme rainfall (Hodgson and Manville, 1999; Tilling, 2005; de Bélizal et al., 2013). A

The emplacement characteristics and mobility will depend on the flow density (e.g. lahar vs hyper-concentrated flow) (Vallance, 2000; Tilling, 2005). Lahars are a very destructive hazard. Extraordinarily large volumes of both unstable rock debris and water can be mobilised, with velocities of several tens of meters per second and traveling hundreds of kilometers from source (Vallance, 2000). Lahars are typically confined to the valleys and gullies draining the volcano.

Volcanic lakes are prone to rapid formation, modification, and destruction by eruption and post-eruption processes (e.g., erosion, sedimentation, tectonic uplift and/or subsidence) (Manville et al., 2007). Breaches of the barriers of these lakes can produce break-out floods that have catastrophic effects on the landscape (Manville et al., 2007). Break-out floods from intracaldera lakes are amongst the largest known floods on Earth and have been identified from both Taupō and Ōkataina calderas where they have likely followed the damming of valleys by large pyroclastic flows. Lake break-out floods at Lakes Taupō (following the 26.5 ka and 232 AD eruptions) and Tarawera have left large-scale erosional and sedimentary landforms that are comparable to catastrophic floods found globally (Hodgson and Nairn, 2000, 2004, 2005). Small scale, historical lake break-out floods at Lake Tarawera in AD 1904 and Crater Lake, Ruapehu, in AD 1953 and 2007, illustrate the hazards these phenomena present to life and property (Lecointre et al., 2004; Manville et al., 2007).

Ashfall

Ashfall is the most likely volcanic hazard to be experienced by communities in New Zealand. During explosive eruptions magma is fragmented and expelled into the atmosphere as pyroclasts or tephra (ash, lapilli, or bombs/blocks depending on the grain size). Larger fragments (bombs/blocks) fall back to the ground in the proximity of the volcanic vent, whereas finer fragments (lapilli and ash) are ejected into the atmosphere in an eruption column and carried away by the wind (Biass et al., 2016; Bonadonna et al., 2021). An eruption column, depending on its size and power, can propel fine particles 100s of meters to many 10s of kilometers in height

(Barker et al., 2019). The material is then transported by wind for distances of 10s to 1,000s of kilometers from source. The size of the area covered by a tephra fall depends on the magnitude (erupted mass) and intensity (eruption rate) of the eruption, and the wind strength and direction. Ashfall dispersal areas can vary in size from just a few 10s of metres, to 100s of thousands of square kilometers, and the largest eruptions can affect whole continents (Hurst and Smith, 2010; Jenkins et al., 2012).

Ash is typically less fatal and devastating than other volcanic hazards, however it can cause health problems for humans and animals, compromise water supplies, damage buildings and infrastructure, and disrupt supply chains (Jenkins et al., 2014). Significant destruction generally only results in areas that are affected by ashfall that is at least several centimetres thick, which causes roof collapses, interrupts power networks, disrupts infrastructure (water, waste-treatment, power, transportation, and communication systems) and damages or kills vegetation including crops (Nairn, 2002; Spence et al., 2005; Horwell and Baxter, 2006; Barnard, 2009; Wilson et al., 2007a, 2007b, 2009, 2012; Craig et al., 2021). A significant amount of noxious gases and other components carried by tephra can also generate hazards (Jenkins et al., 2014).

Caldera Unrest

Caldera unrest occurs when regional tectonic and/or volcanic processes cause magma and/or its fluids to interact with pre-existing rocks and subsurface fluids (Newhall and Dzurisin, 1988). A multitude of resulting phenomena can occur and have the potential to be hazardous – damaging buildings and infrastructure and causing negative economic and social impacts. Physical hazards during unrest include; volcanic earthquakes and tremor (in rare cases inciting severe shaking); deformation (ground movement) ranging from millimetres to metres of uplift or subsidence that can affect wide areas; changes to the volume, temperature and chemistry of fumaroles and springs and generation of steam eruptions (hydrothermal explosions) (Potter et al., 2015a, 2015b). Ground shaking and subsidence can cause building, structure and infrastructure damage or collapse, flooding and large waves or tsunamis (Potter et al., 2015a, 2015b). All of the above phenomena have occurred at Taupō caldera within the last 160 years (Potter et al., 2012, 2015a, 2015b) as well as many overseas calderas, e.g., Tenerife, Canary Islands (Martí et al., 2009) and Campi Flegrei, Naples (Barberi and Carapezza, 1996).

It is important to note that most unrest episodes at calderas do not result in an eruption, and most episodes do not result in significant damage to property or people. Many episodes show only one or two of the total range of features (e.g., earthquakes but no hydrothermal reactivation) and at varying levels of severity (Newhall and Dzurisin, 1988, Potter et al., 2012).

APPENDIX B: ADDITIONAL INFORMATION - ACTIVE VOLCANIC CENTRES

Appendix B provides additional information, context and geological history for the significant volcanic centres capable of producing hazards that could impact the Bay of Plenty Region. Some of the information presented here is duplicated within the body of the report.

Tūhua/Mayor Island

Tūhua/Mayor Island lies 35 km offshore and represents the above-surface peak of a 700 m high, 15 km wide shield volcano containing a 3 km wide caldera at its peak (Kósik et al., 2022). It has erupted on average once every 3,000 years for the past 130 ka (Houghton et al.,1992). Generally, 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 (Houghton et al., 1992). 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 Plinian fall activity, pyroclastic surge and flow activity, welded fall deposits, and both conventional and spatter-fed lava flows and domes (Buck et al., 1981; Houghton et al., 1992; Cochran and Cervelli, 2007). Lava flows and explosive eruptions including (sub)Plinian, strombolian and phreatomagmatic events occurred from 130 and 36 ka (Houghton et al., 1995). The oldest of three caldera-forming events occurred at about 45 ka. Between 33 and 8 ka activity consisted of lava domes, lava ponds and pumice cones.

Around 7.2 ka the largest known eruption occurred, producing a widespread air-fall deposit called the Tūhua Tephra (Kennedy and Froggatt, 1984; Wilson et al., 1995) with numerous pyroclastic flows that entered the sea on all sides of the island followed by caldera collapse. This may have generated tsunamis that impacted the mainland. The eruptive volume is estimated at >1 km^3 (Houghton et al., 1992). Substantial amounts of fall material fell on the North Island, with a maximum thickness of 70 cm occurring in the western Bay of Plenty, and 40 mm thickness recorded at Kaipo Bog near Lake Waikaremoana (Manighetti et al., 2003; Shane et al., 2006). The true extent of the dispersal of the tephra Tephra dispersal is still not fully known. For example, Manighetti et al., (2003) identified the Tūhua Tephra in a marine sediment core approximately 380 km SE from the source, and determined a reconstructed primary thickness of <5-10 mm.

Post-Tūhua Tephra activity has consisted of numerous lava flows and domes erupted within the caldera producing a dome complex. Ages for these flows (and hence the latest activity at the volcano) are poorly constrained. There is limited evidence to suggest that that at least one episode of dome growth occurred around 2.2 ka and that the most recent eruption may have occurred less than 1 ka (Buck, 1985; Houghton et al., 1995). Since human arrival to New Zealand, no activity or unrest is known to have occurred. Virtually no earthquakes at all have been located beneath the island in the past twenty years and our present understanding of the history of the volcano is therefore limited to what we can see on the island (Potter et al., 2012).

Whakaari/White Island

Located 50 km offshore from the Bay of Plenty, Whakaari/ White Island is New Zealand's most active volcano (Kilgour et al., 2021a, 2021b) and the northernmost volcano within the TVZ. Its summit of 321 m elevation represents the emergent peak of a much larger White Island Massif (Cole et al., 2000). Its edifice consists of two overlapping cones comprised of andesitic–dacitic lava flows and tephra with a large prehistoric eastwards sector collapse occurring about 3.5 ka creating a horseshoe-shaped, flat-floored crater breached to the sea to the southeast (Cole et al., 2000; Moon et al., 2009). The main crater (1.2 km × 0.4 km) is a complex of three older, coalesced craters.

Explosions at Whakaari are historically small and weak (Houghton and Nairn, 1991; Kilgour et al., 2021a). Activity primarily comprises phreatic (steam-driven) and phreatomagmatic (magma and steam-driven) eruptions, interspersed by occasional magmatic strombolian activity (small discrete explosive events) (Kilgour et al., 2021a, 2021b). A minimum of 32 small (VEI 1–3) phreatic and phreatomagmatic eruptions have been recorded since 1826 (Kilgour et al., 2021a). All historic activities have occurred within the western subcrater and the western part of the central subcrater (Houghton and Nairn, 1991). A small collapse of the main crater in 1914 formed a debris avalanche which killed 11 sulphur miners and may have entered the sea (Berryman, 2005). The latest significant eruption occurred on 9 December 2019 during a tourist visit to the island, killing 22 and wounding 25.

Knowledge of the early history of the volcano is severely limited. Two major episodes of cone growth with lava flows and explosive eruptions are identified, with 19 prehistoric eruptions documented with return periods ranging from 0.5 to 1.5 ka. These were mostly small magmatic eruptions that emplaced <0.1 km^3 lava flows. No lava flows have been erupted since ~3 ka (Cole et al, 2000).

Edgecumbe/Pūtauaki

Pūtauaki/Mount Edgecumbe (~800 m elevation) is a young, multiple vent andesite–dacite cone complex located onshore, 50 km east of Rotorua and three km east of Kawerau and near the southern boundary of the Kawerau Geothermal Field (Duncan, 1970; Carroll et al., 1997; Norling et al., 2016). The main cone forms the largest part of the complex and was created from series of lava domes and volcanic breccias (Carroll et al., 1997). A lava plug and two small craters occupy the summit. Previous work has identified two main eruptive episodes occurring at approximately 6 ka and 4 ka, with several periods of dome growth and collapse between ~8.3 ka and 2.4 ka formed by several nested lava dome complexes BP (Carroll et al., 1997; Nairn, 1999). Summit lavas are overlain by pyroclastic surge deposits and fall deposits (Nairn, 1999). The resulting deposits form the flanks and the lower ring plain of the volcano. Explosive activity appears to have been very minor (Nairn, 1999). Debris avalanche deposits to north of the mountain indicate that some cold avalanching has also occurred since 1850 years ago, and are possibly seismically-triggered (Nairn, 1999). A small satellite cryptodome on the northeastern flank of Pūtauaki has intruded into and altered the overlying Matahina ignimbrite (Nairn, 1999). The proximity of Pūtauaki to Ōkataina has led some researchers to speculate that it may be linked to the Ōkataina Volcanic Centre and represents its easternmost part (Nairn, 2002). Further evidence of this is that Pūtauaki lies on the same strike as the Tarawera linear vent zone. Steep angles on the flanks of the main cone have led to concerns over flank stability, particularly under earthquake shaking and water table elevations (Hewitt, 2007).

Ōkataina Volcanic Centre (OVC)

The OVC occupies the northern extent of the central zone of the TVZ and is located near the city of Rotorua and the township of Kawerau. Many eruptions at Ōkataina have produced large volumes of rhyolite lava. This lava has piled up over the vent areas to produce two large massifs, Haroharo and Tarawera.

The volcanic history of the OVC includes at least three large caldera-forming rhyolitic eruptions at ~500 ka, ~325 ka and ~45 ka (Cole et al., 2010). The last of these eruptions, the 45 ka Rotoiti Eruption, produced a large, violent Plinian eruption that ejected ~100 km^3 of rhyolitic magma (Shane et al., 2005), depositing it across the northern Bay of Plenty. 12 rhyolitic Plinian eruptions between 45 ka and 31 ka followed the Rotoiti event, depositing the Mangaone Subgroup (MaSg). These eruptions varied greatly in size and the amount of material erupted (up to a factor of 60, Jurado-Chichay and Walker, 2001). The MaSg phase lasted until 31 ka, when a period of relative quiescence commenced (Nairn, 2002; Cole et al., 2010).

From 26 ka to the present, nine rhyolitic Plinian eruptions have occurred, focused along two Linear Volcanic Zones LVZs, the Haroharo LVZ and the Tarawera LVZ (Jurado-Chichay and Walker, 2001; Cole et al., 2010). These volcanic zones run along parallel NE–SW lineaments, which is thought to be an expression of the underlying fault system (Nairn, 2002; Cole et al., 2010). Young eruptions at Ōkataina have been fewer in number than at Taupō, but more uniform in size (ranging in volume from 3.6 to 13 km^3 of magma). All eruptions reached Plinian eruption column heights (between 10–35 km) depositing widespread tephra fall. The smallest rhyolite eruptions at Ōkataina were bigger than all but the four or five largest eruptions at Taupō over the same period (Jurado-Chichay and Walker, 2001). During a single eruption, vents may manifest across the extent of the LVZ they erupt from, and these vents may activate over different timescales, and may last for several years (Nairn, 2002).

Two basaltic eruptions have occurred. The Rotokawau eruption (3.7 ka) comprised a small basaltic fissure eruption that generated localised tephra fall and formed an east-west alignment of four shallow maars (Beanland and Houghton, 1991).

The Kahoroa Tephra (1314 AD)

The Kahoroa is the most recent rhyolitic OVC eruption, occurring from the Tarawera LVZ (Leonard et al., 2010). The eruption occurred from seven different vents aligned along a roughly 8 km long zone. The first 56linian sequence erupted mainly from the central crater vent and lasted approximately 10 days. Early Plinian eruptions from several vents dispersed tephra deposits along the eastern North Island and beyond (Lowe et al., 1998). Plinian eruptions continued at multiple vents for several months. Pyroclastic surges and flows also occurred during the Plinian phases and some travelled more than 10 km from their source vents (Nairn et al., 2001). Four rhyolite domes (Crater, Tarawera, Wahanga, and Ruawahia domes) were emplaced via lava extrusion after the explosive phase, and may have persisted for 4-5 years, eventually erupting about 5 km^3 of magma (Nairn et al., 2001, 2004). A lava body, Green Lake plug, was also extruded on the southwest slope of Mt Tarawera. A ‘break-out’ flood event from Lake Tarawera took place shortly after the eruption (Hodgson and Nairn, 2005).

The Tarawera Eruption (1886 AD)

The Tarawera Eruption (1886 AD) is New Zealand’s largest and most destructive historic eruption, and the only eruption to have occurred in the rhyolitic sector of the TVZ since European settlement of New Zealand (Walker et al., 1986). The basaltic Plinian eruption opened multiple vents across 17 km of the Tarawera LVZ, lasting for 5.5 hours. Phreatomagmatic and magmatic eruptions at vents in the northeast generated significant tephra fall, with four vents spread over ~2 km contributing to a Plinian column, which reached an estimated height of ~34 km (Sable et al., 2006). Phreatic and hydrothermal explosions at vents located in lakes and wet sediments in the southwest generated devastating mudflows and flooding (Nairn, 2002). A great quantity of grey mud was ejected from the floor of the old Lake Rotomahana that was blasted over all the hills around the lake (this was the material that buried Wairoa village, Keam, 1988). Disruptive tephra fall impacted areas throughout the region, and lahars and flooding destroyed towns and encampments proximal to the volcano (Keam, 1988). The rifting eruption split the Tarawera dome complex, extended it through Lake Rotomahana, and created the Waimangu thermal valley - the only major geothermal area in the world to have come into existence in historic times. The short-lived, but extremely violent eruption was heard loudly in Auckland, more than 200 km away.

Historic Caldera Unrest

Research on the 1314 AD Kaharoa Eruption suggests precursors may have been detected up to years in advance had the current monitoring network been in place (Potter et al., 2012). In contrast, significant unrest appears to not have been experienced in the days or months prior to the 1886 Tarawera Eruption. “Peculiar waves” 0.3 m high, 10 days before the eruption were seen on Lake Tarawera, which may have resulted from magma-related ground movements (Nairn, 1991). Earthquakes were felt in nearby areas, increasing in intensity one hour prior to eruption onset. Historical unrest has not been studied in detail, however several periods have been documented including subsidence, increased hydrothermal activity and hydrothermal eruptions, and seismic activity (Potter et al., 2012). The best recorded seismic swarm was centered on the Haroharo LVZ, occurring in April 1998 when over 400 small (>M1.7) earthquakes were recorded (only 4 were reported as felt, maximum magnitude of 4.7) (Potter et al., 2012). Another seismic swarm centered on Rotoehu was recorded in 2004 at the northern caldera margin. Over 1,300 earthquakes (>M1.7) were recorded with magnitudes of up to 5.1. This event was interpreted as a mainshock-aftershock event (Potter et al., 2012).

Rotorua Caldera

Rotorua Caldera is the youngest caldera of the TVZ, with activity beginning at 240 ka (Milner, 2001, Milner et al., 2002). The caldera contains a single large lake that undergoes periodic changes to its size and water depth, some of which is influenced by landscape modifications brought on by volcanic activity. It is generally considered to be a separate, active rhyolitic volcano, however it may equally be regarded as an extension of the OVC (Potter et al., 2012). The caldera was formed during collapse associated with the very large (145 km^3) Mamaku Plateau formation eruption in 240 ka (Gravley et al., 2007). This eruption may have coincided with the Ohakuri eruption located 30 km to the south in the Kapenga area (Leonard et al., 2010). The ignimbrites from the two sources were emplaced only a few weeks apart, and in some areas overlap (Milner, 2001). After the Mamaku Plateau forming eruption rhyolitic lava was extruded, forming a number of small domes including those at 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 (Leonard et al., 2010). Rotorua Caldera contains the Rotorua and Eastern Rotorua geothermal fields.

Historic Caldera Unrest

Potter et al., (2012) report that no major seismic swarms have occurred inside the Rotorua Caldera since 2002, however there is an area of potentially higher seismicity in the southern portion of the caldera. 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.

Taupō Volcanic Centre (TVC)

The Taupō Volcanic Centre (TVC) is the southernmost caldera of the TVZ and considered the most productive individual rhyolitic volcano in the world (Barker et al., 2021). Activity began in ~330 ka and since then it has had a complex history of both very large and very small eruptions, most of which were rhyolitic in composition (Barker et al., 2021).

Taupō's history from 330 ka to 65 ka is poorly understood because the deposits have been either buried or destroyed by subsequent eruptions (Barker et al., 2021). Ten eruptions between 65-27 ka have been documented, at least five of which were explosive (Wilson et al., 2009). The caldera was largely formed during the last and largest eruption of this period, the cataclysmic Oruanui Eruption at ~27 ka. This event ejected a total volume of 530 km^3 over a period of several months (Wilson, 2001; Barker et al., 2021). The eruption involved a complex interaction of magma and water, producing huge, widespread tephra falls interspersed with pyroclastic density currents. Deposits from this eruption formed a dam, which when collapsed, producing huge floods down the Waikato River (Wilson, 2001).

Activity resumed only ~5,000 years after the Oruanui Eruption, although eruptions were of a smaller scale and more frequent (Barker et al., 2021). Post-Oruanui stratigraphy by Wilson (1993) identified 28 eruptions that vary widely in their sizes and eruptive styles. The first four events (~20.5–16 ka) were dacitic and erupted from vents near the northern extent of Lake Taupō. The remaining 25 eruptions from ~12 ka onwards were rhyolitic. A striking feature of post-Oruanui eruptions, and in marked contrast with OVC activity, is the wide range of eruption volumes, the number of explosive events and the geographically focussed vent locations (Barker et al., 2021).

The Taupō (Hatepe) Eruption (232 AD)

The most recent Taupō eruption (232 AD) was uncharacteristically large and destructive compared to the previous post-Oruanui events (Wilson, 1993). The eruption ejected approximately 120 km^3 of material, making it New Zealand's largest eruption within the last 20,000 years, globally the second or third largest eruption in the last 2,000 years, and the most powerful eruption in the past 5,000 years (Barker et al., 2021). The eruption started with a small, phreatomagmatic eruption that increased in size and violence, with an 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 m per second radially outwards from the vent in the north-east part of Lake Taupō (Wilson and Walker, 1985). The eruption devastated a 20,000 km^2 area surrounding Taupō, due to widespread tephra falls and ignimbrite forming pyroclastic flows up to 80 km from source, ignimbrite and climbing over 1,500 m to overtop the Kaimanawa Ranges and Mount Tongariro (Wilson and Walker, 1985). Following the eruption, the lake refilled over several years, eventually reaching a level ~30 m higher than the present-day level. The water eventually cut through the material damming the lake and overflowed at a rate of up to 35,000 m^3 per second., flooding large areas downstream (Barker et al., 2021).