Auckland: A city on volcanoes

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Abstract: The Metropolitan area of Auckland, New Zealand, is built on a potentially active volcanic field. The geologic record indicates that the Auckland Volcanic Field (AVF) is a monogenetic volcanic field in which activity has formed fifty eruptive vents within the last 140,000 years, covering an area of 360 km^2. An eruption from this field has the potential to affect the majority of the region's 1.3 million population. Geological evidence indicates there is a 5 % probability of another eruption occurring from the AVF within the next 50 years, and that the next eruption is likely to be from a new and presently unknown location. While an AVF eruption is expected to cause destruction of a relatively small part of the region (less than 80 km^2), indirect impacts on industry, lifeline services, economy and social well-being are likely to have a much wider geographic extent.

Planning response to such an event is complicated because:

- The site of future eruption cannot be predicted;
- The low viscosity nature of the basaltic magma means there will be a relatively short pre-eruption period (possibly only a couple of days);
- There may be more than one eruption vent (although it is expected that any vents in a multi-vent episode will be in relatively close proximity);
- Unlike many other natural hazards in New Zealand, volcanic activity will occur over a relatively long time period (a period of months up to a year or more); and
- Volcanic activity will give rise to a number of hazards, which will have minor to severe impacts both in terms of damage and geographic extent.

An understanding of the geological character of the AVF and the associated hazards, and formulation of interim and long-term technical solutions, have been fundamental to development of a Volcanic Contingency Plan for Auckland.

Résumé: La région métropolitaine d'Auckland, Nouvelle Zélande, est construite sur une zone volcanique active. Les enregistrements géologiques indiquent que la zone volcanique active d'Auckland (Auckland Volcanic Field – AVF) a généré plus de 50 explosions volcaniques au cours des 140,000 dernières années, couvrant une surface de 360 km^2. Une éruption de cette zone a le potentiel d'affecter la majorité des 1.3 millions d'habitants de la région. L'évidence géologique indique qu'il y a 5 % de probabilité qu'une autre éruption de l'AVF survienne au cours des 50 prochaines années, et que la prochaine éruption se fera à partir d'une source nouvelle et non encore localisée. Alors qu'une éruption ne devrait causer la destruction que d'une petite partie de la région, (80 km^2) les impacts indirects sur l'industrie, les services vitaux, l'économie et le bien être social pourraient être géographiquement beaucoup plus étendus.

Un planning prévisionnel de réaction à un tel évènement est difficile à définir pour les raisons suivantes:

- On ne peut pas prédire le lieu de la prochaine éruption,
- La faible viscosité du magma basaltique signifie qu'il n'y aura qu'une période relativement courte de pré éruption (sûrement seulement de quelques jours)
- Il se peut qu'il y ait plusieurs éruptions (bien qu'il soit prévu que les éruptions multiples soient relativement proches en termes de localisation)
- Contrairement à beaucoup d'autres risques naturels en Nouvelle Zélande, l'activité volcanique se déroulera sur une période relativement longue (qui se comptera en mois et portrait atteindre un an ou plus), et
- L'activité volcanique donnera naissance à un certain nombre de risques, qui vont avoir des impacts divers, faibles ou importants, en termes de dommages et d'étendue géographique.

Une compréhension du caractère géologique de l'AVF et des risques associés, et la formulation de solutions techniques intérimaires et long terme ont été fondamentales pour le développement d'un Plan de prévention volcanique pour Auckland..

Keywords: geological hazards, geology of cities, infrastructure, regional planning, volcanic risk

INTRODUCTION

The Auckland Region, located in the North Island of New Zealand (Figure 1), has a land area of 5,024 km^2. The Auckland Metropolitan area is built on a potentially active volcanic field, presently covering an area of about 360 km^2

within which some 530,000 people live (Figure 2). Auckland's Central Business District, and key infrastructure such as ports and international airport are located within the Auckland Volcanic Field (AVF) and eruption of a new vent has the potential to significantly affect the region's 1.3 million population. Geological evidence indicates there is a 5 % probability of another eruption occurring from the AVF within the next 50 years, and that the next eruption is likely to be from a new and currently unknown location.

A Volcanic Contingency Plan, VCP (Auckland Regional Council 2002) has been prepared for the Auckland Region to provide for co-ordinated management of response and restoration operations. The VCP is set in the context of the National Civil Defence Plan, which identifies actions to be undertaken by Government, local authorities and other Civil Defence and Emergency Management (CDEM) agencies in preparation for and response to a volcanic episode.

The purpose of the VCP is to provide for continuity of operations and functions through an eruptive event. This has been achieved by:

- Establishing protocols for the timely and efficient warning of volcanic activity;
- Initiation of immediate communication and public information activities;
- A transparent process of declaration;
- Appropriate deployment of information for the management of a civil defence emergency; and
- Appropriate prioritisation and allocation of regional resources in the event of eruption.

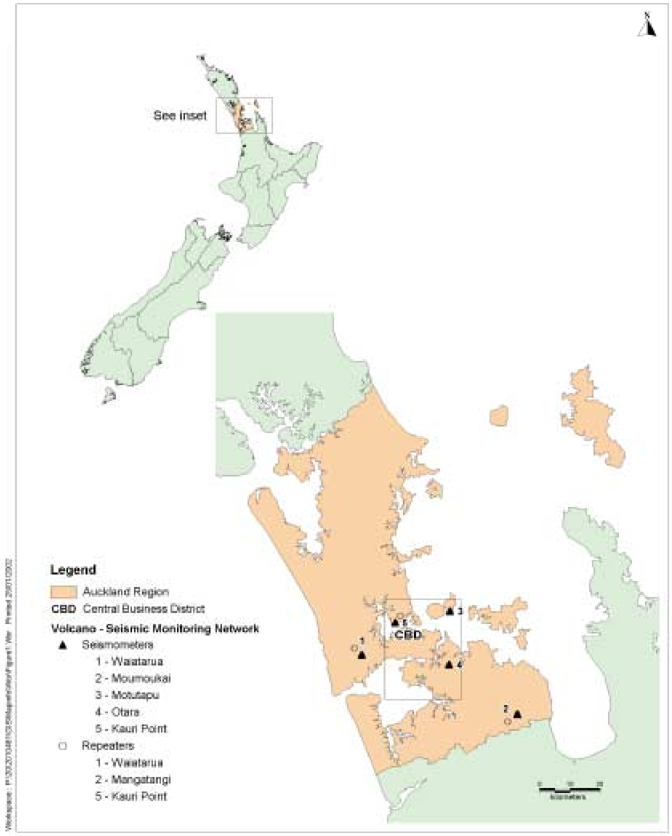

Figure 1. The Auckland Region, showing the distribution of the volcano-seismic monitoring network.

The success of the VCP is in part dependant on capturing the special character of the AVF and the nature of the associated hazard (that is, the geology and engineering geology) in development of protocols and in the formulation of interim and long-term technical solutions (engineering).

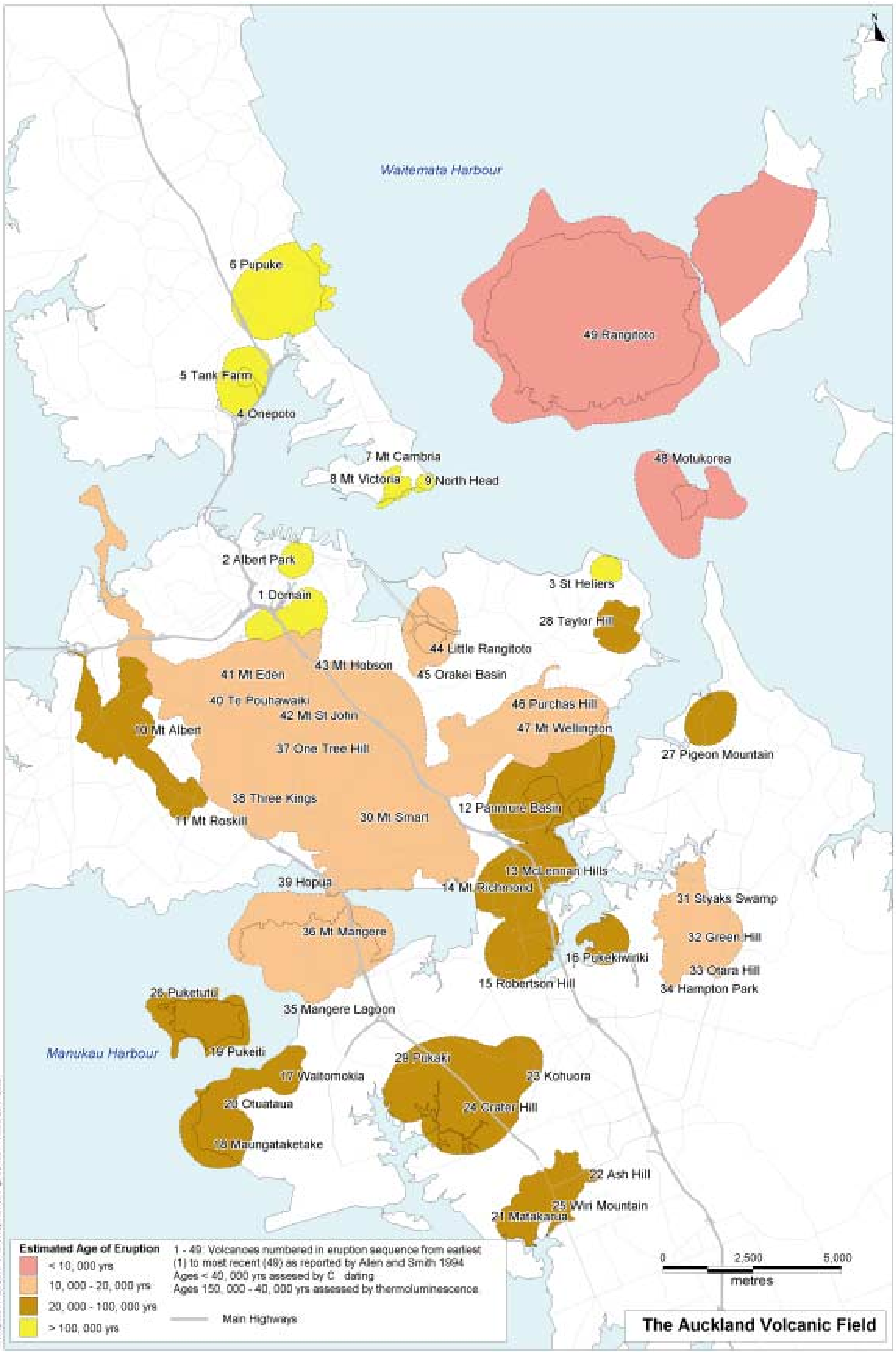

Figure 2. The Auckland Volcanic Field. The most recent, and one of the larger eruptions from the AVF, was of Rangitoto Island in the northeast, some 600 years ago.

THE AUCKLAND VOLCANIC FIELD

The geological record indicates that the AVF is a monogenetic volcanic field, in which activity has formed 50 volcanoes within the past 140,000 years over an area of 360 km^2 (Smith and Allen 1993; Smith and Wood 1997) (Figure 2). The return period between past events has ranged from hundreds to thousands of years. The latest eruption occurred some 600 to 800 years ago. A future eruption may therefore occur at any time in the future. Ages of Auckland's volcanoes determined from carbon dating and thermo-luminescence techniques indicate a trend of increasing size and frequency of eruption over the last 20,000 years (Smith and Allen 1993), with events in the last 20,000 years occurring every 1000 years on average. There is also a general trend of activity moving from South to North. However, trends in timing and location of eruptions have not been established and it is therefore difficult to predict where and when future activity might occur within the field.

Most of the volcanoes are small cones of less than 150 m in height, which developed by eruption over periods of a few months or years (Figure 3). In most cases a single cone resulted from the eruption, but there is evidence that some eruptions have built several adjacent cones. The monogenetic nature of Auckland's volcanoes means that in the event of a future eruption, a new volcano will be formed, rather than an existing volcano re-activated. Therefore, the VCP needs to be sufficiently flexible to be applied to a hazard of unknown location.

Figure 3. Left: Orakei Basin (volcano 45, Figure 2) with Mt St John (volcano 42) in the background. Right: One Tree Hill (volcano 37, Figure 2).

Volcanic activity in the AVF is due to a hot spot located about 100 km beneath the city of Auckland (Smith and Allen 1993). Basalt magma has a low viscosity, which allows it to rise relatively quickly through the crust (estimated speeds of 5 km/hr). This means that the warning period for impending eruption is likely to be short, perhaps only a few days. The rise of magma is likely to be controlled by the location of faults within the crust. However, because the position of such faults is not known, these indicators cannot be used in predicting the site of a future eruption.

The character of eruptions from the field varies according to the availability of water to the eruption site. Wet (phreato-magmatic) and dry (magmatic) activity often alternate from the same event as the availability of water (groundwater, surface water, seawater) changes. With high water input, activity is dominated by production of a vertical eruption column and the development of base surges. With low water input, activity is dominated by ejection of cooled magma as scoria, tuff and ash, and lava flow. This means that the VCP needs to address a wide range of volcanic hazards and hazard interactions.

In summary, the following characteristics specific to the AVF needed to be addressed in the VCP:

- The site of future eruption cannot be predicted;
- There will be a relatively short pre-eruption period (possibly only a couple of days);
- There may be more than one eruption vent (although it is expected that any vents in a multi-vent episode will be in relatively close proximity);
- Unlike many other natural hazards, volcanic activity will occur over a relatively long time period (a period of months to years); and
- Volcanic activity will give rise to a number of hazards, which will have minor to severe impacts both in terms of damage and geographic extent.

ASSESSMENT OF VOLCANIC HAZARDS AND RISKS

The likely nature and impact of hazards associated with an AVF eruption were evaluated in a Volcanic Hazard Matrix to identify those hazards for which mitigative action might be viable. Two hazards for which some mitigation might be viable are presented in Table 1. The matrix combines the findings of hazard and risk studies with the anticipated effects on key lifelines services and structures identified by stakeholders as part of the Auckland Engineering Lifelines Project (AELP). Key inputs include:

- The geological record of Auckland's 50 volcanoes;
- Design factors of safety for different structures;
- Volcanic hazard scenarios developed by Auckland Regional Council (1999);
- Observed performance and recovery of similar structures in other volcanic eruptions (Capelinhos, Azores 1957/58; Surtsey, Iceland 1964; Taal, Philippines 1965; Heimaey, Iceland 1973 and Surtsey and Kalapana, Iceland 1990) (Nairn and Scott 1995; Manville et al 2000).

Table 1. Extract from Hazard Matrix for the Auckland Volcanic Field

Hazard*	Area Affected	Infrastructure Damage	Damage to Life	Warning	Recovery†	Mitigation
Airfall Tephra and Eruption Column	Ash plume may rise 6 – 15 km resulting in the deposition of up to 1 million m^3 of tephra spread up to 100 km from the vent (although at 100 km, there will be no risk to infrastructure other than air traffic). Ash distribution will depend on eruption size, prevailing winds (direction and strength) and particle weight. As westerly winds predominate in Auckland, tephra is most likely to be deposited thickest to the north-east and east of a vent. Tephra thickness is likely to range from a few mm to 600 mm.	**Domestic and Commercial Structures** Enters buildings through openings/ broken windows; tephra loading may cause collapse of roofs, walls or columns‡; abrasion **Communications** Emergency generation and air conditioning plants vulnerable to abrasive dust and over-heating resulting in service interruption; potential for damage to CBD fibre optic ring and isolation due to power failure; land lines more vulnerable than cellular system; congestion of services **Transport** Temporary road closure, impaired visibility, vehicle damage; blockage of drains resulting in flooding; engine damage resulting in disruption of port activity; closure of air-space, airports. **Energy** Electricity supply restriction and outages due to insulator flash-overs at transmission and distribution systems; minor affect on petroleum or gas pipeline valve controls and petroleum SCADA systems; heavy ash fall may sink floating roofs on petrol tanks causing spills and creating hazardous vapour cloud with risk of explosion **Water Supply** Suspension of ash in water supply reservoirs and leaching of contaminants (eg F), lowering of pH, disruption of treatment process; interference with electrical equipment, filter stations overloaded; damage to pumps **Wastewater and Stormwater** Pipe blockage and local flooding, damage to pumps and plant equipment, interference with treatment process; operational, maintenance and odour problems, overload bypassed to land or harbour with consequences for sanitation	Hinder visibility resulting in accidents. Inhalation of gas and particles causing respiratory problems. Burial of crops and damage to fruit. Flow of hot ash into homes or workplaces would cause burns, fire and roof collapse and deaths	An eruption column will be generated following commenceme nt of the eruption. Tephra will be produced within hours over the wider area. Prediction of wind directions critical to defining likely hazard zones. Earthquakes a few hours and up to a few days prior to eruption due to upwelling may provide an indication of the area likely to be affected by these hazards at that time. (Established at SAL 5, Table 3).	**Domestic and Commercial structures** Dependent on availability of water supply and access **Communications** May be hindered by ability to access sites and high temperatures. Full recovery within 2 to 7 days **Transport** Regular removal of ash from roads, rail, port and airport; increased maintenance of aircraft to exclude ash from engines and machinery. Full capacity within 1 week of cessation of ash fall **Energy** Temporary repairs and alternative supplies in place within 1 week **Water Supply** Turbidity and acidity of water returns to normal levels within a few hours to days of cessation of ash fall. Essential water supply recovered within 1 week; non-essential supply provided by tanker **Wastewater** Full recovery within 1 week of cessation of ash fall Contingency plan for ash disposal must be prepared to avoid limiting recovery.	**Clean-up and removal**. Develop and maintain hospital equipment and products required to treat severe burns. **Commercial structures** Prioritise key structures (eg hospitals) and check for likely ash loading; upgrade to withstand as necessary **Communications** Fit temporary pre-filters to internal/ external air-conditioning units within exchange centres; Seal off exchange centres during the event to minimise ash effects **Transport** Remove from roads and stockpile during eruption; Minimise driving movements; Install extra air filters in vehicles operating within ash fall-out zones **Energy** Encapsulate gas gate stations and shut down gas supply prior to eruption Water Supply Prevent ash ingress to water pumping stations, cover filters; Monitor water quality **Wastewater** Bypass and/or shut down vulnerable parts of the plant during ash fall.
Airfall Tephra	**3 – 100 km**	**Immediate Risk Moderate; Ongoing Risk Moderate to High; Anticipated loss Moderate**		**Hours, up to a few days**	**1 week to several months**	**Moderate**

Hazard*	Area Affected	Infrastructure Damage	Damage to Life	Warning	Recovery†	Mitigation
Lava	Streams of magma that flow by gravity into/ along topographic lows; 1000°C or more; associated with 61% of AVF volcanoes. May comprise: Continuous and voluminous discharge of fluidised lava, often with gas-driven fire fountaining of scoria to hundreds of metres above the vent; *or* Lava flows directly from primary or secondary vents; partial cone collapse or breaching. AVF lava flows have travelled distances of 0.5km to 9.5km dependant on lava volume, viscosity and topographic gradient. Damage limited to within a few kilometres of the erupting vent.	Burn, crush and bury everything in their path. **Domestic and Commercial Structures** Loss of integrity of structures in path; generation of fires in buildings. **Communications** Interruption of distribution where transmission lines destroyed by lava flows; damage to distribution centres impacted by lava flows. **Transport** Blockage of shipping channels and loss of access to ports; obstruction of transport routes. **Energy** Interruption of distribution where transmission lines destroyed; damage/destruction of power stations in flow path; risk of explosion and fires if lava impacts petroleum product storage facility. **Water Supply** May explode on contact with water; heat from lava flows may pressurise water remaining in underground pipes, causing local explosions; may block or break existing reticulation and alter local topography causing local flooding. **Wastewater** May explode on contact with water or organic gases. May block or break existing reticulation and alter local topography leading to local ponding of sewage.	Generation of fires. May explode when coming into contact with water or as a result of organic gases produced when hot lava over-runs vegetation. Move at speeds slow enough for people and animals to move out of their way. Lethal if caught in path of lava.	Generally occur later in the sequence of volcanic activity, following fire-fountaining. Because lava flows are strongly controlled by topography, the shape of the area destroyed by a flow can be easily predicted. Develops at SAL 3 to 4 and continues through SAL 5	**Transport** Redevelopment of ship passage if feasible (if severe, may require development of new port site); lava removal and road and rail re-construction or re-routing around affected section; depending on vent location, port or airport facilities may be destroyed – partial recovery within 6 months to 1 year. **Energy** Full recovery up to several weeks depending on the extent of loss of services. **Water Supply** Essential services supplied within 1 week; Full recovery within 4 months, but with temporary stations, and catchments re-routed around devastated region. **Wastewater** Major problem areas identified and essential sites repaired within 1 week; Full recovery with temporary pump stations within 4 months.	Immediate evacuation within 3km of the expected vent and topographic lows. Possibly slow progress by cooling with water to increase viscosity (not found to be effective elsewhere). Barriers may be able to be constructed (earth) or explosives used to divert /control flow (not found to be effective elsewhere). Issue warnings of potential lava path. Maintain hospital based services for treatment of major burns, injuries and other medical emergencies. **Transport** Signage to direct traffic away from areas in path of flows **Energy** Shut down gas supply in area likely to be affected prior to eruption **Water Supply** Controlled release of ponded surface water
Lava	**3 km – 5 km**	**Immediate Risk High; Ongoing Risk Low; Anticipated loss Moderate to High**		**Hours to days**	**Several weeks to several months**	**Moderate**

* A description of each hazard is given in Appendix 1
† Following cessation of volcanic activity
‡ Auckland has a temperate climate and structures are not designed for loadings such as snow

Risk

A Risk Matrix (Table 2) (where risk = hazard x vulnerability, and vulnerability is a function of the perceived effect on the Auckland community and infrastructure) was developed from the Hazard Matrix. The Risk Matrix identifies the level of risk likely to be associated with each hazard and broadly evaluates those hazards for which mitigative solutions could be considered. For example, crater formation poses a severe risk, but there are no known options for mitigation (other than evacuation with sufficient prior warning), whereas lava flow and airfall tephra pose high and moderate risks for which options for risk reduction are available. Particular consideration can be given in planning to those hazards that pose a high or severe potential risk for which some mitigation options are available. These matrices together provide the understanding of the hazards and risks necessary to allow responsibilities and contingency planning to be allocated and implemented.

Table 2. Volcanic Risk Matrix

Hazard	**Area Affected†**	**Immediate Risk**	**Ongoing Risk**	**Anticipated Loss**	**Mitigation**	**Recovery Period**
Earthquake	3 – 5	Low	Nil	Small	Not applicable	Not applicable
Crater, Cone or Ring Formation	0.3 – 1.5	Extreme	Low	Extreme	None	Several months to years
Fire Fountaining*	0.2 – 0.5	High	Low	Extreme	Minor	1 week to months
Lava*	3 – 5	High	Low	High	Moderate	Weeks to months
Base Surge	3 – 5	High	Low	Extreme	None	1 week to months
Shock Waves	3 – 5	High	Low	High	None	1 week to months
Lava bombs*	0.4 – 0.5	Moderate	Low	Moderate	Minor	1 week to months
Airfall Tephra	3 – 100	Low	Moderate	Low	Moderate	1 week to months
Gas	3 – 5	High	Moderate	Moderate	Minor to Moderate	Not applicable
Lightning	3 – 100	Low	Low	Low	None	Up to 1 - 2 days
Tsunami	1	Low	Nil	Low	Moderate	Up to 1 - 2 days

* Events which are likely to be repeated over a period of time (weeks to months) following the initial event.
† Radial distance from vent, km.

WARNING

Physical Warnings

The next AVF eruption will occur when magma presently forming beneath Auckland rises to the surface. As the magma rises through the crust, it will generate micro-tremors which can be detected using seismometers, and then small earthquakes which can be felt. Volcanic eruption is expected to occur after a period of small earthquakes lasting a few days to a few weeks. Seismometer monitoring to date indicates a very low level of background seismicity, which improves the likelihood of detection of an impending eruption and eventual location of its vent.

Auckland Volcano-Seismic Monitoring Network

The AVSN comprises five sites at which seismic activity is monitored continuously (Figure 1). The AVSN is designed to monitor seismic activity associated with the onset of volcanic activity, but also detects non-volcanic earthquakes. By recognising a change in the prevailing seismic pattern that would signify magma movement within the volcanic field, some warning of impending volcanic eruption could be given.

Under the National Contingency Plan – Volcanic Eruption, the Institute of Geological and Nuclear Sciences (GNS) is responsible for the interpretation of the data and preparation of Surveillance Reports and Scientific Alert Bulletins containing the allocation of appropriate Scientific Alert Levels (SALs).

Scientific Alert Levels

SALs define the status of the volcanic field at any time. The SALs applied to Auckland's Volcanic Field are those developed for "reawakening" volcanoes, applied to a number of other volcanic centres such as Ruapehu, an andesitic volcano located in the central North Island of New Zealand.

Because the basaltic volcanic activity in the AVF is likely to develop over a relatively short time, and Auckland is an area of high population and infrastructure density, warning periods appropriate to the AVF have been assessed for each SAL and warning phases assigned, to assist in contingency planning (Table 3). The periods indicated in Table 3 do not reflect either the minimum or maximum duration of each level, but provide an indication of a realistic lower bound time period between warning levels. These periods are an indication of the mobilisation or resourcing time that can be anticipated. The durations suggest that early changes in seismicity (SAL 0 to 1) provide the most valuable warning of impending eruption because such changes occur over a time period in which mitigation can be reasonably implemented. This is also the period where emergency managers have an opportunity to prepare for response to a volcanic eruption. Once volcanic activity progresses beyond SAL 1, hazardous effects could be experienced within hours, and full-scale eruption within as little as a day.

Table 3. Scientific Alert Levels

SAL*	Indicative Phenomena	Volcano Status	Period†
0	Typical background surface activity; deformation, seismicity, and heat flow at low levels.	Usual dormant or quiescent state. **Advisory Phase**	Not applicable
1	Apparent seismic, geodetic, thermal or other unrest indicators.	Initial signs of possible volcanic unrest. No significant eruption threat. **Alert/ Warning Phase I or II**	A few days and up to a few weeks
2	Increase in number or intensity of unrest indicators (seismicity, deformation, heat flow etc).	Confirmation of volcanic unrest. Eruption threat. **Warning Phase II**	Up to 1 to 3 days
3	Minor steam eruptions. Relatively high and increasing trends shown by unrest indicators. Significant effects in eruption area and beyond.	Commencement of minor eruptions. Real possibility of hazardous eruptions. **Warning Phase III**	A few hours to 1 day
4	Eruption of new magma. Sustained high levels of unrest indicators, significant effects beyond volcano.	Hazardous local eruption in progress. Large-scale eruption now appears imminent. **Warning Phase IV**	Up to a few hours
5	Hazardous volcanic eruption in progress. Destruction within HZO Zone 1, major damage beyond active volcano. Significant risk over wider areas.	Large hazardous volcanic eruption in progress. **Warning Phase IV**	Not applicable

* Scientific Alert Level
† Warning periods assessed for the Auckland Volcanic Field. Periods have been assigned to Scientific Alert Levels (SALs) as a tool for planning purposes only. The SAL may rise to 1 and then return to 0 and is not intended to be a predictive tool.

The warning system proposed for the AVF therefore utilises the established SALs, but because of the likely rapid progression through the levels beyond SAL 1, sets the SALs in the context of warning phases (Table 3) as follows (see also Figure 5):

- Advisory Phase: The status quo (AVSN monitored by GNS and reported to ARC).
- Alert Phase: Activated with an SAL 1 announcement. Possible volcano-seismic activity has been detected.
- Warning Phase I: Commences within SAL 1 once a general vent area is identified.
- Warning Phase II to IV: Generally coincident with the SAL stages, but in areas of high population density or significant infrastructure risk, Warning Phase II may be issued during SAL 1.

Hazard Zone Overlay

One of the key requirements for civil defence emergency management is to understand the risks associated with an event, and the areas most likely to be at risk. As the future site/s of volcanic eruption in Auckland cannot be predicted, predicting the hazards and risks associated with volcanic eruption in the AVF is more difficult. That is, hazards from volcanic eruption will depend on whether the eruption occurs on land or below water and the risks will depend on the location of the eruption in the AVF.

Eruption scenarios have been effectively used in Civil Defence planning and the Auckland Engineering Lifelines Project (AELP) to identify the hazards and risks that are likely to be associated with future eruption within the AVF, and to model the potential effects of these on Auckland's key infrastructure (Auckland Regional Council 1999). As part of this work, generalised hazard zones were modelled (see "Area Affected", Table 1) based on the geological record for the existing AVF volcanoes. These hazard zones provide a visual perception of the potential distribution of hazards associated with eruption. The scenario examined as part of the AELP (Figure 4) was selected because it impacts both land and water and therefore displays the range of eruption styles seen in Auckland volcanoes, and because it is centred within the central business district, the area of highest daytime population and commercial density within Auckland.

For contingency planning, the hazard zones identified for the scenario eruption have been adopted, but have been modified to show a uniform distribution of hazard about the vent, (ie no prevailing wind direction has been inferred, and no lava flow route identified) (Figure 5). The actual hazard distribution will be dependent on factors such as the nature of the eruption, local topography, wind direction and strength, as outlined in Table 4.

Table 4. Hazard Controls

Volcano Parameter	Hazard Variable
Rate of magma rise and availability of water	Type of eruptive activity
Volume of magma	Magnitude of hazard zones
Topography	Extent and shape of hazard zones
Wind direction and wind speed	

As the centre of a future eruption is not clear, a uniform hazard approach allows the hazard distribution to be used as a template for superposition over any other potential vent location once the likely eruption area or site has been identified. This template or Hazard Zone Overlay (HZO) forms a very broad first estimate of the potential area that might be affected by volcanic hazard, and allows response planning to be immediately focused on the areas most likely to be affected by high risk impacts.

Recognising that the HZO is a tool for *initial* assessment of the likely area at risk from volcanic eruption, following detection of a change in seismicity by the AVSN, it has been recommended that a volcanic Scientific Advisory Group (SAG) be established. This would be mobilised following detection of atypical seismicity. The SAG will assess and map areas of hazard impact as eruption progresses, and provide advice to the lead Civil Defence Emergency Management agencies.

At SAL 1, a Technical Advisory Group (TAG) would be convened to provide advice to stakeholders on mitigation or response options. The TAG will include those able to provide recommendations for temporary engineering works such as works to mitigate lava flow, bypass or repair works, or structural recovery of buildings. The warning system developed for the AVF is presented in Figure 6.

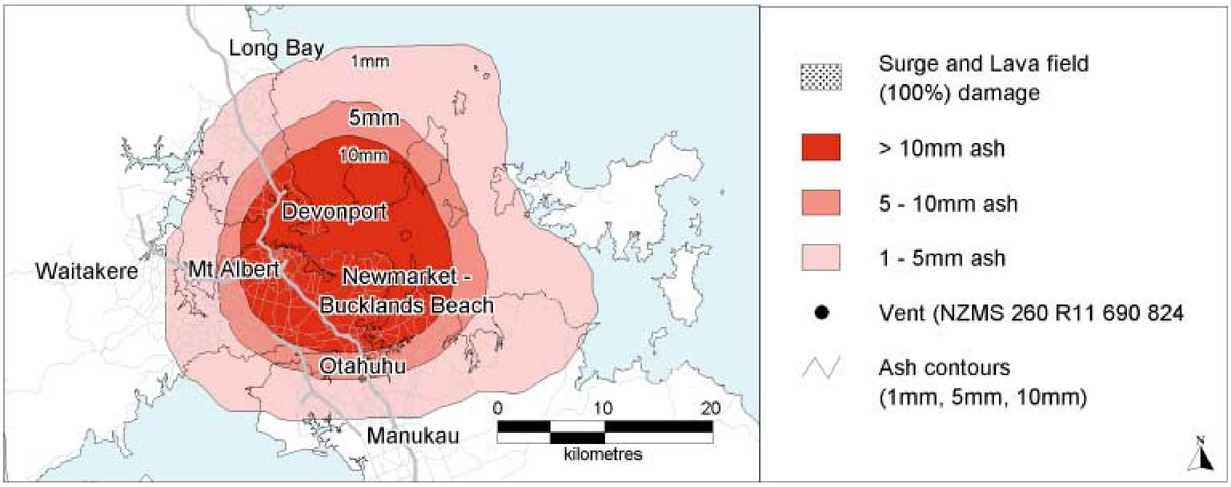

Figure 4. The scenario eruption, located in Auckland's Central Business District, assumes a column height of 6 km, eruptive mass of 0.01 km^3 and prevailing westerly wind.

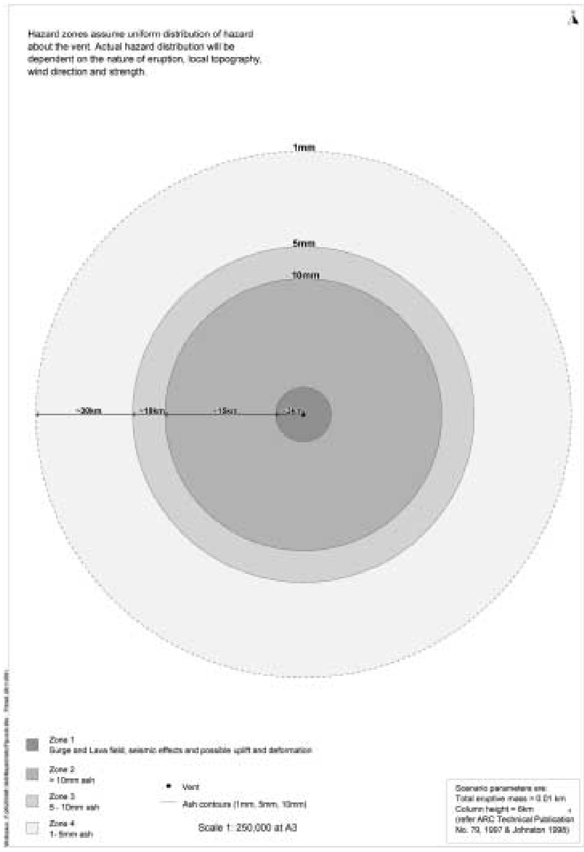

Figure 5. Hazard Zone Overlay

Advisory Phase	SAL 0	GNS – Monitoring AVSN ARC and Ministry CDEM – Receive Reports EMO, CEG, SAG and TAG established and meet Review, monitor and amend VCP as appropriate	→ EMO, SAG and TAG established
Alert Phase	SAL 1	Inform key organisations (within region) HZO to identify general area potentially affected Convene EMO, TAG and Nominate Lead Agency Public Information Commences	→ CEG, SAG and TAG convened
Warning Phase I	SAL 1	Area of volcanic activity/possible vent identified CDEMG identified as Lead Agency (consider alternative) Consider Declaration	
Warning Phase II	SAL 1 & 2	Evacuation of HZO 1 Area Review Lead Agency Consider Declaration… (as above)	
Warning Phase III	SAL 3	Evacuation of HZO 1 Area SAG mobilised to monitor hazard and hazard effects TAG mobilised to respond to hazards (resource mobilisation)	
Warning Phase IV	SAL 4 & 5	Emergency responses to eruption SAG continues monitoring hazard and hazard effects TAG continues to respond to hazards (resource mobilisation)	

Figure 6. AVF Warning Systems

CONCLUSIONS

The city of Auckland is located within a potentially active volcanic field. The next eruption will be from a new, presently unknown location at some unknown, but potentially short, time in the future. Development of a contingency plan for eruption from an unknown centre has been possible through a pragmatic consideration of the geological history, and engineering geological issues (hazards and risks) associated with the AVF. In summary:

- The Auckland Volcano-Seismic Network (AVSN) monitors volcanic earthquakes in the region and could warn of volcanic activity some days or perhaps weeks before an eruption.
- Changes in the status of Auckland's volcanic field will be identified by Geological & Nuclear Sciences (GNS).
- Once atypical seismicity is indicated, the Hazard Zone Overlay (HZO) will be used as a preliminary tool to rapidly assess the areas potentially at risk.
- Disruption to most lifeline utilities is anticipated, but will depend on the vent location. Direct effects could require evacuation of up to 200,000 people. More people may need to be evacuated if lifeline services are disrupted for any length of time.
- Scientific and Technical Advisory Groups (SAG and TAG) will be mobilised to monitor changes in the volcanic field and advise of technical solutions to mitigate hazards as these arise.
- The VCP outlines the roles and responsibilities of local authorities, GNS, the ministry of CDEM and other key organisations, SOE's and Utility providers. It outlines how command and control will work in eruption response, resource requirements, the process of issuing warnings and declaring a civil defence emergency, evacuation processes and welfare considerations.
- Testing and maintaining the Plan will be key to its success.

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APPENDIX 1 – DESCRIPTION OF VOLCANIC HAZARDS

Hazard	**Description**
Volcanic Earthquake*	Ground shaking caused by movement of magma through the crust both before and during eruptions.
Crater, Cone or Ring Formation	Maars, tuff rings and tuff cones may be produced during an eruption. Maars: vertical-walled craters cut into pre-eruption country rock and surrounded by low rims. Tuff rings: constructional craters lying mostly on or above pre-eruption surface. Tuff cones: smaller cones with higher rims.
Fire Fountaining†	Eruption of hot magma which may rise hundreds of metres above an active vent. Lumps of cooled magma are deposited as ash, lapilli and bombs. Restricted to a vent or series of vents along a fissure. Preserved at 77 % of AVF volcanoes.
Lava†	Streams of magma which flow by gravity into and along topographic lows; hot (1000°C or more); associated with 61% of AVF volcanoes. Generated by dry eruptions. May comprise: continuous and voluminous discharge of highly fluidised lava, often with gas-driven fire fountaining of scoria to hundreds of metres above the vent; or lava flows produced directly from primary or secondary vents; possibly associated with partial cone collapse or breaching.
Base surge	Ground-hugging turbulent mixtures of steam and solid ejecta that flow out laterally from the base of the eruption column in phreato-magmatic eruptions. Surges range from wet to dry and cool to hot. May develop rapidly as lateral blasts without an associated eruption column. Multiple explosions at short time intervals. Associated with 73 % of AVF volcanoes.
Shock Waves	Sound and pressure waves associated with energetic eruptions.
Lava Bombs†	Blocks and bombs (cobble to boulder sized material > 60 mm) follow ballistic trajectories from the vent and are released from the eruption column at 100 – 500 m height. Includes both cooler country rock and hot lava.
Airfall Tephra and Eruption Column	Eruption Column: Explosive reactions generate an eruption column of pyroclastic material rising several kilometres into the air. In phreatomagmatic eruptions, steam condensation in the eruption plume produces ash rainout. Airfall tephra: Includes all volcanic products aerially ejected from the vent (ash < 2 mm, lapilli 2 – 64 mm and bombs > 64 mm, derived from fire fountaining, ballistic projectiles and fall-out from the eruption column).
Gas	CO, CO_2 and HF may escape from vents. CO_2 generated by burning vegetation may become concentrated in low-lying areas. Boiling of seawater due to flowing lava creates dense white clouds of HCl aerosols (laze) carried downwind at low elevation. Discharge of SO_2 gas adjacent to lava flows. SO_2 and laze generate acid rain. Steam hazard.
Lightning	Pulses within the eruption column generated as a result of electrically charged ash in a convecting eruption column.
Tsunami	Long-period waves generated by uplift of the seafloor or coastal area, fall-out of the lava column into a body of water, base surges and accompanying shock waves, pyroclastic flows impacting on water and submarine explosions.

* Earthquakes may also be generated by fault movement. Such earthquakes are tectonic earthquakes, not caused by volcanic processes.
† Hazards which are likely to be repeated over a period of time (weeks or months) following the initial event