Auckland Lifelines Group

VISG Project ALG-RRP-008

Health and Safety in Volcanic Environments

August 2024

ISBN 978-0-473-72774-1

The Auckland Lifelines Group has established a Volcanic Impacts Study Group (VISG) to carry out research into the impacts of volcanic hazards on lifelines and associated issues. This report presents the findings of VISG project ALG-RRP-008 and has been prepared by:

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Suggested Citation

Stewart, C., Wilson, T.M., Weir, A., 2024. Health and Safety in Volcanic Environments. 50 pages. Version 1, October 2024.

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ISBN: 978-0-473-72774-1

Publication date: 10/24

Executive summary

Volcanic environments pose a number of health and safety risks for people, yet there is relatively limited available guidance for individuals and agencies to inform management of those risks while carrying out work during or after volcanic eruptions. This report substantively updates a 2005 report commissioned by the Auckland Lifelines Group on health and safety issues in volcanic ash environments. It provides a specific focus on meeting the requirements of the 2015 Health and Safety at Work Act (HSWA) for lifeline utilities staff working during or after volcanic eruptions, broadens the focus from volcanic ash to other volcanic hazards, and incorporates lessons from recent volcanic eruptions in Aotearoa New Zealand and around the world.

Aotearoa New Zealand is one of the most volcanically active regions in the world. Within the next 50 years, the probabilities of a large eruption are >50% for Ruapehu and Whakaari and ~30-40% for Ngāuruhoe, Tongariro and Taranaki, posing a major, credible hazard to populations, infrastructure, and buildings.

Volcanic life safety hazards include highly destructive, fast-moving and lethal hazards such as pyroclastic density currents and volcanic ballistic projectiles. For these hazards, complete avoidance of risk zones is the best risk management approach. With this caveat, we provide current best practice advice on PPE and safety measures for workers who may need to access high risk areas, such as managed access zones.

All Aotearoa New Zealand volcanoes can produce volcanic ash, which is a far-reaching hazard that can affect large areas. However, it is generally safe to work in volcanic ash environments with use of appropriate personal and respiratory protective equipment (PPE and RPE) and knowledge of safe working methods. Specific concerns of working in ashy environments include respiratory health hazards, working at height hazards, driving, electrical safety hazards, roof collapse risk and strain injuries during clean-up operations. One challenge identified during this project is that while airborne ash is a primary hazard of explosive eruptions, it is currently unclear where the responsibility for monitoring post-eruption air quality would sit, particularly in regions that do not routinely monitor air quality for regulatory purposes.

The 2002 Civil Defence and Emergency Management Act requires that lifeline utilities be prepared for natural hazard events including volcanic eruptions, and plan to function as fully as possible during and after an eruption. The 2015 Health and Safety at Work Act requires that all reasonable and practicable measures be taken to protect workers, including employees, contractors and subcontractors and volunteers, while carrying out this work.

In our view, key considerations for lifeline utilities operating during and after volcanic eruptions will be:

- To understand the hazards and risks of working during or after volcanic eruptions (Chapters 3-5);
- To understand the range of mitigation options available for these hazards (Chapters 4-5);
- To understand key tasks required in the event of a volcanic eruption (Chapter 6);
- To pre-plan these tasks as far as possible, including clarifying roles and responsibilities with contractors and subcontractors (Chapters 2 and 6).

Quick guide to volcanic life safety risks and available safety measures and PPE

Any decision to enter managed access zones needs to be made jointly with CDEM.

Basic/universal PPE for working in managed access zones: tough long-sleeved clothing such as overalls, sturdy heatproof boots, gloves, eye protection (goggles without side vents), hard hat secured to the head with a chin strap. Carry communication devices, tested in the conditions.

	Injuries and hazards	**Additional PPE**	**Safety measures**
PDCs	Skin and airway burns and asphyxiation from exposure to hot, fast-moving flows of ash, gas and rock. Trauma from ballistics also possible.	Heatproof and chemical-resistant suit and heat-shielded supplied air respirator may offer some protection. **No PPE will give complete protection from PDCs.**	**Avoid hazard zones as far as possible. PDCS are extremely hazardous.** If outdoors, take shelter from approaching PDCs if possible. Even sheltering behind boulders may offer some protection. Shelter on the side of buildings not facing the volcano. If working on fresh PDC deposits, carry a probe to test the ground ahead for unstable areas or hidden hazards.
Ballistics	Trauma injuries, fractures, lacerations and burns from being hit by flying hot rocks.	Heatproof clothing **No PPE will protect against large and/or fast-moving ballistics.**	**Avoid hazard zones as far as possible. Ballistics are extremely hazardous.** If ballistics are falling, move out of their path, seek shelter, cover your head and make yourself as small a target as possible. Shelter on side of buildings not facing volcano. If inside building, shelter under structures such as tables or bunks. If outdoors, sheltering behind boulders may offer some protection.
Lahars	Asphyxiation by drowning, trauma injuries.	**No PPE will protect against a lahar.** Waterproof, heatproof clothing and boots if working on fresh lahar deposits.	**Avoid active lahar paths. Lahars are extremely hazardous.** If working in lahar hazard zones, pay close attention to weather forecasts as heavy rainfall may trigger lahars. Be prepared to move quickly out of valleys to higher ground. If working on fresh lahar deposits, wear waterproof and heatproof clothing and boots to protect body in case of sinking into hot mud. Consider laying planks across deposits for easier access.

Lava flows	Skin burns from direct contact or through radiant heat. Trauma injuries from being hit by explosion debris or blocks rolling down flow fronts, particularly where lava contacts water. Airways constriction from exposure to high concentrations of irritant gases (primarily SO_2).	Heatproof clothing, full facepiece respirator, personal gas sensors.	Check projected lava flow paths before entering the hazard zone. Stay well back from active lava flows. Closely monitor the movement of the lava front and ensure that escape routes are not cut off. Monitor the heat hazard and gas concentrations and be aware of the potential of the lava flow to ignite flammable material and start fires. If working on cooled lava flows, be aware that surfaces can be fragile and very sharp, and severe lacerations can result from falls.
Gases	Close to eruptive vents, irritant gases such as SO_2 and HCl, which cause airways constriction, may be at extremely hazardous or lethal concentrations. Asphyxiant gases (CO_2 and H_2S) flow downslope and can accumulate in low-lying areas or poorly ventilated spaces where they can reach lethal concentrations.	Either supplied air respirator or full facepiece respirator. Gas detection equipment including personal gas sensors. **Refer to cautions about RPE use on page 28.**	Stay well back and upwind of eruptive vents. Avoid low-lying areas such as pits or ditches. Monitor gas concentrations closely. Concentrations can change rapidly.
Ash	Trauma injuries due to building collapse associated with very thick ashfalls (typically 200+ mm). Respiratory hazard from ash inhalation. Trauma injuries from falls from roofs.	Fit-tested disposable P2/N95 respirator.	Monitor accumulation of ash on roofs. Use safe working methods when clearing ash from roofs.

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1 Introduction

Volcanic environments pose a number of health and safety risks for people, yet there is relatively limited available guidance for individuals and agencies to inform management of those risks while carrying out work in such environments.

In 2005, the Auckland Lifelines Group (formerly the Auckland Engineering Lifelines Group) and the Volcanic Impacts Study Group (VISG) commissioned an initial assessment of the risks of working in a volcanic ash environment and made recommendations to manage health and safety risks (Lindsay and Peace, 2005).

This report updates the 2005 report and provides a specific focus on meeting the requirements of the 2015 Health and Safety at Work Act (HSWA) for lifeline utilities staff working during or after volcanic eruptions. It also broadens the focus from volcanic ash to other volcanic hazards and incorporates lessons from recent volcanic eruptions in Aotearoa New Zealand and around the world.

The specific objectives of this report are to:

- Describe health and safety issues for staff working during or after eruptions;
- Provide advice on steps employees and staff can take to keep themselves safe (including safe working procedures and safety equipment) in the context of the HSWA;
- Identify gaps in knowledge or preparedness for safely carrying out activities in post-eruption conditions and make recommendations for further work and/or research to fill these gaps.

Chapter 2 provides an update of the legislative context for working in volcanic environments.

Chapter 3 provides an overview of volcanic hazards in Aotearoa New Zealand, including recently available estimates of eruption probabilities from our active volcanoes and a probabilistic ashfall hazard map for the North Island/Te Ika-a-Māui.

Chapter 4 focuses on volcanic ashfall as the most widely dispersed and far-reaching volcanic hazard. This chapter discusses the nature of volcanic ash hazards in detail, ash hazard characterisation and testing, monitoring of airborne particulates, hazards of working in ash environments and recommended safe practices for this work.

Chapter 5 discusses volcanic life safety risks. We emphasise that for highly destructive, fast-moving and lethal hazards such as pyroclastic density currents and volcanic ballistic projectiles, complete avoidance of risk zones is the best risk management approach. With this caveat, we provide current best practice advice on PPE and safety measures for workers who may need to access risk zones. Chapter 5 includes a concise guide to volcanic life safety risks and available mitigation measures and PPE.

Finally, Chapter 6 describes key operational tasks and management activities for lifeline utilities operating during or after a volcanic eruption, including sector-specific advice.

2 Update of legislative context

Lindsay and Peace (2005) noted that at the time, two sets of legislation were relevant to staff working in volcanic ash environments. These were the 2002 Civil Defence and Emergency Management Act (CDEM Act) and the 1992 Health and Safety in Employment Act (HSIE Act). Taken together, this legislation required that lifeline utilities be ready for emergencies and function as fully as possible during and after that emergency; and that employers take all practicable steps to protect employees from harm. Updates to legislation since 2005 are provided in Sections 2.1 and 2.2.

All persons in Aotearoa New Zealand have their right to life and security protected by the 1990 Bill of Rights Act (BORA) (Section 8)[1]. Therefore, people cannot be ordered to work in a dangerous situation without specific and proportionate legal instructions to do so. Legislation is interpreted to conform with BORA, where possible, and Regulations made under other legislation including those discussed in sections 2.1 and 2.2 would be subject to it.

2.1 2015 Health and Safety at Work Act (HSWA)

The HSWA replaced the HSIE Act in 2015. The principal aim of the HSWA is to provide the highest level of protection from harm in the workplace. Key differences from the previous legislation are the introduction of new entities ('duty holders') with different responsibilities (Table 1), a focus on involving all duty holders in protection from harm, and that substantially higher penalties are possible for cases prosecuted successfully.

Table 1 Duty holders defined under the HSWA

Entity	Examples	Responsibilities
PCBU[1]	Retailer, franchisor, government department, council, lifeline utility, school, charity, non-governmental organisation	Primary duty of care
Officer	Company director, board member, chief executive	Due diligence to make sure PCBU complies with its health and safety responsibilities
Worker	Employee, volunteer, trainee, apprentice	Take reasonable care with their own health and safety, comply with reasonable workplace policies and procedures
Other person at workplace	Visitors, customers, casual volunteers	As for workers

1 Person conducting a business or undertaking

Detailed descriptions of the roles and responsibilities of each of these entities are available from WorkSafe NZ (www.WorkSafe.govt.nz). A brief summary is provided below.

PCBUs are the duty holder with the primary duty of care under the HSWA. PCBUs can be an individual person, but more commonly will be an organisation. The PBCU must, as far as is reasonably practicable, ensure the health and safety of workers, and ensure that other people are not put at risk by its work, such as visitors to the workplace. It includes the following:

- Providing and maintaining a work environment that is without risks to health and safety;

[1] https://www.legislation.govt.nz/act/public/1990/0109/latest/DLM225504.html

- including both physical and psychological aspects;
- Providing and maintaining safe plant and structures;
- Providing and maintaining safe work systems;
- Ensuring the safe use, handling and storage of plant, structures and substances;
- Providing adequate facilities for the welfare of workers carrying out work for the business or undertaking;
- Providing necessary information, training, instruction or supervision with respect to risks to health and safety;
- Monitoring health of workers and conditions at workplace to prevent injury or illness arising from the conduct of the business or undertaking; and
- Maintaining any worker accommodation so that workers are not exposed to health or safety risks from the accommodation.

Officers are people who occupy positions that allow them to exert significant influence over the management of the business or undertaking, such as company directors. As such, their duty is to exercise due diligence to ensure that the PCBU complies with its health and safety duties.

Workers are defined, under the HSWA, as individuals who carry out work in any capacity for the PCBU. This encompasses a broad range of arrangements, including employees, contractors and subcontractors, apprentices, trainees, outworkers, people on work experience, and volunteers who work for PCBUs on a regular basis and whose work is an integral part of the PCBU's business. Workers must take reasonable care for their own health and safety, ensure they do not endanger themselves or others, and comply with reasonable health and safety policies, procedures, and instructions from the PCBU. Worker engagement, participation, and representation in health and safety matters is also an important principle.

Other persons in the workplace include visitors to the workplace, such as customers if the workplace is a shop, or people touring or visiting a workplace. Casual volunteers are also included in this category. Other persons need to take reasonable care for their own health and safety and comply with reasonable health and safety instructions.

2.1.1 Responsibilities for chains of contractors

Contracting chains can be complex, with lead PCBUs, lead contractors, contractors, subcontractors and workers involved. A key principle in the HSWA is that no one can contract out of their health and safety duties. In practice this means that consultation, coordination and cooperation between duty holders is necessary. A second key principle is that the more influence a duty holder has over a workplace, the more responsibility they will have.

A 2017 prosecution by WorkSafe NZ[2] illustrates the shared nature of responsibility for health and safety between PCBUs and contractors. In 2014, Wellington Electricity Lines Ltd. (WEL) contracted Northpower Ltd. to carry out maintenance on its network. A Northpower trainee suffered a serious electric shock from an arc flash during the decommissioning of equipment at a substation. The decommissioning work was conducted above live equipment, and when the trainee unbolted a transformer, a support bracket fell into the live equipment which caused the arc flash. While Northpower had created a work plan for the decommissioning project, which was peer reviewed by WEL and approved by both organisations, the substation in question had a different configuration to

[2] https://www.districtcourts.govt.nz/assets/unsecure/2017-08-11/2017-NZDC-17527-WorkSafe-NZ-v-Northpower-Ltd.pdf

other substations, and the hazard controls were not appropriate for this configuration. Northpower acknowledged its key failings as: not undertaking an adequate site-specific risk assessment for the substation; not de-energising the substation; and carrying out the work while the substation was energised. WEL acknowledged its key failings as not identifying the site-specific risks to Northpower, and not including specific instructions within the work plan for substations with different configurations. Fines of $26,000 plus reparation and $30,000 plus reparation were imposed for WEL and Northpower respectively. These were substantially discounted in view of the guilty pleas entered, cooperation with WorkSafe, willingness to take remedial action, and pre-existing good safety records.

As a further example of the shared responsibility for health and safety between PCBUs and contractors, WorkSafe laid two charges against GNS Science (GNS) following the December 2019 eruption of Whakaari volcano. The primary charge was dismissed, leaving a remaining charge under section 48 of the HSWA. This charge alleged that GNS failed to ensure the health and safety of helicopter pilots who regularly flew GNS staff to Whakaari prior to the 2019 eruption and was unrelated to the eruption. On 30 May 2023, GNS pled guilty to a reduced charge under section 49 of the HSWA, acknowledging that there should have been a more structured exchange of information with the helicopter pilots about the risks of travel to Whakaari[3].

2.2 2002 Civil Defence and Emergency Management Act (CDEM Act)

Section 60 of the CDEM Act[4] specifies that every lifeline utility[5] must:

(a) ensure that it is able to function to the fullest possible extent, even though this may be at a reduced level, during and after an emergency:

(b) make available to the Director in writing, on request, its plan for functioning during and after an emergency:

(c) participate in the development of the national civil defence emergency management strategy and civil defence emergency management plans:

(d) provide, free of charge, any technical advice to any Civil Defence Emergency Management Group or the Director that may be reasonably required by that Group or the Director:

(e) ensure that any information that is disclosed to the lifeline utility is used by that utility, or disclosed to another person, only for the purposes of this Act.

Reforms to Aotearoa New Zealand's emergency legislation have recently been proposed with an Emergency Management Bill[6] introduced to Parliament on 7 June 2023. However, this Bill was withdrawn on 2 April 2024[7].

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[3] Whakaari Update – GNS Science pleads guilty to a reduced charge under the Health and Safety at Work Act 2015 (HSWA) - GNS Science | Te Pū Ao

[4] https://www.legislation.govt.nz/act/public/2002/0033/51.0/DLM150765.html

[5] We use the term "lifeline utility" throughout this report as specified in the 2002 CDEM Act. However we note that it will likely be replaced by the term "critical infrastructure" in the future to align with the Sendai Framework for Disaster Risk Reduction: https://www.undrr.org/resilient-infrastructure/enhance-infrastructure-resilience

[6] https://www.legislation.govt.nz/bill/government/2023/0225/8.0/d16197443e2.html

[7] https://www.civildefence.govt.nz/assets/Uploads/documents/proactive-release/Release-version-Documents-relating-to-the-Governments-decision-to-not-proceed-with-the-Emergency-Management-Bill.pdf

2.3 Summary of implications for lifeline utilities during and after volcanic eruptions

In summary, the CDEM Act requires that lifeline utilities be prepared for natural hazard events including volcanic eruptions, and plan to function as fully as possible during and after an eruption. The HSWA requires that all reasonable and practicable measures be taken to protect workers, including employees, contractors, subcontractors and volunteers, while carrying out this work.

We emphasise that this is not a definitive interpretation of the law and that we are not providing legal advice. In our view, key considerations for lifeline utilities operating during and after volcanic eruptions will be:

- To understand the hazards and risks of working in a volcanic environment (during or after a volcanic eruption);
- To understand the range of mitigation options available for these risks;
- To understand key tasks required in the event of a volcanic eruption;
- To pre-plan these tasks as far as possible, including clarifying roles and responsibilities with contractors and subcontractors.

3 Volcanic hazards in Aotearoa New Zealand

Aotearoa New Zealand is one of the most volcanically active regions globally, with a number of active volcanoes located on, or offshore of, the North Island Te Ika ā Maui. Though we have relatively little lived experience of eruptions and their impacts, oral histories, historical and geological records all indicate that our volcanoes are highly active. The volcanoes can broadly be classified into three main types: volcanic fields, strato (cone) volcanoes, and calderas and domes (Figure 1).

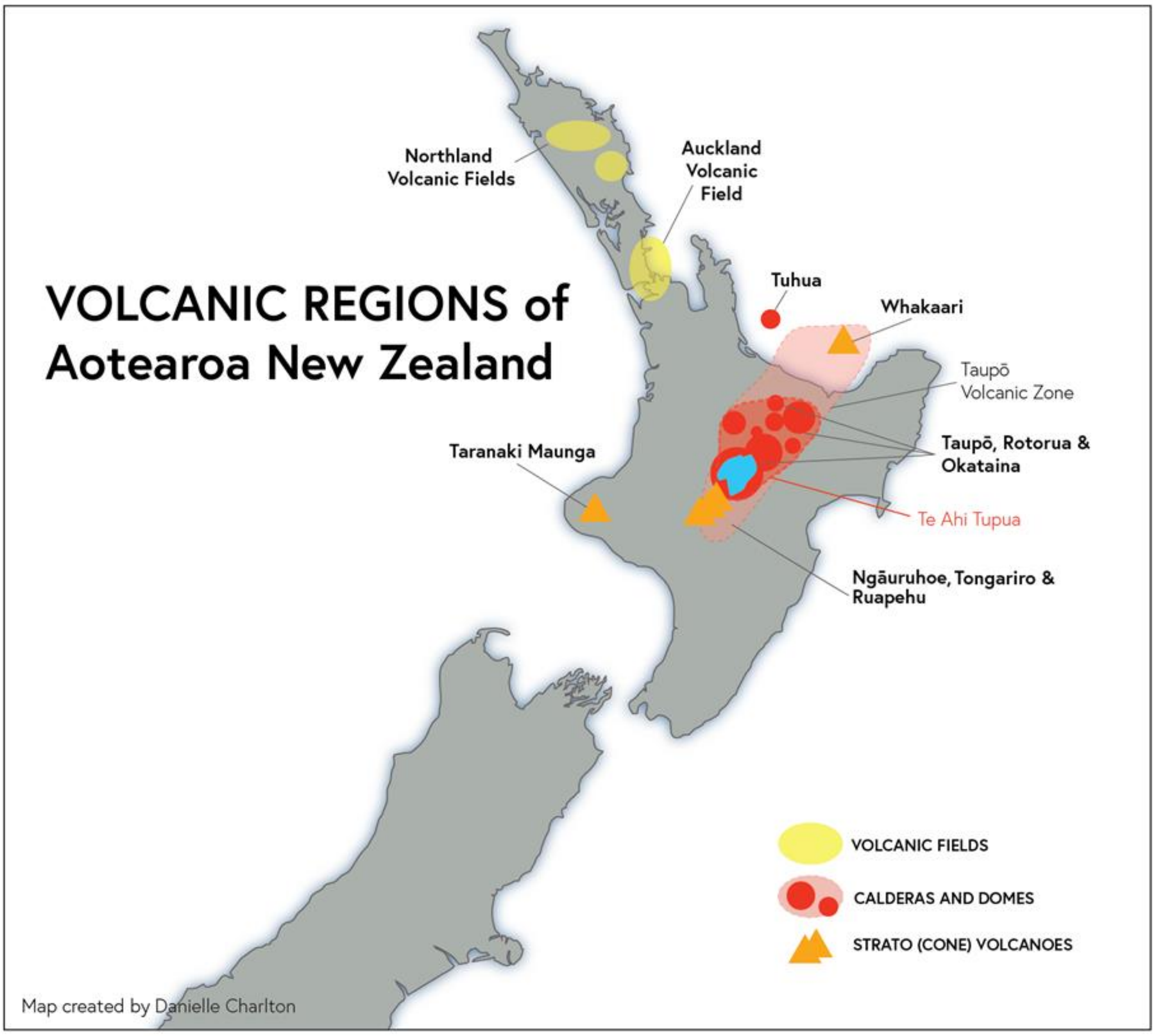

Figure 1 Volcanic regions of Aotearoa New Zealand. Te Ahi Tupua is the term for the caldera complex in the central Taupō Volcanic Zone. Map courtesy of Danielle Charlton, GNS Science.

3.1 Volcanic activity and volcanic hazards

Volcanoes have different states of activity. In Aotearoa New Zealand, the Volcanic Alert Level (VAL) system is used to describe the current activity status at each monitored volcano (Appendix 1). The VAL scale ranges from VAL 0 (no volcanic unrest) to VAL 5 (major eruption). VALs are not a forecast.

Volcanoes are considered active if they have erupted within the Holocene period (from approximately 11,700 years ago to the present). A dormant volcano is an active volcano that is showing no signs of unrest. This corresponds to VAL 0. An extinct volcano is one that is not expected to erupt again. In Aotearoa New Zealand, this includes the ancient volcanoes of Banks Peninsula and the Otago Peninsula.

Volcanic unrest is increased activity that may or may not lead to a volcanic eruption (VAL 1-2 for minor and moderate/heightened unrest, respectively). Unrest can produce hazards on or near a volcano such as volcanic earthquakes, increased gas emissions and land deformation. Most eruptions follow unrest, but not all unrest episodes lead to eruptions. This makes managing unrest challenging. Unrest can last for days, years or potentially decades.

Volcanic eruptions are complex phenomena that can produce multiple near- and far-reaching hazards such as ashfall, lava flows, pyroclastic density currents and lahars (Figure 2). Eruptions can last for days to years and can range in size from minor (VAL 3) to major (VAL 5). The area affected by eruptions can be extremely large due to far-reaching hazards such as ash and gas emissions, and effects can continue for years or even decades. Eruptions can vary in size and style as they progress and can be interspersed with periods of quiescence (no eruptive activity).

Post-eruption: Some volcanic hazards can persist long after an eruption has ceased. For example, lahars (volcanic mudflows) can occur when heavy rains wash unconsolidated volcanic deposits into river systems. Volcanic ashfall deposits can be remobilised by wind, traffic or clean-up activities.

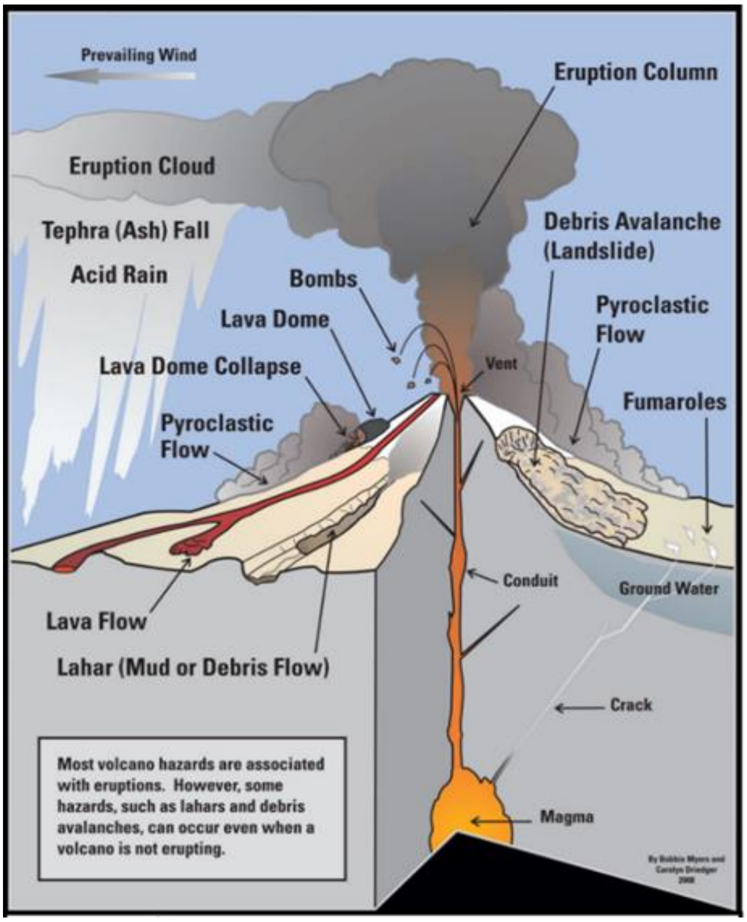

Figure 2 Overview of volcanic hazards (US Geological Survey, 2008, open source)

Volcanic hazards can be classified into unrest hazards, near-vent eruption hazards and far-reaching eruption hazards (Table 2). Volcanic ashfall hazards are covered in detail in Section 4, and the specific near-vent life safety hazards of ballistics, pyroclastic density currents, lava flows, lahars and gases are covered in detail in Section 5.

Table 2 Unrest, near-vent eruption and far-reaching eruption hazards

Unrest hazards typically occur on or near the volcano.	
Earthquakes	Volcanic earthquakes can be caused by magma moving, and pressure building, inside or beneath a volcano.
Edifice destabilisation	Hydrothermally altered ground may be weaker and more prone to collapse.
Gases	Unrest may be accompanied by increased emissions of magmatic gases such as carbon dioxide (CO_2), hydrogen sulfide (H_2S) and sulfur dioxide (SO_2)
Ground deformation	Changes to the ground surface, such as swelling, sinking or cracking, are often associated with unrest. Near-surface deformation can affect water tables and borewater supplies.
Near-vent eruption hazards can be highly destructive and dangerous but are generally confined to within 10-15 km of the vent.	
Ashfalls (thick)	Volcanic ash consists of small fragments of rock, minerals and volcanic glass generated during explosive volcanic eruptions and dispersed downwind. Close to volcanoes, ashfalls can be thick enough to collapse roofs and cause structural damage to buildings.
Volcanic ballistic projectiles (VBPs)	VBPs, commonly known as ballistics, are fragments of rock or lava, from a few cm to metres in diameter, thrown from a vent during explosive eruptions.
Earthquakes	*As for unrest*
Floods	When fine ashfall covers soil, it can reduce infiltration and increase runoff, leading to flooding during heavy rain. Flooding can also occur when lahar deposits fill river channels.
Gases, aerosols and acid rain	Emissions of volcanic gases increase during eruptions. Near vents, <u>irritant gases</u> such as SO_2 and HCl may be at hazardous concentrations. SO_2 gas oxidises to sulfate <u>aerosol</u> which forms hazy volcanic air pollution known as 'vog'. <u>Asphyxiant gases</u> such as H_2S and CO_2 are denser than air and flow downslope where they may accumulate in low-lying areas or poorly ventilated spaces to hazardous concentrations. <u>Acid rain</u> occurs when rain falls through a plume of acidic volcanic gas such as HCl. Close to the vent, rainfall can be as acidic as freshly squeezed lemon juice (pH 2).
Ground deformation	*As for unrest*
Hydrothermal (phreatic) eruptions	Hydrothermal eruptions can occur in geothermal fields as well as at active volcanoes and occur when groundwater flashes to steam and causes a small-scale but violent eruption of steam, water, mud and rock fragments. They pose a risk to people and property nearby.
Lahars	Lahars (volcanic mudflows) are masses of rock, mud and water that travel rapidly down valleys.
Landslides	Landslides (debris avalanches) are moving masses of rock, soil and snow that occur when the flank of a mountain or volcano partially collapses and slides downslope.

Lava flows	Lava flows are rivers of molten rock that flow downslope. Important secondary hazards include SO_2 emissions and combustion of flammable materials such as vegetation.
Pyroclastic density currents (PDCs)	PDCs include pyroclastic flows and surges. These are hot, ground-hugging mixtures of ash, gas and rock fragments that travel away from vents at high speeds for tens of kilometres.
Shockwaves	Explosive eruptions generate shock (pressure) waves that can damage buildings. Very large explosions may damage peoples' hearing.
Tsunami	Eruptions, particularly submarine eruptions, can generate highly destructive tsunami both near the vent and at distant locations.
Far-reaching eruption hazards can travel far from the eruption site and affect distant areas.	
Ashfalls (thin to moderate)	Ashfalls can cover large areas. Eruptions from Taranaki Mounga, Ruapehu and Tongariro volcanoes are likely to produce thin ashfalls in downwind areas. Remobilisation of ashfalls by wind, traffic or clean-up activities can prolong health hazards of airborne ash.
Floods	*As for near-vent hazards*
Gases, aerosols and acid rain	*As for near-vent hazards, except that vog is likely to dominate further downwind.*
Lahars	*As for near-vent hazards.* Lahars can travel for tens of kilometres or more from volcanoes.
Tsunami	*As for near-vent hazards.*

3.2 Expected frequency and magnitude of future eruptions

All Aotearoa New Zealand volcanoes have unique frequency/magnitude relationships based on their eruptive history, which directly informs forecasting future eruptions for each volcano. Eruption magnitude is generally measured by the volume of material erupted. A common measure is the Volcanic Explosivity Index (VEI; Newhall and Self, 1982, which ranges from VEI 0 to VEI 8 (VEI 8 being the largest known eruptions in Earth's geological history). Aotearoa New Zealand volcanoes have produced eruptions ranging from VEI 0 to VEI 8, with Taupō caldera producing some of the largest known eruptions (VEI 8). Bebbington et al. (2018) present eruption probabilities for Aotearoa New Zealand volcanoes, using expert elicitation methods (Table 3). While this work represents the most current, robust understanding of eruption probabilities, these probabilities can change drastically following change at a volcano such as the onset of unrest.

Table 3 The likelihood of future eruption magnitudes and timings at active volcanic centres in Aotearoa New Zealand. Values show the elicited probabilities of the next eruption being of a certain magnitude, measured by the Volcanic Explosivity Index (VEI), and the elicited time to the next eruption in years from the study publication date (Bebbington et al., 2018).

Volcano	**VEI probabilities for next eruption**								***Time to next eruption (years from 2018)***		
	VEI ≤2	VEI 3	VEI ≤ 3	VEI 4	VEI 5	VEI ≥6	VEI 6	VEI ≥7	*10% quantile*	*median*	*90% quantile*
Whakaari	0.75	0.23		0.011	0.004	0.004			0.17	5.4	38
Ruapehu	0.68	0.27	-	0.039	0.015	0.003	-	-	*0.58*	*9.9*	*52*
Ngāuruhoe	0.8	0.14	-	0.046	0.005	0.004	-	-	*0.72*	*17*	*162*
Tongariro	0.79	0.15	-	0.035	0.017	0.004	-	-	*0.84*	*19*	*227*
Taranaki Mounga	0.095	0.76	-	0.13	0.01	0.003	-	-	*4.5*	*82*	*619*
Okataina	0.46	0.073	-	0.16	0.16	0.15	-	-	*4*	*150*	*6460*
Taupō	-	-	0.29	0.46	0.17	-	0.068	0.016	*49*	*1040*	*7510*
Tūhua	0.38	0.30		0.23	0.084	0.007			4	2370	9110
Auckland	0.77	0.22	-	0.006	0.003	0.004	-	-	*35*	*2450*	*36400*

Within the next 50 years, the probabilities of a large eruption are >50% for Ruapehu and Whakaari and ~30-40% for Ngāuruhoe, Tongariro and Taranaki, posing a major, credible hazard to populations, infrastructure, and buildings.

3.3 Probabilistic volcanic ash hazard assessment and eruption scenarios

All Aotearoa New Zealand volcanoes can produce volcanic ash. As ashfall is a far-reaching hazard that can affect large areas, probabilistic ash hazard assessment is relatively well-developed, and several recent studies have produced national-scale probabilistic ash hazard assessment maps (Figure 3). This map shows the probability of at least 3 mm of ashfall occurring in any given year for the North Island Te Ika-a-Māui. Due to low annual eruption probabilities, the Auckland Volcanic Field and Taupō volcano make relatively little contribution to the ashfall annual exceedance probability. Areas with the highest probability of receiving ≥3 mm ashfall in any given year are located adjacent to and downwind of the cone volcanoes Taranaki Mounga, Ruapehu, Ngāuruhoe and Tongariro, which have the shortest expected times to next eruption (Table 3) of the mainland volcanoes.

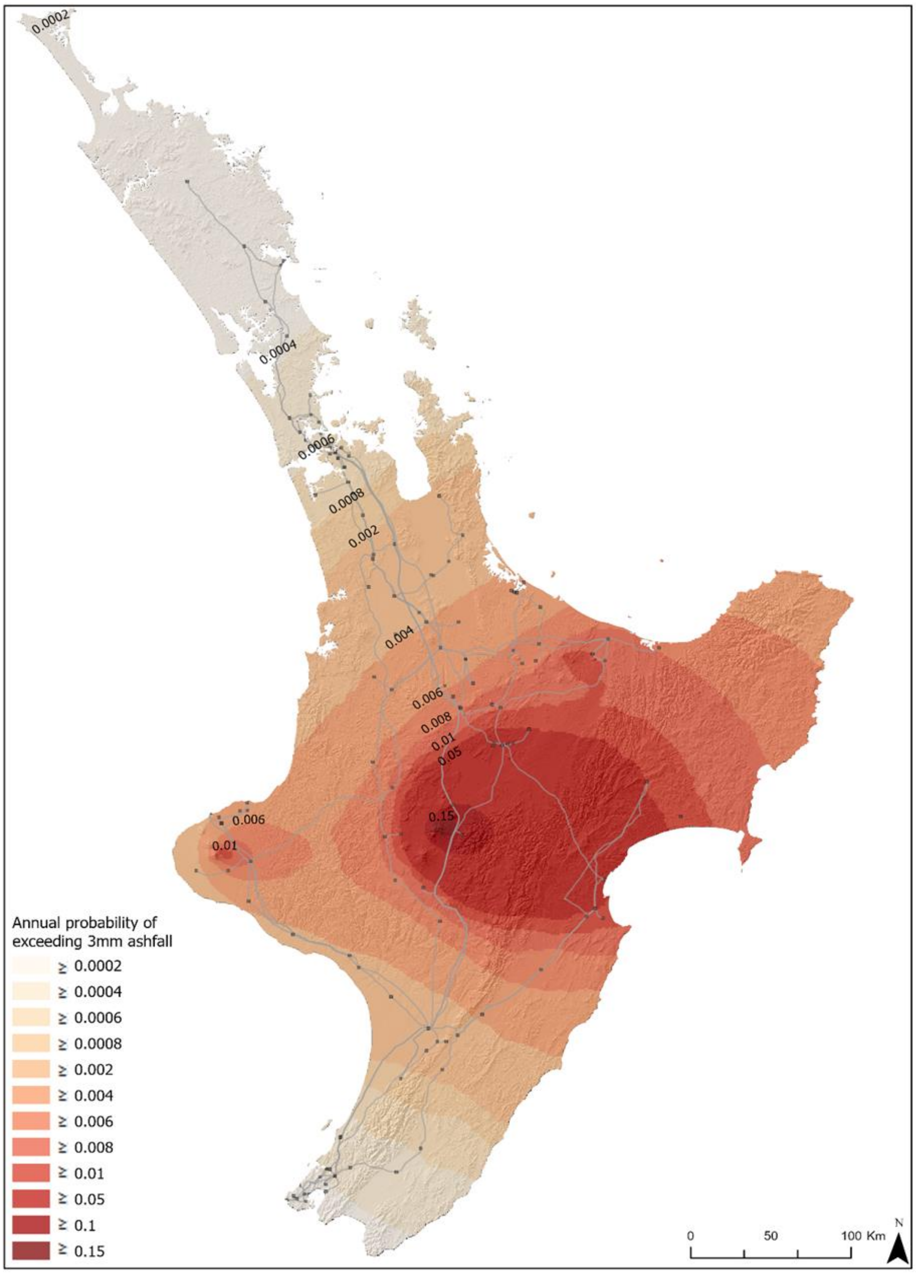

Figure 3 Annualised probability of ashfalls exceeding 3 mm depth from Aotearoa New Zealand volcanoes, from NZ Lifelines Council (2023). The map is overlain with Transpower's high-voltage transmission lines and sites.

Other volcanic hazards, including pyroclastic flows, lahars and volcanic gases, have not been robustly assessed probabilistically for Aotearoa New Zealand volcanoes. This is a priority for future volcanic research (NZ Lifelines Council, 2023).

Robust and scientifically credible suites of scenarios are available for future eruptions in the Auckland Volcanic Field (Hayes et al., 2018) and at Taranaki Mounga (Weir et al., 2022). These may be valuable for health and safety preparedness planning. Eruption scenario development has also been part of recent research programmes on the caldera volcanoes, such ECLIPSE[8], and work is underway on scenario development for future eruptions of Ruapehu and Tongariro volcanoes.

[8] https://www.gns.cri.nz/research-projects/eclipse-eruption-or-catastrophe/

4 Hazards and risks of working in volcanic ash environments

Although volcanic ash is the most widely dispersed and far-reaching volcanic hazard (Section 3), in general it is safe to work in ashy environments with use of appropriate PPE and knowledge of safe working methods. This section discusses the nature of volcanic ash hazards in more detail, ash hazard characterisation and testing, monitoring of airborne particulates, hazards of working in ashy environments and recommended safe practices for this work.

Figure 4 Workers clear ash from a substation in Junin de los Andes, Argentina. This town received ~20 mm basaltic andesite ashfall from the 2015 eruption of Calbuco volcano, Chile, 200 km away (photo credit: Bomberos Voluntarios de Junin de los Andes, Argentina)

4.1 What is volcanic ash and how is it generated?

Volcanic ash is formed during explosive volcanic eruptions or lava dome collapse events. Explosive eruptions occur when the gases dissolved in magma (molten rock) escape violently, fragmenting the magma. Lava domes form when magma is extruded that is too viscous (sticky) to move away as a lava flow and accumulates into a steep-sided dome around the vent. Collapse of lava domes can generate both PDCs (section 5.4.1) and volcanic ash. Lava domes often form within caldera volcanoes, such as Taupō and Okataina, but can also form on cone volcanoes such as Taranaki Mounga and Ruapehu (Figure 1).

The general term for particles formed by these mechanisms is ‘tephra’, with ‘ash’ referring to particles <2 mm diameter. Ash particles are hard, sharp and abrasive. Freshly erupted ash may have a surface coating typically comprised of soluble salts and acids, formed from the interaction of acidic plume gases such as hydrogen chloride (HCl) and sulfur dioxide (SO_2) with ash particle surfaces. This makes ash corrosive and able to conduct electricity when moisture is present.

4.2 Ash hazard characterisation

The properties of volcanic ash are widely variable (Figure 5), therefore, for each new ashfall event, ash hazard characterisation is an important part of the immediate emergency response. Standardised ash hazard characterisation protocols are available on the website of the International Volcanic Health Hazard Network (IVHHN)[9]. These include protocols for collecting ash samples, assessing the ash for respiratory hazard including particle size distribution, and assessing the leachable element burden (surface coating). Ash hazard analyses are carried out on bulk samples collected from fall deposits. Ash samples need to be collected in a pristine state prior to rainfall; once ash is affected by rain only limited information can be obtained from analyses.

In Aotearoa New Zealand, this work will be coordinated by the New Zealand Volcanic Science Advisory Panel, carried out in a range of university and government laboratories across the country, and results disseminated to stakeholders.

		
Coarse basaltic tephra, Pacaya volcano, Guatemala	Andesitic ash, Ruapehu volcano, New Zealand	Rhyolitic ash, Chaitén volcano, Chile

Figure 5 Variable types of tephra. All these types may be generated by Aotearoa New Zealand volcanoes.

4.2.1 Respiratory ash hazard assessment

A protocol for assessing the respiratory health hazard of volcanic ash samples is included as Appendix 2 ('the IVHHN protocol'). As a first step, a particle size distribution is obtained for each bulk ash sample. This is the most important predictor of the potential of the ash to cause respiratory impacts because particle size determines how deeply inhaled particles can penetrate into the respiratory system, which in turn influences the potential health outcomes (Figure 6). Following particle size screening (Phase 2 of the IVHHN protocol), a range of further analyses may be carried out. These will include determining leachable element concentrations, the presence of fibrous or needle-like particles and crystalline silica. Other analyses may be carried out if warranted.

[9] https://www.ivhhn.org/guidelines#ash-collection

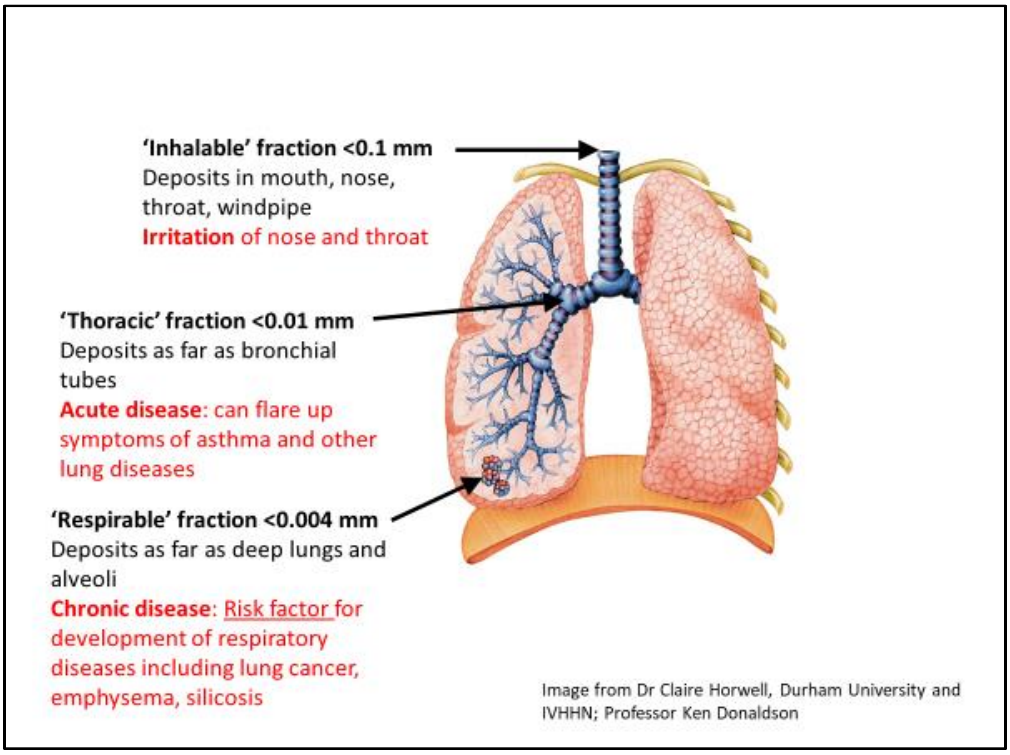

Figure 6 Schematic depiction of human respiratory system illustrating dependence of health outcomes on size of inhaled particles.

4.2.2 Ash characteristics relevant to lifeline utilities

The properties of an ashfall sample relevant to lifeline utilities are presented and discussed in Table 4.

Table 4 Ash characteristics of particular relevance to lifeline utilities

Parameter	Importance
Grainsize distribution	Ashfalls with high proportion of fine material (<100 µm/0.1 mm) · Have a higher potential for becoming remobilized/airborne due to wind, traffic and/or clean-up activities, which will affect visibility · Pose a greater respiratory hazard to field crews, particularly if proportion <10 µm (0.01 mm) is high · May adhere to insulators more strongly, increasing flashover potential
Leachate pH	Ashfalls with more acidic leachates (pH 5 or lower) · Will have a higher potential to cause eye, skin and respiratory tract irritation to field crews · Will be more corrosive towards metal surfaces
Leachate conductivity	Ashfalls with high conductivity[1] (dissolved salt burden) · Will be more corrosive towards metal surfaces · Will have higher potential to initiate flashover

1 Conductivity is a convenient proxy for ESDD (Equivalent Salt Deposit Density, Wardman et al. 2012)

4.3 Hazards of working in volcanic ash environments and recommended safe practices

The following sections are based primarily on guidance from WorkSafe New Zealand and supplemented by the experience of the authors where necessary.

4.3.1 General advice for field teams working in volcanic ash environments

- Ensure that workers are provided with appropriate PPE (long clothing such as overalls, heavy footwear, gloves, goggles without side vents, hard hat, RPE);
- Monitor worker wellbeing closely: pay attention to fatigue and overheating;
- Provide facilities to remove ash-contaminated clothing and showering facilities as well as eyewash stations;
- Workers with pre-existing respiratory conditions should avoid working in ashy conditions;
- Ensure that there is a process is in place to notify WorkSafe of any incidents.

4.3.2 Respiratory health hazards

Airborne ash is a respiratory hazard and can also irritate exposed eyes and skin. Concentrations of ash in air can be high when ash is falling or when ash deposits on the ground become remobilised (lifted into the air). Resuspension is promoted by deposits having higher proportions of fine particle sizes, by dry conditions, and by wind, traffic and clean-up activities.

In general, the health impacts of exposure to airborne ash (in the absence of any mitigation measures) depend on ash concentrations in the air (reported as particulate matter (PM) in the health-relevant metrics $PM_{2.5}$ and/or PM_{10}, in units of $\mu g/m^3$), the characteristics of the ash, individual vulnerability and duration of exposure. Short-term effects of exposure to volcanic PM can include irritation of the nose, throat, eyes or skin; a cough or phlegm; chest tightness or irritation; shortness of breath; headache; worsening of asthma symptoms (wheezing); and cardiovascular effects.

Within the community, vulnerable groups include people with pre-existing lung conditions such as asthma, chronic obstructive pulmonary disease (COPD) or chronic bronchitis; those with cardiorespiratory disease, babies, children and older adults. Undiagnosed asthmatics are particularly vulnerable as they are unlikely to recognise the onset of asthma symptoms or to have preventer or reliever medication at hand.

4.3.2.1 Workplace Exposure Standards for airborne PM

Workplace Exposure Standards (WES) are guidance values provided by WorkSafe NZ. They refer to the airborne concentrations of substances at which it is believed that nearly all workers can be repeatedly exposed day after day without coming to harm. They are intended to be used as guidelines for risk management.

There are two applicable WES for airborne PM. These are for inhalable dust (not otherwise classified) and respirable dust (not otherwise classified) (Table 5). These are both time-weighted averages (TWAs) which are the average airborne concentrations calculated over an eight-hour working day.

Table 5 Workplace exposure standards for inhalable and respirable dust

	Definition	WES-TWA	Particle size fraction
Inhalable dust	The portion of airborne PM taken in through mouth and nose during breathing.	10 mg/m^3	<100 µm (0.1 mm) equivalent to PM_{100}
Respirable dust	The portion of inhalable dust that penetrates and deposits in the lower bronchioles and alveolar region of deep lungs.	3 mg/m^3	<4 µm (0.004 mm) equivalent to PM_4

We note that in practice, most airborne PM concentrations measured in recent volcanic eruptions globally have been considerably lower than the WES. The best-documented example in recent years is the 1995-2003 explosive eruption of La Soufrière volcano, Montserrat, which subjected residents to prolonged exposure to high concentrations of fine airborne ash. Exposures for both the community and different occupational groups were assessed by a team of occupational medicine specialists (Searl et al., 2002). For 172 environmental samples collected using standard occupational hygiene methods, the range for respirable dust was <0.005-0.96 mg/m^3, with means ranging from 0.021-0.24 mg/m^3. No measurements exceeded the NZ WES for respirable dust.

Searl et al. (2002) also assessed personal exposures to respirable dust for a range of occupations. They noted that activities such as cleaning, gardening or clearing roads disturbed deposited ash such that workers created dust clouds around themselves. The highest personal exposures were for road workers, with mean concentrations of over 20 mg/m^3. For all other occupational groups including police at checkpoints, gardeners, and housekeepers, mean concentrations remained below 1 mg/m^3.

4.3.2.2 Alternative workplace exposure standards

PCBUs who wish to take a more precautionary approach to respiratory protection may wish to consider applying the following workplace exposure standards or limits for respirable dust used in other jurisdictions (Table 6). We note that the British Institute of Occupational Medicine considers the current UK workplace exposure limit for respirable dust of 4 mg/m^3 to be unsafe (IOM, 2011), and recommends that employers aim to keep exposure to respirable dust below 1 mg/m^3. This stance is supported by other occupational medicine specialists (Cherrie et al., 2013).

Table 6 Current workplace exposure standards or limits for respirable dust used in other jurisdictions

	Respirable dust limit/ standard as TWA	Notes	Reference
Germany	1.25 mg/m^3	General Dust Limit Value (respirable)	DGUV (2020)
Australia	1.5 mg/m^3	WES for coal dust (containing <5% quartz) (respirable dust)	Safe Work Australia (2024)
United Kingdom	4 mg/m3	Current workplace exposure limit under the Control of Substances Hazardous to Health Regulations 2002	HSE (2020) EH40/2005
United Kingdom	1 mg/m^3	More protective limit recommended by British Institute of Occupational Medicine	IOM (2011); Cherrie et al. (2013)

4.3.2.3 Aotearoa New Zealand and international air quality guidelines for airborne PM

Aotearoa New Zealand and international ambient air quality guidelines for community protection are shown in Table 6. They are intended to protect the most-vulnerable groups in the community. We emphasise that they do not apply in workplaces, but we include them here as data on airborne ash (measured as PM_{10} and $PM_{2.5}$) can provide important situational awareness information. For example, high levels of airborne PM will reduce visibility, which affects driving conditions (see Section 4.3.4).

Table 6 Regulatory and recommended guidelines for airborne particulate matter (PM).

	PM_{10} (µg/m^3)		$PM_{2.5}$ (µg/m^3)	
Time averaging period	24 hour	Annual	24 hour	Annual
NZ NES-AQ[1]	50	-	25[2]	10[2]
NZ NAAQG[3]	-	20	25	10
WHO 2021[4]	45	15	15	5

[1] NZ National Environmental Standards for Air Quality. These are legally enforceable with one allowance of this value permitted annually.
[2] Proposed new NES-AQ for PM2.5, Ministry for the Environment (2020)
[3] National Ambient Air Quality Guidelines
[4] https://apps.who.int/iris/handle/10665/345329

4.3.2.4 Exposure assessment

Workplace exposure standards apply to concentration measurements made in the worker's breathing zone. As noted by Searl et al. (2002), personal exposures following ashfall can be considerably higher than environmental exposures because the workers disturb the fallen ash and create dust clouds around themselves.

For inhalable dust, WorkSafe suggest the use of Method AS 3640-2009, and for respirable dust Method AS 2985-2009. Both documents are available from Standards Australia[10]. In the event of an eruption, particularly an unheralded eruption, PCBUs may not find it practicable to adopt these specialised methods if they are not part of their regular monitoring activities. Low- to medium-cost options for monitoring airborne PM include portable instruments and sensors. Further details about these options are available as an IVHHN Crisis Briefing Note[11] and in Appendix 2. Instruments such as the DustTrak have successfully been used to determine airborne PM concentrations following eruptions (Searl et al., 2002; Damby et al., 2013) and would have utility as a screening tool.

Airborne PM (PM_{10} and $PM_{2.5}$) is also measured by some regional councils throughout NZ. Monitoring stations can be visualised at the site www.lawa.org.nz. Data are reported on this site as running

[10] https://www.standards.org.au/
[11] https://www.ivhhn.org/uploads/IVHHN_briefing_note_air_quality_monitoring.pdf

hourly, daily, monthly and annual averages, and in relation to regulatory guidelines (Table 6) and may be useful for situational awareness.

4.3.2.5 Crystalline silica hazard

Silicosis is a progressive and deadly occupational lung disease caused by the inhalation of crystalline silica. Volcanic ash can contain respirable crystalline silica, particularly from magmas containing high amounts of SiO_2 (andesitic, dacitic or rhyolitic magmas, known as 'silicic' compositions) or eruptions that destroy lava domes. While no cases of silicosis have yet been definitively attributed to volcanic ash exposure, monitoring of this hazard following volcanic ashfall is essential to inform responses to public and workplace safety concerns. Analysis of bulk ash samples to determine crystalline silica content is conducted where the eruption is known to have a silicic composition or to have destroyed lava domes, and when performed rapidly, will inform initial hazard assessment. Monitoring of airborne concentrations of respirable crystalline silica may then be required. This is a specialised procedure for which we advise engaging the services of an occupational hygienist. There is an applicable Workplace Exposure Standard (WES-TWA[12]) of 0.025 mg/m^3 (WorkSafe New Zealand, 2022).

4.3.2.6 Respiratory protective equipment (RPE)

Respiratory protective equipment (RPE) is a type of personal protective equipment (PPE) that protects people from inhaling substances, including airborne volcanic ash, that may be hazardous to health. Common types of RPE are shown in Figure 7.

For working in ashy conditions, outdoor workers should wear disposable respirators, also known as filtering facepieces. Respirators must be industry certified (N95, P2 or equivalent). Fit testing is required for all types of respirators. Facial hair and stubble prevent masks fitting well. PCBUs should seek advice from an occupational hygienist or similarly qualified professional.

A further consideration is that wearing respirators can impose stress on the heart and lungs, particularly for workers who wear RPE for extended periods and suffer from conditions such as emphysema, asthma, heart disease or claustrophobia. Duration of exposure is a critical consideration.

Readers are referred to WorkSafe's guide[13] on 'Respiratory protective equipment - advice for businesses' for further information on the duties of PCBUs in relation to RPE.

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[12] https://www.worksafe.govt.nz/topic-and-industry/monitoring/workplace-exposure-standards-and-biological-exposure-indices/all-substances/view/silica-crystalline-all-forms

[13] https://www.WorkSafe.govt.nz/topic-and-industry/personal-protective-equipment-ppe/respiratory-protective-equipment/

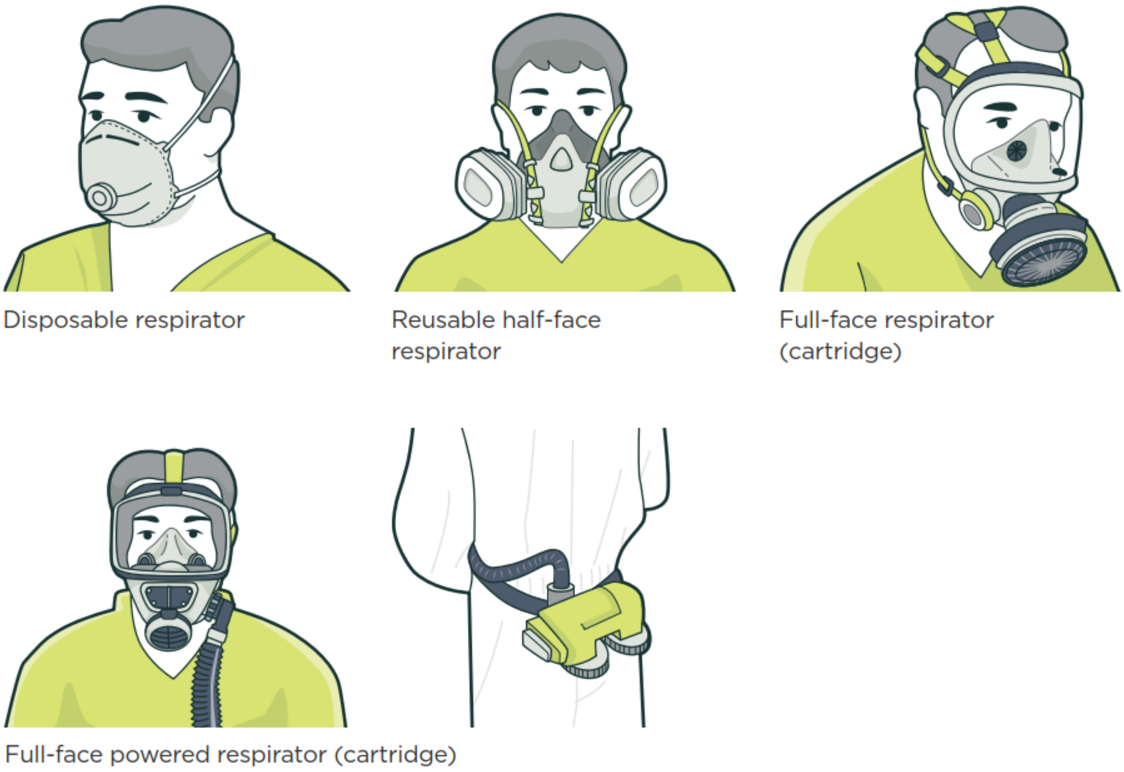

Figure 7 Common types of RPE (from WorkSafe NZ)

4.3.3 Working on roofs or ladders

Following an eruption, cleaning of ash from roofs and other structures is likely to be necessary. Working at height is highly hazardous, and WorkSafe has produced detailed and comprehensive best practice guidelines and/or fact sheets for working at height[14], working on roofs[15] and working with ladders and stepladders[16].

We further note that the presence of volcanic ash makes working at height additionally hazardous, because ash makes surfaces slippery, can reduce visibility, and can conceal hazards such as brittle areas of roof cladding. Many injuries and some fatalities have occurred while clearing ash from roofs, either due to falls or roof collapse.

Recommended safe practices for clearing ash from roofs, additional to WorkSafe best practice guidelines[8,9,10]:

- Keep at least 6 metres away from any electricity or telephone lines.
- Be aware that roofs may have reduced capacity due to ash loading.
- Be aware that ash-covered surfaces are slippery; do not work on steep roof sections.
- Consider placing crawl boards or roof ladders on the roof for more secure footing. This is also recommended if areas of brittle roof cladding are suspected.

[14] https://www.WorkSafe.govt.nz/topic-and-industry/working-at-height/working-at-height-in-nz/
[15] https://www.WorkSafe.govt.nz/topic-and-industry/working-at-height/roofs/working-on-roofs-gpg/
[16] https://www.WorkSafe.govt.nz/topic-and-industry/working-at-height/safe-working-with-ladders-and-stepladders-construction/#:~:text=Ensure%20that%20the%20stepladder%20is,two%20steps%20of%20the%20stepladder.

- Avoid any weak sections of the roof such as skylights or Perspex panels and be aware that ash will cover weak sections of roof cladding.
- People working on a steel-clad roof should always step along the lines of nails/screws, if visible, and avoid working too closely together.
- A broom is usually the best option for clearing ash from a roof. Sweep the ash off the edge of the roof onto the ground. Remove ash from gutters with a scoop. It is preferable to remove ash while it is dry. Be mindful of workers downwind.
- Isolate the area below the roof cleaning work to protect people on the ground from falling debris.
- When piling ash on the ground, don’t block building fire exits.

4.3.4 Driving

Driving in ashy conditions is hazardous due to loss of traction on roads, coverage of road markings, reduced visibility, and potential problems with vehicle operation. Driving while ash is falling, or during a resuspension episode, is like driving in a whiteout. Ash entering and blocking drains can also cause surface flooding, exacerbating driving conditions.

Recommended safe practices for driving in ashy conditions:

- Drive to the conditions: reduce speed and maintain safe following distances.
- Consider using slow-moving, well-spaced convoys of vehicles (in partnership with other infrastructure providers).
- Use headlights.
- Carry spare air filters in vehicles.
- Avoid using wipers as ash will scratch windscreens.
- Be aware of reduced traction when driving off-road.
- Set air conditioning to recirculate to keep ash-laden air out of car.
- Increase preventive maintenance on vehicle fleet.
    - Clean vehicles thoroughly when back at base.
    - Check, clean and/or replace air and oil filters regularly.
    - Apply lubricant/grease more frequently and check for wear.
    - Rinse ash from windscreens and vehicle paintwork with water.

4.3.5 Electrical safety risks

Ash contamination of line and substation insulators can lead to flashover, particularly in conditions of light precipitation such as dew, fog, drizzle or light rain. Cleaning ash from line insulators and from substation equipment is required to reduce this risk but can be hazardous. For comprehensive advice on cleaning station and line insulators, readers are directed to IEEE Standard 957 (2005)[17].

Recommended safe practices for cleaning ash from substation equipment and line insulators:

- <u>All substation equipment should be de-energised and earthed before cleaning</u>
    - Clean ash from transformer bushings and radiator fins by hand, using soft rags followed by high-pressure washing.
    - Insulators, bus bars, circuit breakers, metering transformers and other critical apparatus should be cleaned by hand in a similar procedure as for transformers. Ensure that all surfaces are cleaned, including the undersides of insulator sheds.

[17] https://standards.ieee.org/ieee/957/1327/

    - If ash is strongly adhered to ceramic surfaces, then measures such as using steel wool or solvents or detergents may be necessary. However, care must be taken not to damage insulator surfaces or leave a residue of metal particles.
    - The substation can be re-energised once all equipment has been dried using soft rags.
- For cleaning line insulators, it may be possible to clean some sections of the system without de-energising. For live line cleaning:
    - Compressed air can be used to remove initial large amounts of ash (>3 mm deposit thickness). Limit air pressure to <210 kPa (<30 psi) to avoid 'sandblasting' of ceramic surfaces. Avoid blowing ash into other equipment.
    - A set of insulated tools for wiping, brushing and washing ash from energised equipment should be devised (refer to IEEE Standard 957).
    - If ash has become cemented onto insulators, water blasting may be required to remove it.

4.3.6 Building collapse from ash loading

A common concern during and after volcanic ashfall is structural damage and potential collapse of buildings from the weight of accumulated ash on roofs. However, this is a rare impact as it requires very thick deposits of ash to accumulate on roofs/buildings (for buildings in Aotearoa New Zealand, typically >200 mm dry ashfall or >100 mm wet ashfall). Buildings closest to eruption vents are most exposed to thick ashfalls and are thus generally most at risk of structural damage from ash loading.

Non-engineered, long span and low-pitched roofs are more vulnerable to collapse. Roof cladding with pre-existing damage such as corrosion may also be more vulnerable to collapse. Lifeline utilities should be mindful of lightly- or non-engineered structures (such as equipment sheds or lean-tos) which are typically most at risk. Be mindful that non-structural elements (e.g., gutters) are much more vulnerable to breaking and creating a hazard for people or equipment underneath. Gutters are particularly at risk of collapse, as they accumulate ash sliding from the roof catchment.

Our recommendation is that organisations monitor the accumulation of ash on roofs and avoid entering buildings or structures potentially at risk of collapse. Operational plans should include provision for assessing the safety of buildings with thick (>50 mm) ashfall deposits on the roof.

4.3.7 Strain injuries

Volcanic ash is heavier than many people expect, and ash clean-up is a time-consuming and physically demanding process.

Recommended practices to reduce the likelihood of strain injuries:

- Practice safe lifting techniques.
- Ensure that that the work demands match the worker's abilities - no worker should lift something that is too heavy for them.
- Provide the right tools for the job.
- Ensure that workers take regular breaks and stay hydrated.
- Do not overfill bags to be lifted or carried.
- Use wheelbarrows to move loads of ash.

We refer readers to WorkSafe resources on preventing manual handling injuries[18], and on managing fatigue[19] and strain and sprain risks[20] when handling contaminated flood silt following Cyclone Gabrielle.

[18] https://www.WorkSafe.govt.nz/topic-and-industry/manual-handling/preventing-manual-handling-injuries-acop/
[19] https://www.WorkSafe.govt.nz/managing-health-and-safety/keeping-safe-during-cyclone-and-flooding-recovery/managing-fatigue-after-cyclone-gabrielle/
[20] https://www.WorkSafe.govt.nz/managing-health-and-safety/keeping-safe-during-cyclone-and-flooding-recovery/managing-strain-and-sprain-risks-after-cyclone-gabrielle/

5 Volcanic life safety hazards and risk management

Volcanoes can create a range of direct and indirect life safety hazards (Figure 2 and Table 2), which require risk management. **We emphasise that for highly destructive, fast-moving and lethal hazards such as pyroclastic density currents (PDCs) and volcanic ballistic projectiles (VBPs), complete avoidance of risk zones is the best risk management approach.** However, if workers do need to access risk zones, we have provided current best practice advice on PPE and safety measures in Section 5.4.

The establishment of an exclusion zone or zones is a common risk management strategy, particularly around any eruptive vent and in areas expected to be impacted by PDCs and lahars, the latter of which may continue to generate life safety risks for months or even years after an eruption ends. A common observation from eruptions around the world is that risk tolerances may evolve, especially following the initial phase of an eruption, when reasons to enter exclusion zones may become more compelling, e.g., for repairs to lifelines. Thus, cordon management may move from a primary focus on life safety to a focus on restoring livelihoods and habitability and promoting recovery.

There is growing interest in the strategy of 'managed access', which allows for permeable cordons around exclusion zones. Managed access typically involves restricted and short-duration daytime access in close partnership with emergency management personnel. The National Emergency Management Agency (formerly Ministry of Civil Defence and Emergency Management) Director's Guidelines on Emergency Movement Control (2015) state that the main drivers of emergency access for lifeline utilities are: service continuity to the wider community, public safety (e.g. isolation of electricity and gas), worker safety, and asset protection.

Lack of clarity between partners involved in cordon management can hamper access by infrastructure providers, which may in turn hamper response and recovery objectives. The 2015 Director's Guidelines note that it is crucial that lifelines coordinators are involved in movement control planning and are regularly updated.

5.1 Key considerations for planning work in managed access zones

1) Coordinate with local Civil Defence Emergency Management and/or DOC (i.e.. the local Risk Manager). Expect to provide justification for the proposed work, plus scope and timing.
2) Ensure national and regional lifelines advisory groups are involved in coordination.
3) Obtain up-to-date process and ideally hazard forecasts and science advice from relevant science agencies (coordinated with and possibly via CDEM and/or DOC), and consider your own risk calculation, acceptability and risk management. This should include GNS Science (including GeoNet), Metservice, and regional councils for flood forecasts.
4) If necessary, seek advice on use of PPE and RPE from suitably qualified professionals such as occupational hygienists with experience in disaster response.

5.2 General considerations for working in managed access zones around active volcanoes

Volcanic activity can be prolonged and can present multiple hazards at different times. Some hazards, such as lahars, can occur without a new eruption, and hazardous conditions can persist for months or years.

It is vital to minimise time spent in hazard zones, to minimise exposure. Field teams entering hazard zones should be kept to an appropriate minimum and should have clear roles, appropriate training and experience with PPE. Workers should use equipment they are familiar with and are trained to use.

It is important to remember that there is no PPE that will offer full protection from all volcanic hazards. Additionally, PPE may affect the comfort and mobility of wearers. Bulky, heavy PPE will slow the wearer and increase exposure time; it may impede vision and hearing, reducing situational awareness and possibly exacerbating other risks; and it may be very hot, leading to fatigue and dehydration. Hydration prior to and, if possible, during deployment using sports supplement drinks or similar is recommended. Regular welfare checks of field teams should be carried out. Hazard-specific PPE and RPE are covered in Section 5.4.

Within hazard zones, field teams should minimise time spent in channels and topographic lows. Flow hazards such as lahars and PDCs travel down channels and asphyxiant gases can accumulate in topographic lows. This includes repair work on bridges and aerial pipe crossings.

Response plans should be made before entering the hazard zone, including access and egress points and emergency evacuation procedures. Recognise that helicopter support for evacuation may not be an option due to the effects of ash on aircraft. Consider making an escape or shelter plan, ideally with multiple contingencies.

Workers should carry radios (HF, UHF or VHF) and/or satellite phones and/or cellphones, and personal locator beacons. Communication devices should be tested in the working conditions.

Field teams must be able to conduct their own dynamic risk assessments as conditions change. Consider including a sentry or 'spotter' in the team to maintain situational awareness. Mark routes in and out of an area with highly visible poles or flags. Ensure field team members remain within sight of each other at all times. A drone fly-through is helpful for up-to-date ground orientation.

Advice should be sought from GeoNet and appropriate volcanic hazard and risk scientists respectively about important changes in volcanic activity and consequences for hazard and risk. There should be continuous communication between volcano monitoring staff, local Civil Defence Emergency Management and/or DOC (i.e.. the local risk manager) and field teams. Field teams must also monitor weather conditions and understand the implications of changes in the weather, such as an increased risk of lahars in heavy rainfall.

5.3 General ground conditions during and after eruptions

Landscapes may be completely unrecognisable following an eruption. Landmarks, buildings, roads and waterways may be buried in debris and deposits or destroyed. Airborne ash can reduce visibility. If possible, overlay the hazard footprint on a map for planning, and use GPS and aerial support in the field.

A common impact is the change to local and regional drainages, with remobilisation creating a very dynamic and unstable environment for months to years post eruption.

Volcanic deposits (e.g., from PDCs, lava flows and lahars) may remain hot enough to burn skin or ignite fires for a considerable time after the initial eruptions and may be unstable and dangerous to walk on. They may also continue to discharge volcanic gases, which should be monitored for using personal or handheld devices. People accessing an area on foot should carry stainless steel poles to probe the ground ahead. Good quality footwear with vulcanised rubber soles (such as Vibram) should be worn.

5.4 General cautions on RPE use

In general, we caution that providing workers with RPE is not a quick and easy fix to manage risks, and specialised expertise and training is required, as well as awareness of any competency requirements[21]. For PCBUs for whom this is not business as usual, we advise seeking guidance from a workplace health and safety professional with expertise in disaster response (see HASANZ Register[22] for a directory of registered Occupational Hygienists).

Specific consideration needs to be given to the following issues:

- RPE needs to be certified to a recognised standard such as SA/SNZ ISO 16975-2:2023
- Appropriate choice of respirators:
    - IDLH[23] limits can assist in making decisions about the appropriate respirator to use. Above the ILDH, only supplied air respirators should be used; below the IDLH, air-purifying respirators may be used. However, the use of supplied air (closed circuit) systems may not be practicable as they are very expensive and require significant training to use and there is a limited number of currently trained in the use of these systems.
- Workers need to be trained in the care and maintenance of RPE.
- Workers should undergo a medical evaluation prior to wearing RPE.
- Fit-testing of RPE is essential, with facial hair and stubble preventing a good fit.
- Workers must wear personal gas detectors with alarms linked to actions at preset levels.
- The PCBU should have a written gas detection programme that covers the selection, use, storage, maintenance and calibration of the system, reviewed by a suitably qualified health and safety professional.

[21] https://www.worksafe.govt.nz/topic-and-industry/personal-protective-equipment-ppe/respiratory-protective-equipment/
[22] https://www.hasanz.org.nz/hasanz-register
[23] Concentrations immediately dangerous to life and health; see Tables 8 and 9

5.5 Specific impacts and mitigation information for different volcanic life safety hazards

5.5.1 Pyroclastic density currents (PDCs)

PDCs include pyroclastic flows and surges. These are hot, ground-hugging mixtures of ash, gas and rock fragments that travel away from vents at high speeds for tens of kilometres (Figure 8). They are highly destructive and lethal, and mortality rates of people overrun by PDCs are typically >90% (Baker et al., 2021). PDCs cause severe skin burns and inhalation injuries to the upper and lower respiratory tract, as well as trauma injuries from entrained debris. PDCs can ignite or melt clothing and ignite buildings or vegetation. PDCs may also contain harmful concentrations of acidic volcanic gases, particularly SO_2, HCl and sometimes HF.

Figure 8 Pyroclastic flows travelling down the flanks of Ngāuruhoe volcano on 19 February 1975. Photo by Graham Hancox, made available under Creative Commons license.

Fresh PDC deposits can be hazardous for a considerable time after the initial eruption. Even after the surface has cooled, the subsurface can remain hot enough to cause severe burns, for days or longer. PDC surfaces may be unstable and conceal obstacles, cavities and pockets of steam. Streams draining fresh PDC deposits may be hot enough to cause burns.

Avoidance is the best risk management approach. However, if workers do need to access PDC risk zones current best practice advice is as follows:

- PPE: No PPE will give complete protection from PDCs. The following may provide partial protection: Heat-shielded self-contained breathing apparatus[24]; hard hat; heatproof and chemical-resistant clothing (such as Tychem® coveralls over charcoal-impregnated suit); heatproof and chemical-resistant gloves; heatproof and chemical-resistant boots (such as butyl rubber). See Section 5.5.5.1 for advice on cartridges and filters for respirators.
- Safety measures: take shelter from approaching PDCs if possible. Even sheltering behind boulders, or huddling together as a group, may offer some protection. If working on fresh PDC deposits, carry a stainless steel probe to test the ground ahead for unstable areas or hidden hazards.

5.5.1.1 Lessons from the 2019 Whakaari eruption

On 9 December 2019, Whakaari volcano had a sudden eruption at 2:11 PM. Forty-seven people were on the island at the time, in three different tour groups at different locations from the vent (Figure 9). A base surge (a type of PDC) travelled across the floor of the crater at approximately 10-15 m/s, thus the three groups had varying amounts of time to seek cover depending on their distance from the vent and how visible the eruption was to them (Burnett and Taylor, 2021). All people had been provided with activated charcoal respirators for protection against some gases and PM. Most were dressed lightly as it was midsummer.

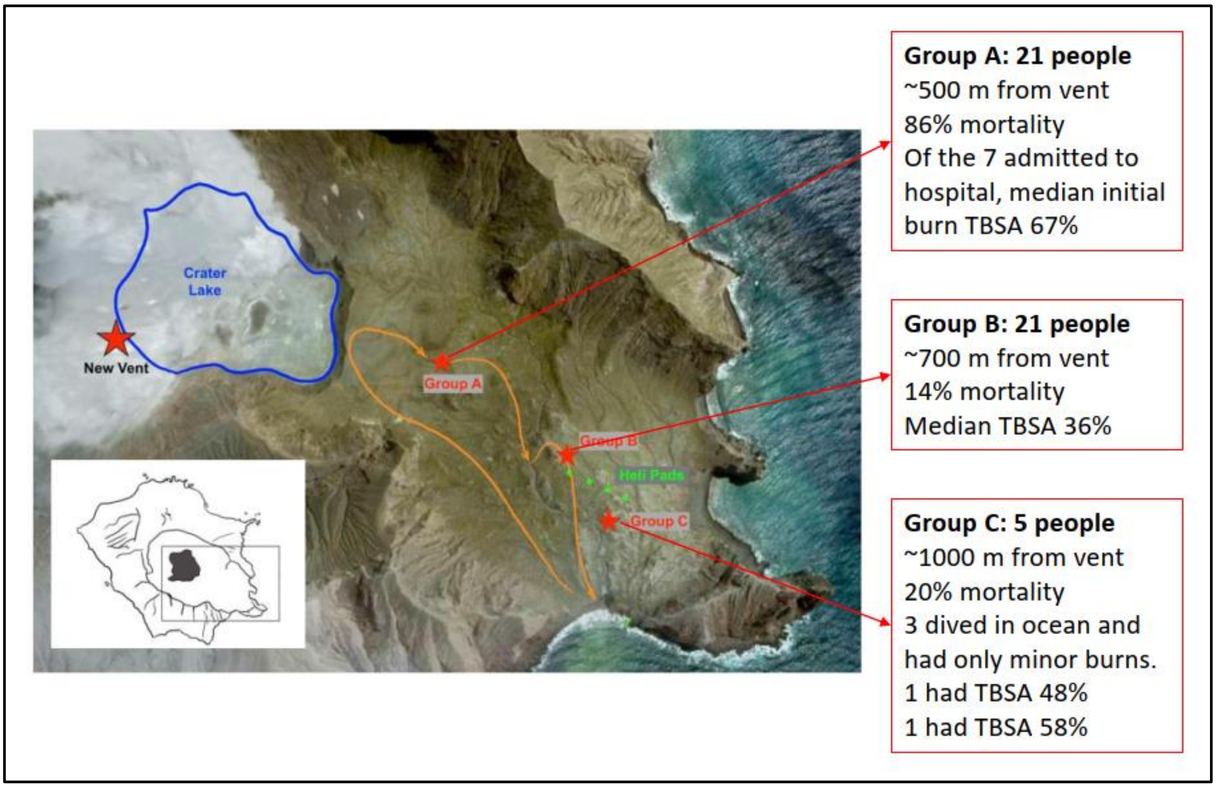

Figure 9 Map of walking tour route (in orange) and group locations relative to eruptive vent of Whakaari. TBSA refers to Total Body Surface Area with burns. Adapted from Burnett and Taylor (2021).

[24] Thermal Performance of Self-Contained Breathing Apparatus Facepiece Lenses Exposed to Radiant Heat Flux (nist.gov)

Group A (21 people) was closest to the vent, in an exposed location where the surge was hidden from view until it was upon them. This group had no chance to take cover and suffered the highest mortality rate of 86%, as well as the most severe burn trauma within the group who survived the eruption and were admitted to hospital.

Group B (21 people) was approximately 700 metres from the vent. This group had more advance warning of the surge, and their guides instructed them to seek shelter behind a large rock mound some 50 metres away, huddle together and put on respirators. This group had a much lower mortality rate of 14%, and a lower level of burn trauma. People not wearing respirators, or not able to re-don respirators displaced by the force of the surge, developed significant inhalation injuries. The party had variable exposure to the surge depending on their position within the group, with those near the centre more protected from the heat flux. The rock outcrop appears to have provided some protection from the full force of the surge.

Group C (5 people) was located 1 km from the vent and close to the shoreline. The surge took approximately 90 seconds to reach them, by which time three of this group had managed to submerge themselves in the ocean, and to remain underwater for the 30 seconds it took the surge to pass overhead. The two people exposed to the full force of the surge were badly burned and one later died.

The overall mortality rate for the eruption was 47%, which is notably low in comparison to most historical PDCs. Human factors contributing to this are the actions of the tour guides in Group B, which substantially reduced this group’s exposure to the full force of the surge, and the early first aid measures provided to people evacuated from the island. Other factors influencing the severity of outcomes were whether or not respirators were worn and the coverage of clothing worn, with even light clothing providing some protection from the surge (Baker et al., 2021; Burnett and Taylor, 2021). Clinicians observed that many patients had badly burned palms, which they attributed to survivors of the initial explosion crawling across hot surge deposits, and recommended adding gloves to the PPE for any personnel at risk of exposure to PDCs (Baker et al., 2021).

5.5.2 Volcanic Ballistic Projectiles (ballistics or VBPs)

Volcanic Ballistic Projectiles (ballistics or VBPs), known as blocks and bombs by volcanologists, are fragments of rock or lava, from a few cm to metres in diameter, thrown from a vent during explosive eruptions (Figure 10). They follow ballistic trajectories and typically land within 5 km of the vent although some may travel further. Bombs can also travel further by rolling or bouncing downhill (Day et al., 2022). Ballistics have very high kinetic energy and primarily cause trauma injuries, including blunt force trauma, fractures, and lacerations, as well as causing serious damage to buildings (Williams et al., 2017). Hot ballistics can melt or ignite clothing or other materials, including sparking vegetation or building fires. Contact with the skin can cause full thickness burns.

Figure 10 Left: Large volcanic bomb from 2021 La Palma eruption, Canary Islands, Spain. Right: Damage caused by ballistics to Ketetahi Hut on the Tongariro Alpine Crossing from the 2012 eruption of Te Maari vent, Tongariro volcano. Photo credits: Left: Photo from James Day, Day et al. (2022), available under licence CC BY 4.0. Right: Photo by Nick Kennedy, University of Canterbury.

Avoidance is the best risk management approach. However, if workers do need to access ballistic risk zones current best practice advice is as follows:

- PPE: No PPE will give complete protection from larger or higher energy VPBs. The following may provide partial protection: hard hats to protect against smaller VBPs, heat-protective clothing that will not melt or ignite; sturdy heatproof boots and gloves.
- Safety measures: If ballistics are falling, move out of their path, seek shelter, cover your head and make yourself a small target (Fitzgerald et al., 2017). Backpacks have successfully been used as shields for smaller ballistics. Ballistics that do not move across your field of view are likely to be travelling straight towards you. Buildings will offer some protection, but projectiles can penetrate some roofs. Actions likely to increase life safety include sheltering on the side of the building facing away from the vent, dropping to the ground and covering your head, and, if indoors, putting as many barriers between yourself and incoming

projectiles by sheltering under structures such as tables (Figure 11; Williams et al., 2017; Oikawa et al., 2016). Close to the vent, ballistics may have more horizontal trajectories, threatening your whole body. Sheltering behind boulders or other solid obstacles may offer some protection.

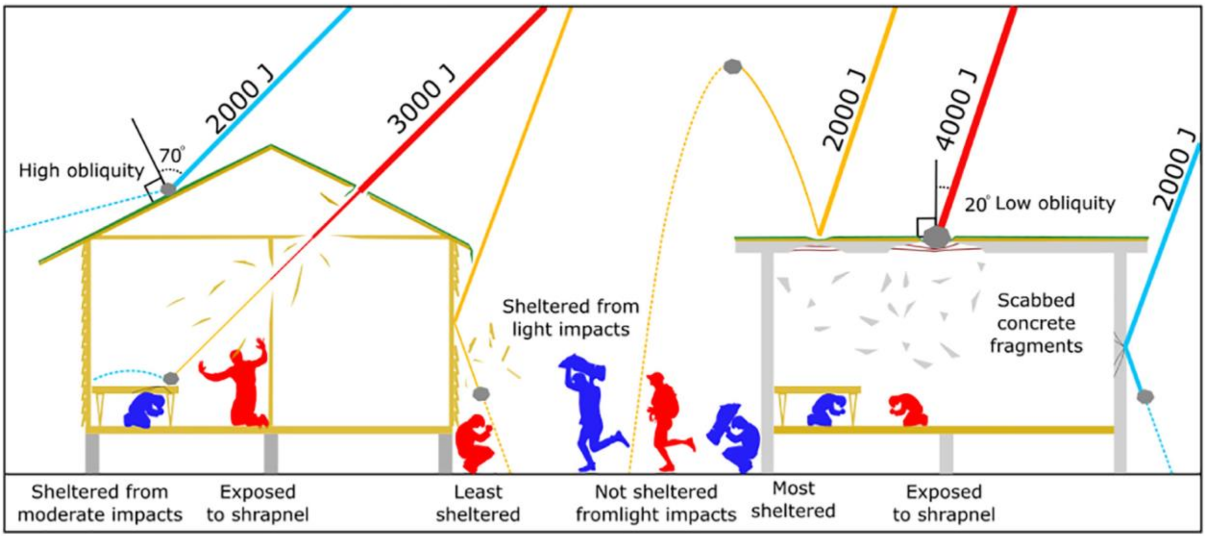

Figure 11 Likely ballistic damage to buildings at different impact energies (in joules, J) and angles, with pairs of figures illustrating actions likely to increase life safety (blue) and actions likely to decrease life safety (red). From: Williams et al. (2017).

5.5.3 Lava flows

Lava flows are rivers of molten rock. They develop a dark surface as they cool, but this may conceal a molten centre under a fragile surface. Lava flows are rarely life-threatening because they typically move slowly enough that people can move out of the way easily. However, fatalities have occurred in fluid fast-moving flows or if lines of retreat are cut off. Lava fronts can be highly unstable, particularly on steeper slopes, and large blocks can break off and roll down (Figure 12). Fully cooled lava surfaces may be fragile, hollow and unstable.

Lava can cause severe burns through direct contact, by radiant heat or from secondary fires, as lava can ignite flammable material such as wooden buildings and vegetation. Combustion can generate a complex mixture of fine PM including black carbon, gases such as carbon monoxide, methane, and other combustion products, which can cause severe deterioration of air quality.

Explosions may occur if lava flows reach water bodies or ice, endangering anyone within range of debris. If lava flows into seawater, it reacts vigorously to generate acidic steam plumes ('laze') laden with HCl gas and volcanic glass particles. Two fatalities in Hawaii Volcanoes National Park in 2000 were attributed to volcanic laze (Heggie et al., 2009). Fatalities have occurred when lava has caused fuel tanks to explode. If lava flows enter grasslands or forests, methane explosions can occur around the margins of the flow.

Further away from active lava flows, the main hazard is high ground level concentrations of SO_2 gas (Barsotti et al., 2023). Close to erupting vents or fissures, SO_2 concentrations may be life-threatening.

Figure 12 A slow-moving lava flow advancing down the flank of Mayon volcano, Philippines, 1993. Photo by Philippine Institute of Volcanology and Seismology, made available as a Public Domain Work.

If workers do need to access lava flow hazard zones current best practice advice is as follows:

- PPE: Full length, heatproof clothing, boots and gloves, hard hats, fit-tested half or full-face respirators and gas sensors (Figure 7) should be worn. See section 5.5.5.1 for further information on gas cartridges for respirators. Note that disposable P2/N95 respirators do not provide any protection from volcanic gases.
- Safety measures: check projected lava flow paths before entering the hazard zone. Stay well back from active lava flows. Closely monitor the movement of the lava front and ensure that escape routes are not cut off. Monitor the heat hazard and gas concentrations and be aware of the potential of the lava flow to ignite flammable material and start fires. If working on cooled lava flows, be aware that surfaces can be fragile and very sharp, and severe lacerations can result from falls.

5.5.4 Lahars (volcanic mudflows)

Lahars are masses of rock, mud and water that travel rapidly down valleys (Figure 13) and sometimes overtop banks. Eruptions may trigger lahars by melting snow or ejecting water from a crater lake, but lahars can also be triggered by intense or prolonged rainfall mobilising tephra deposits during and after eruptions.

Injuries are similar to non-volcanic mudflows and landslides, with drowning and trauma from debris. However, lahars are sometimes hot enough to cause burns, or can be acidic (such as lahars from Mt Ruapehu's crater lake).

Lahar deposits are also similar to other mudflows, being potentially unstable, obscuring obstacles and cavities and containing a range of debris. They can set like concrete and be very difficult to extract casualties from or to travel over. Subsequent rainfall can remobilise lahar deposits and can cause substantial landscape change over short periods of time.

Figure 13 View of Whangaehu river from road bridge at Tangiwai, showing deposits from the 2007 Ruapehu crater lake breakout lahar. The lahar covered the carpark area at the left of the photo. (Wikimedia Commons)

Avoidance is the only protection against lahars. If work requires working on or crossing a fresh lahar deposit, best practice advice is as follows:

- PPE: wear sturdy, waterproof and heatproof boots, trousers and gloves, to protect in case of sinking into hot mud, and to protect against sharp objects.
- Safety measures: if crossing fresh lahar deposits, lay materials such as planks across the deposits for access. Deposits can be highly unstable and erodible, so care needs to be taken, especially working adjacent to undercut and unstable deposits. Wash mud off exposed skin to prevent irritation. If a new lahar approaches, move quickly out of valleys and to higher ground. Keep a close eye on weather forecasts and be aware that heavy rainfall may trigger lahars.

5.5.5 Volcanic gases

Volcanic gases may be primarily categorised as irritants or asphyxiants. Irritant gases cause tissue injury by direct contact due to their chemical reactivity. Asphyxiant gases either displace oxygen in the breathing atmosphere or interfere with oxygen utilisation in the body.

5.5.5.1 Irritant gases

Acidic volcanic gases such as sulfur dioxide (SO_2), hydrogen chloride (HCl), and hydrogen fluoride (HF) are irritants. Close to eruptive vents, SO_2 concentrations may be at extremely hazardous or lethal concentrations. HCl and HF concentrations close to eruptive vents are generally well below workplace exposure standards or effects thresholds and there have been no documented incidents involving high concentrations of these gases associated with volcanic activity hence they are not discussed further here[25].

The health impact of SO_2 varies considerably with concentration and duration of exposure. SO_2 is a fast-acting respiratory irritant, and short-term exposure can irritate the eyes, nose, throat and lungs, leading to coughing, wheezing and bronchoconstriction. High-risk groups include people with respiratory or heart conditions, older adults and children. Asthmatics are particularly sensitive to SO_2 exposure.

Short-term exposure guidelines are the most appropriate metrics to assess risk. Selected Aotearoa New Zealand and international short-term exposure guidelines for SO_2 are shown in Table 4. For workplaces, the Aotearoa New Zealand Workplace Exposure Standard short-term exposure limit (WES-STEL) of 660 µg/m^3 SO_2 applies to any 15-minute period in the working day.

Table 8 NZ and international short-term effects-based thresholds and workplace exposure standards for SO_2

Guideline	Effects	Exposure period						
		10 min	15 min	30 min	60 min	4 hr	8 hr	24 hr
		SO_2 concentration (µg/m^3)						
AEGL-1[1] (Level 1)	Notable discomfort and irritation, effects non-disabling, transient and reversible when exposure stops	520	-	520	520	520	520	-
AEGL-2 (Level 2)	Irreversible or other serious long-lasting health effects	2000	-	2000	2000	2000	2000	-
AEGL-3 (Level 3)	Life-threatening health effects or death	79000	-	79000	79000	50000	25000	-
IDLH[2]	Immediately dangerous to life or health	262,000						
NZ WES-STEL[3]		-	660	-	-	-	-	-

[1] https://www.epa.gov/aegl/sulfur-dioxide-results-aegl-program AEGLS are developed by a robust and formal process and describe the human health effects of infrequent, short-term exposures to high concentrations of airborne pollutants. They are designed to be protective of sensitive groups such as children, older adults and those with pre-existing respiratory conditions.
2 https://www.cdc.gov/niosh/idlh/intridl4.html
[3] NZ Workplace Exposure Standard Short-term Exposure Limit https://www.WorkSafe.govt.nz/topic-and-industry/monitoring/workplace-exposure-standards-and-biological-exposure-indices/all-substances/view/sulphur-dioxide

Low- to medium-cost sensor options for monitoring SO_2 include gas detection tubes, personal or handheld gas monitors, including personal gas detectors, and broadcast-capable sensors.

[25] https://www.ivhhn.org/information/information-different-volcanic-gases

Comprehensive details about these options are available as a IVHHN briefing note[26], and as Appendix 1.

The following best practice advice may enable work to be carried out in environments with SO_2 gas present in compliance with the exposure thresholds summarised in Table 8:

- PPE: chemical-resistant suits, half or full face respirators (Figure 7), personal gas monitors. Full face respirators, which cover the entire face, are preferable to avoid eye irritation. Glasses inserts can be used for full face respirators where prescription lenses are required. Fit testing of respirators is required. Respirators should be equipped with one of the following cartridges: multi-gas/vapour; organic vapour/acid gas; or acid gas. Additional particulate filters may also be useful depending on the situation. Manufacturers' instructions for care of respirators, cartridges and filters should be carefully followed and service life monitored.

Note: P2/N95 disposable respirators do not provide any protection from volcanic gases.

- Safety measures: Monitor SO_2 concentrations, stay away from and upwind of eruptive vents. Be prepared to evacuate the area if uncomfortable concentrations are experienced. Personnel with pre-existing respiratory conditions such as asthma should not be involved in field teams.

[26] https://www.ivhhn.org/uploads/IVHHN_briefing_note_air_quality_monitoring.pdf

5.5.5.2 *Asphyxiant gases*

Volcanic and geothermal emissions can include the asphyxiant gases carbon dioxide (CO_2) and hydrogen sulfide (H_2S). As these gases are denser than air, they flow downslope and can accumulate in low-lying areas or poorly ventilated spaces. Sufficiently high concentrations of these gases can be a life safety hazard (Figure 14, Table 9).

Figure 14 CO_2 hazard area following the 2021 Tajogaite eruption of Cumbre Vieja volcano, La Palma, Canary Islands, Spain. Photo by Alana Weir, May 2023.

Table 9 Health effects of CO_2 and H_2S gas at different concentrations[1]

CO_2	Concentration (ppm)	%	Symptoms/effects
	~420	~0.042	Current global background concentration
	2,000-5,000	0.2-0.5	Headaches, drowsiness, poor concentration, increased heart rate
	20,000-50,000	2-5	Worsening headaches, dizziness, sweating, shortness of breath
	40,000	4	IDLH (immediately dangerous to life and health)
	60,000-100,000	6-10	Hyperventilation, tachycardia, worsening dizziness
	110,000-170,000	11-17	Drowsiness, muscle spasms, loss of consciousness
	>170,000	>17	Convulsions, coma, death

	Workplace exposure standards		
	5,000	0.5	WES-TWA[2]
	30,000	3	WES-STEL[3]
H_2S	**Concentration (ppm)**		**Symptoms/effects**
	<1		Rotten egg smell, odour threshold as low as 0.01 ppm
	3-5		Smell is strong
	20-100		Headache, dizziness, irritation of nose and throat[2]. Eyes may sting. Prolonged exposure may cause coughing, hoarseness, shortness of breath and runny nose.
	100 (IDLH)		Levels of >100 ppm are immediately dangerous to life and health
	150-200		Sense of smell blocked.
	200-250		Major irritation of nose, throat and lungs, headaches, nausea, vomiting, dizziness. Prolonged exposure can cause fluid build-up in lungs (pulmonary oedema) which can be fatal.
	300-500		Symptoms as above but more severe, death can occur with 1-4 hours of exposure.
	>500		Immediate loss of consciousness, death is rapid, sometimes immediate.
	Workplace exposure standards		
	5		WES-TWA[3]
	10		WES-STEL[4]

[1] Compiled from: https://www.esr.cri.nz/assets/Hydrogen-Sulphide-Fact-Sheet.pdf; Public Health England (2015) and WorkSafe NZ (2022b)
[2] While H_2S is primarily of concern as an asphyxiant, it is also an irritant at lower concentrations.
[3] WorkSafe NZ (2022a) Workplace Exposure Standards Time-Weighted Average
[4] WorkSafe NZ (2022a) Workplace Exposure Standards Short-Term Exposure Limit

Low- to medium-cost sensor options for monitoring CO_2 and H_2S include gas detection tubes, personal or handheld gas monitors, including personal gas detectors, and broadcast-capable sensors[18].

- PPE: Half or full face respirators do not remove CO_2, therefore closed-circuit breathing apparatus is required for working in situations where there may be accumulations of CO_2 to concentrations exceeding IDLH values (Table 9). RPE must be fit-tested. Gas detection equipment, including personal gas sensors, should be carried.
- Safety measures: Seek advice from experts to understand likely asphyxiant gas hazards. Avoid low-lying areas (hollows, caves, basements, ditches) or unventilated indoor spaces where gases may accumulate. Carry personal gas detectors and pay close attention to concentrations encountered, and trends in those concentrations.

5.5.5.3 Lessons from Mammoth Mountain incident, 2006

Unrest beneath Mammoth Mountain lava dome complex, California, has led to extensive emissions of CO_2 from soil and fumaroles since 1990. In 2006, two ski patrollers at Mammoth Mountain ski area fell through snow into a deep hole created by a fumarole and rapidly lost consciousness. Another patroller descended into the hole carrying an oxygen mask but lost consciousness before he could affix the mask. A fourth patroller descended partway down the hole, quickly recognised the danger, and affixed his oxygen mask before losing consciousness. All were extracted by personnel wearing closed-circuit breathing apparatus. The first three victims were in cardiopulmonary arrest and could not be resuscitated; the fourth patroller recovered. Autopsies suggested their deaths were due to asphyxiation (Cantrell and Young, 2009). The concentration of CO_2 in Mammoth Mountain fumaroles has been measured at 98.7%. Cantrell and Young (2009) noted that non-rebreather oxygen masks appeared to be ineffective at protecting the wearers and that self-contained breathing apparatus is required in situations of extremely high CO_2 concentrations.

5.5.5.4 CO_2 and H_2S hazards in Rotorua

Elevated ambient concentrations of both CO_2 and H_2S have been recorded across the Rotorua geothermal field, emitted from both geothermal features and from diffuse soil degassing (Durand and Scott, 2005; Werner and Cardellini, 2005).

High concentrations of CO_2 (10-15%) have been reported in vents near buildings in Rotorua (Durand and Scott, 2005), but nearby ambient air concentrations are generally lower at 0.4-1%. For H_2S, concentrations >200 ppm have been recorded near venting areas and in enclosed spaces, and indoor air concentrations of 0.3-20 ppm recorded (Durand and Scott, 2005). Measured outdoor H_2S concentrations range from 0.002-0.07 ppm (Bates et al., 2013).

No documented fatalities in Rotorua are associated with exposure to high concentrations of CO_2. For H_2S, there have been 14 fatalities recorded in the area attributed to H_2S poisoning since 1946 (IVHHN[27], Bassindale and Hosking, 2011; Officer of the Chief Coroner 2022/4[28]). Many of these deaths have been associated with bathing in hot pools, leading to strong recommendations from the coroner investigating the most recent fatality in 2020 that warning signage in the area be markedly improved[17]. There have also been incidents where workers carrying out maintenance on sewer pipes or entering sumps or septic tanks have been overcome by H_2S.

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[27] https://www.ivhhn.org/index.php/information/information-different-volcanic-gases/hydrogen-sulphide

[28] https://coronialservices.justice.govt.nz/assets/Documents/Publications/Rec-Recap-2022-Q4-FINAL.pdf

6 Important tasks for lifeline utilities during and after a volcanic eruption

This section summarises important tasks for lifeline utilities during and after a volcanic eruption with an emphasis on volcanic ash as the most widespread hazard. We emphasise that this section contains general advice only and is not intended to replace specific operational directions in individual operational plans.

The advice provided in this section is based on the ALG-funded New Zealand volcanic ashfall impacts and mitigation poster series. For this section we have updated and expanded the advice from the original poster series in two ways. Firstly, all poster content was reviewed and updated where necessary for a project funded by the US Geological Survey, US Volcano Disaster Assistance Programme and US Agency for International Development to create international versions of the posters. Secondly, we have continued to update our knowledge base based on new research and recent events. Details of both poster series are listed in Table 10.

Table 10 Current status of New Zealand and international volcanic ashfall impacts and mitigation poster series

Sector	New Zealand poster series (version and date)	International poster series (version and date)
Available at:	https://www.gns.cri.nz/our-science/natural-hazards-and-risks/volcanoes/ash/	https://volcanoes.usgs.gov/volcanic_ash/resources.html
Generators and HVAC	Version 2, December 2018	Version 1, November 2020
Water supply	Version 3, June 2018	Version 1, November 2020
Wastewater	Version 3, June 2018	Version 1, November 2020
Road networks	Version 3, June 2018	Version 1, November 2020
Buildings and facilities	Version 2, June 2018	Version 1, November 2020
Urban clean-up	Version 2, June 2017	Version 1, November 2020
Electricity generation	Version 2, September 2013	Version 1, November 2020
Computers and electronics	Version 2, September 2013	Not included in update
Electricity transmission	Version 2, May 2013	Version 1, November 2020
Airports	Version 2, February 2013	Version 1, November 2020
Telecommunications	Version 1, August 2024	Not yet completed

6.1 General activities

The following activities are likely to be required across multiple sectors.

6.1.1 Management and coordination tasks

- Maintaining situational awareness by actively monitoring GeoNet for Volcanic Activity Bulletins, ashfall forecasts and advice.
- Liaising with emergency managers and Emergency Operations/Coordination Centres (EOCs, ECC, NCC if active)
- Following risk management advice from Controller, including advice to evacuate
- Liaising with other lifeline utilities
- Providing information to workers on safe working practices
- Providing appropriate PPE to workers
- Maintaining awareness and keeping records of field crew members' locations and tasks.

6.1.2 Protecting facilities and equipment

- Preventing ash from entering buildings by:
  - Setting up a single entry/exit point and 'ash lock' with double doors if possible
  - Sealing remaining doors and windows with damp towels or duct tape
  - Shutting down HVAC equipment
  - Leaving ash-contaminated clothing and footwear outside or in 'ash lock'
- Removing ash from gutters to avoid flooding into ceiling spaces or gutters breaking
- Clearing ash from solar panels
- Monitoring accumulation of ash on roofs for awareness of structural damage/roof collapse hazard
- Protecting computers and electronic equipment with plastic sheeting and duct tape, and/or sealing off rooms
- Protecting generator air intakes, e.g. by adding temporary filtration
- Monitoring exposed metal surfaces for corrosion damage from volcanic ash or gas and replacing if necessary
- Initiating schedule for inspection, cleaning and preventive maintenance of key equipment such as air filters
- After ash has stopped falling: initiating ash clean-up of worksites to restrict further ash contamination.

6.1.3 Vehicle maintenance

- Cleaning vehicles thoroughly when back at base
- Ensuring vehicles carry spare air filters
- Regularly checking and changing oil and air filters
- Applying lubricant/grease more frequently and checking for wear.

6.2 Sector-specific activities

6.2.1 Water supply

- Monitoring turbidity in raw water sources
- Monitoring wear and tear on pumping equipment
- Closing raw water intakes to limit ash ingress into treatment train
- Adjusting dosage of treatment chemicals to cope with additional turbidity
- Considering covering open-air clarifiers and/or sand filters
- Increased cleaning schedule for clarifiers and/or sand filters
- Inspecting network for any damage from other volcanic hazards such as lava flows
- Communicating with city and emergency managers to manage water demand during clean-up operations.

6.2.2 Wastewater collection and treatment

- Communicating with city and emergency managers to keep ash out of sewer lines (e.g. around manhole covers) and stormwater drains (in case of combined sewers)
- Deploying vacuum trucks to clear ash from underground drainage and/or storage chambers as required
- Monitoring wear and tear on pumping equipment
- Monitoring for the presence of ash in raw wastewater
- Monitoring for presence of ash throughout treatment process and stepping up maintenance accordingly

- Monitoring torque on mechanically cleaned pre-treatment equipment (e.g. step or bar screens)
- Being prepared for emergency discharge of raw wastewater to the environment to protect the treatment plant:
    - Communicating with city and emergency managers and health agencies
    - Installing warning signage for beach closures.

6.2.3 Stormwater

- Preventing ash from entering stormwater drains (placing sandbags around inlets may be useful)
- Deploying vacuum trucks to clear ash from catchpits and other underground drainage as required
- Monitoring stormwater detention structures for blockages and stepping up maintenance if needed.

6.2.4 Hydroelectric power generation facilities

- Keeping rain gauges clear of ash
- Monitoring for presence of suspended ash (turbidity) and/or pumice in catchments
- If pumice is present, setting up floating booms to keep it out of intakes
- Considering bypassing turbines to protect them from ash
- Developing schedule for inspecting and cleaning essential sites and components
- Cleaning sites to reduce ash remobilisation. Equipment should be de-energised before cleaning, and cleaning should be done using dry methods.

6.2.5 Thermal power generation facilities

- Checking and clearing air intakes, air filters and sub-aerial condenser systems
- Checking for damage to mechanical seals
- Considering pre-emptive shut down to protect plant.

6.2.6 Electricity transmission and distribution

- Liaising with NZVSAP infrastructure working group about resistivity testing of ash
- Initiating specialist inspection and cleaning procedures for substation equipment
- Initiating specialist inspection and cleaning procedures for line insulators
- Checking distribution lines for damage from treefall or other volcanic hazards, and trimming back branches laden with ash
- Maintaining protection and cleaning programmes until the threat of wind-remobilised ash is over.

6.2.7 Communications

- Managing network overloading by advising customers to keep calls to a minimum
- Protecting equipment by covering with plastic sheeting where possible
- Inspecting sites to establish degree of ash contamination and associated damage
- Repairing customer faults and affected equipment
- Cleaning ash from equipment as soon as practicable.

6.2.8 Road networks

- Inspecting bridges for lahar or PDC damage
- Inspecting roads to map ash accumulation
- Advising the public to avoid unnecessary travel

- Working with agencies such as Waka Kotahi on road closures
- Implementing traffic management measures such as:
    - Headlight use
    - Warning signage and reduced speed limits
    - Temporary one-way systems
    - Spacing vehicles
    - Dampening road surfaces to reduce remobilisation and improve visibility
- Coordinating with other agencies, particularly emergency and city managers, on clean-up and keeping ash out of drainage systems
- Road clean-up:
    - Identifying a hierarchy of roads for clean-up, prioritising access to critically important sites such as hospitals and evacuation routes
    - Using a range of methods such as sweeping, air blasting, suction and/or spraying to clear roads
    - Assisting with transport of ash to disposal sites.

6.2.9 Rail networks

- Inspecting and cleaning track switches
- Clearing ash from rail lines
- Inspecting and cleaning overhead power lines
- Inspecting and cleaning electronic signal equipment.

6.2.10 Airports

- Responding to ashfall warnings issued by Geonet
- Sharing information with the New Zealand NOTAM office of any volcanic hazard to aviation at the airport
- Monitoring accumulation of ash on large, long-span structures such as hangars for awareness of roof collapse hazard
- Considering impact of volcanic ash entering any drainage systems and taking appropriate steps if required
- Liaising with road network managers for clean-up of airport roads
- Coordinating with other agencies on the clean-up of runways, drainage, taxiways, aprons, and (if present) landing aids, radar equipment, optical systems and ground support equipment, prioritised as appropriate
- Liaising with Civil Defence Emergency Management to facilitate emergency aircraft requirements where practicable
- Considering use of airport facilities in support of non-aviation civil defence requirements.
- Specialised guidance on these topics is available in the International Civil Aviation Organization Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds[29] (ICAO Document 9691).

[29] https://skybrary.aero/sites/default/files/bookshelf/2997.pdf

7 Acknowledgements

We are extremely grateful to the following reviewers for their thoughtful and constructive review comments: Emma Coultas (University of Canterbury); John Hopkins (University of Canterbury); Nico Fournier (GNS Science); Paula Acethorp and Paul Tench (Civil Aviation Authority of New Zealand); Craig Campbell-Smart (Taranaki Emergency Management Office); Claire Horwell (Durham University, UK and International Volcanic Health Hazard Network); Heather Craig (University of Canterbury); Ravi Reddy (Massey University); Matt Carey (Ministry of Health National Health Coordination Centre), Ery Hughes (GNS Science), Agnes Mazot (GNS Science), Rebecca Fitzgerald (GNS Science), Graham Leonard (GNS Science) and David Damby (US Geological Survey and International Volcanic Health Hazard Network). We also thank Philippa Gibson for helpful discussions.

We thank Auckland Lifelines Group for financial support of this project and particularly thank David Rei Miller for final review comments and Ross Roberts for ongoing support.

CS and TW thank the RNC2 Volcano programme, the DEVORA programme and GNS's SSIF_23-24_HRM14 programme for co-funding this project.

We acknowledge, with thanks, early work by Jan Lindsay and Chris Peace in this area in their 2005 report "Health and safety issues in a volcanic ash environment".

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Appendix 1 New Zealand Volcanic Alert Level System

New Zealand Volcanic Alert Level System

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

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

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

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

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

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

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

From: Potter et al., 2014

Appendix 2 IVHHN briefing note on air quality monitoring options for volcanic emissions

Air quality monitoring for volcanic emissions: briefing document

Volcanic ash and gas are types of airborne pollution and should be monitored to check if air quality is exceeding public health standards. Government agencies may want to use air quality data to provide public information and recommend actions associated with different levels of an air quality index (e.g. https://www.airnow.gov/aqi/aqi-basics/).

Air quality monitors may be real-time or may provide retrospective data. Real-time monitors are more useful for immediate public health advisories.

Ideally, regulatory-grade instruments would be installed but these are expensive, challenging and time-consuming to install in a crisis, and need regular maintenance. Cost also prohibits installation of a monitoring network. Low-cost sensors are a good alternative during a crisis and are suitable for establishing a network, with sensors across populated centres. The data are not as reliable as regulatory data but may be used as an indication of air quality, rather than absolute values. Therefore, advisories associated with the data should be given with caution. The monitors recommended below are all low-to-medium cost.

Particulate monitoring

The two main low-to-medium cost **non-regulatory** instruments used for airborne particulate monitoring during volcanic eruptions are the TSI DustTrak aerosol monitor and PurpleAir sensors.

	DustTrak	**PurpleAir**
	 DustTrak DRX Aerosol Monitor 8533	 PA-II-SD
Cost	Approx. $US 15,000	$US 279 per unit
What they measure/report	Simultaneous measurement of PM_1, $PM_{2.5}$, PM_4, PM_{10}, TSP	Simultaneous measurement of PM_1, $PM_{2.5}$, PM_{10}, Temperature, Humidity Derived air quality indices (e.g., USEPA $PM_{2.5}$ AQI)
Power requirements	Battery life is approximately 6-8 hours.	Work best with mains power. Can be run for several days from a power bank. Can be run from vehicle with USB outlet.
Data access	Data must be downloaded from instrument.	With access to wifi, data can be uploaded to PurpleAir's cloud where it can be visualised in real time, on a

		map with different averaging periods and with clear links to health information and advice. Without wifi, the SD card-enabled devices save data to a microSD card which can be extracted and the data downloaded.
Are they regulatory quality?	No, but the DustTrak is used extensively for air quality research around the world, including during volcanic eruption (e.g. the Soufrière Hills).	No, but the PurpleAir has been tested against other low-cost PM sensors and performs well and is an excellent choice for setting up a network of sensors.
Ease of use and maintenance	Easy to use, very little training required. Requires daily calibration and data download every few days. Should be placed in a sheltered (from rainfall/ash) environment such as a veranda. Environmental enclosures can be purchased.	Easy to use, very little training required. Requires data download every few days if no wifi. Installation is straightforward but important to consider location. Should be checked and cleaned (to remove insects) frequently.

Gas monitoring

The following low-cost gas detection techniques are **non-regulatory** methods for assessing gas concentrations. The methods presented below can help characterize gas concentrations over time and space, for the purposes of evaluating hazards. These instruments have a higher minimum detection limit and lower resolution than regulatory methods but are cheaper and require less infrastructure.

Technique	Gas detection tubes	Personal or handheld gas monitors	Better resolution or broadcast capable sensors
		   Dock station  Aeroqual	 AreaRAE  Aeroqual
Cost	~US $500 for Hand pump + $100-150/10 tubes	~US $400-1,000/ monitor (+ ~$1,000 – $3,000 for docking station/calibration gases, except Aeroqual)	~US $10,000 – $20,000

Example manufacturers/products	Drager, RAE systems, Sensidyne	Industrial scientific, BW technologies, Drager, Aeroqual	RAE systems (areaRAE or multiRAE), Interscan corporation, (GasD 8240), Aeroqual
What they measure	Single gas concentration in ppm (i.e SO_2, H_2S)	Single or multiple gas concentration in ppm (i.e. SO_2, H_2S, CO_2)	Single or multiple gas concentration in ppm (SO_2, H_2S, CO_2, others)
Resolution	0.1 - 1 ppm	0.1 ppm	0.1 - 0.01 ppm
Range	0.1 - 200 ppm options	Generally, 0 - 200 ppm	SO_2: 0-2, 20, or 100 ppm
Power requirement	none	Internal battery	AC, limited internal battery, or configure for external battery
Data access	Direct readout on tube	Screen readout + logging capability. Data download via stand-alone or networked docking station	Log onsite or telemetered
How to use	Operator needed for manual pumping of gas through tube. 3-20 min/sample	Can use for personal protection or field deploy in environmental enclosure	Deploy to field location for time series data. Some have wireless radio option for real-time data acquisition
Ease of use and maintenance	Easy, little training required. Used tubes may be considered chemical waste so consult local regulations for disposal.	Easy. Basic technical skill needed for docking station set-up and badge programming. Monthly calibration recommended. Calibration gas cylinders required.	Basic technical expertise required. Aeroqual monthly/quarterly maintenance: filter replacement, flow/leak and calibration checks, clean inlet. Pump replacement 12-18 months. AreaRAE maintenance as needed: sensor, filter, battery, pump replacement.
Limitations	Single data point manually collected in time and space.	Not wifi enabled - manual data download required, except Aeroqual 300/500 has voltage output/relays for datalogger interface.	Wireless capability is 2-3 km. Some configurable with 900 MHz radio or cloud-based user interface for real-time, remote access.

Appendix 3 Protocol of analysis of bulk ash samples for respiratory health hazard assessment

(also available at: https://www.ivhhn.org/guidelines#ash-collection)