Volcanic Impact Assessment for the Auckland Volcanic Field

A report prepared for

AUCKLAND REGIONAL COUNCIL

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Cover Photo: The 1973 eruption of Heimaey, Iceland and the tephra covered town of Vestmannaeyjar.
(photograph courtesy of T. Einarsson)

SUMMARY

Auckland is a monogenetic volcanic field, covering an area of 360 km^2, in which activity has occurred from scattered vents during the past 140 000 years. There are 49 identified vents, although there is evidence that some adjacent vents may have been active in the same episode. By definition, monogenetic volcanoes erupt only in a single episode, after which the magma conduit is blocked by solidification. Subsequent eruptions occur from new pathways to the surface, and from different and unpredictable vent locations.

This report aims to identify the likely impacts within the Auckland region of future volcanic eruptions from the Auckland Volcanic Field. The effects of such eruptions on the buildings, main infrastructure, critical facilities, population, economic activities and natural features are considered. The study has two phases; 1: scenario development and 2: impact assessment/ vulnerability statement.

The purpose of the scenarios is not to predict what the next eruption at Auckland will be like, but to identify some of the processes and effects that could be expected in a likely eruption. The parameters used in these scenario eruptions are based on evidence from the geological record of the Auckland Volcanic Field, plus observed eruptions at similar volcanoes overseas. However, a future Auckland eruption will not necessarily be similar to any of the scenario events, in sequence, size, duration, or vent location.

Scenario 1 An offshore, surtseyan-style, phreatomagmatic eruption, centred in the Rangitoto channel, producing a smaller version of Rangitoto volcano.

Scenario 2 A phreatomagmatic eruption centred in the Tamaki Estuary, affecting residential and industrial areas.

Scenario 3 A waterfront phreatomagmatic/magmatic eruption centred in the railyards, affecting central business district, port, and residential areas.

Scenario 4 A magmatic eruption from a vent at the top (south) end of Queen Street, Auckland City, affecting the central business district (CBD).

Scenario 5 A magmatic eruption from a vent at the intersection of Mt Albert/Mt Eden roads, affecting residential and commercial areas.

Lava flows, ballistic block impacts, pyroclastic surges and lightning strikes from ash clouds present a high risk to life, and destroy near-vent structures in the scenario eruptions but the extent of these hazards (in a typical Auckland eruption) is mostly limited to within a few kilometres of the vent. Severe near-vent ground shaking accompanying volcanic earthquakes will also damage buildings, possibly also in areas not greatly damaged by eruption products. Apart from the evacuation of people and removal of transportable assets (if possible) there are few or no mitigation options available to counteract any of these near-vent hazards, which apply to all structures.

Evacuation, where necessary to save lives in high-risk, near-vent (<5 km) areas (affected by lava flows, ballistic block impacts, pyroclastic surges), should be carried out before an eruption commences, and would have to be completed before the eruption peaks. Evacuation may involve in excess of 150 000 people. Elsewhere, later evacuation of people may became necessary in areas where loss of services (electricity, water supply, sewage) makes continuing habitation untenable.

The various scenario impacts illustrate the vulnerability of urban areas where the deposition of only a few mm-cm of ash is sufficient to cause disruption of transportation, electricity, water, sewage and stormwater systems. Most systems, if affected only by thin tephra fall (<50 mm), can be restored within a few days to weeks after an eruption has ended.

Falls of volcanic ash can disrupt electricity supply depending on weather conditions, with power outages occurring if the ash is wet (i.e. conductive). Immediate ash removal is the best mitigation option to prevent widespread outages. Volcanic ash falls can cause severe damage to sewage and stormwater systems. The most effective mitigation measure to lessen the affects of ash falls is to reduce the input of ash into the system. Sewage treatment plants can be severely affected by ash falling directly on the plant or by the receipt of ash-laden sewage. Water supplies are vulnerable to contamination by ash fall into storage lakes preventing their use, and to excessive water demand during post-eruption ash clean-up operations. Water management plans will be required to manage excessive demands, and should include procedures to fill service reservoirs (if possible) on receipt of an ash fall warning. Information messages outlining water conservation measures will need to be broadcast to the public.

Urban areas in the region will be forced to undertake expensive and time-consuming clean-up operations as a consequence of any of the scenario eruptions. In each case there will be a need to develop coordinated community-wide ash-removal plans, which identify appropriate methods

of ash removal, collection and disposal. The public will need to be adequately informed on how to deal with volcanic ash.

This eruption scenario/impact exercise has highlighted the value of prior emergency management planning that will identify likely impacts on community lifelines and strengthen the links between agencies that will have to respond to such events. This needs to be done well in advance of any volcanic activity.

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INTRODUCTION

Auckland is New Zealand's largest urban centre with approximately one million inhabitants occupying the area surrounding the narrow isthmus between the Hauraki Gulf and Manukau Harbour. Auckland is New Zealand's major airport, seaport and commercial/industrial centre and the focus of one of the most rapidly growing areas of the country. Metropolitan Auckland has developed across the Auckland Volcanic Field (Fig. 1.2) in which small eruptions have occurred from 49 scattered vents during the past 140 000 years (Allen and Smith 1994). The most recent, and largest, eruptions formed Rangitoto Island which has grown within the last 800 years. The Auckland Volcanic Field is classified as active, and further eruptions can be expected.

The risk to Auckland from a volcanic eruption can be expressed by the relationship:

$$Risk = Hazard \times Vulnerability$$

in which the hazard from a future volcanic eruption is a combination of the probability of an eruption occurring in any given (say 100 year) period, plus the extent of damage from the eruption. Vulnerability is an expression of the effects of the eruption on people, buildings, infrastructure and economic activity. The probability of an eruption occurring in the Auckland Volcanic Field is quite low (cf. say Hawaii) and the extent of devastation is limited (cf. say a Taupo eruption), but the vulnerability is very high. Although the time of the next Auckland eruption cannot presently be determined, its effects can be assessed using knowledge gained from the studies of past eruptions in New Zealand and overseas.

This report uses geological, seismological and volcanological technical terms. Explanations for these terms can be found in the Glossary (p. 203).

BRIEF

The Auckland Regional Council has commissioned a volcanic risk assessment which aims to identify the likely impacts of future volcanic eruptions from the Auckland Volcanic Field. The effects of such eruptions on the buildings, main infrastructure, critical facilities, population, economic activities and natural features, of the Auckland region are to be studied. This study is presented in two parts; 1: scenario development (hazard definition) and 2: qualitative impact assessment/vulnerability statement. Quantification of the impacts will be necessary before a comprehensive risk assessment can be undertaken.

PART 1 - ERUPTION SCENARIOS FOR THE AUCKLAND VOLCANIC FIELD

I A Nairn, D M Johnston, T Thordarson

1.1 PART 1 - INTRODUCTION

Part 1 of this report provides:

a) a brief description of the history of the Auckland Volcanic Field and associated hazards.

b) descriptions of five potential eruption scenarios at Auckland which are intended to cover the range of expected eruption styles, and the differing landuse environments (residential, commercial and industrial) which could be affected by a future eruption.

Scenario 1 An offshore, surtseyan-style, phreatomagmatic eruption, centred at grid reference R11/730860, producing a smaller version of Rangitoto volcano.

Scenario 2 A phreatomagmatic eruption centred at R11/780780 in the Tamaki Estuary, affecting residential and industrial areas.

Scenario 3 A waterfront phreatomagmatic/magmatic eruption centred at R11/690824, affecting central business district, port, and residential areas.

Scenario 4 A magmatic eruption from a vent at the top (south) end of Queen Street, Auckland City (at R11/675812), affecting the central business district (CBD).

Scenario 5 A magmatic eruption from a vent at the intersection of Mt Albert/Mt Eden roads (at R11/671755), affecting residential and commercial areas.

Figure1.1 shows the locations of the five eruption scenarios.

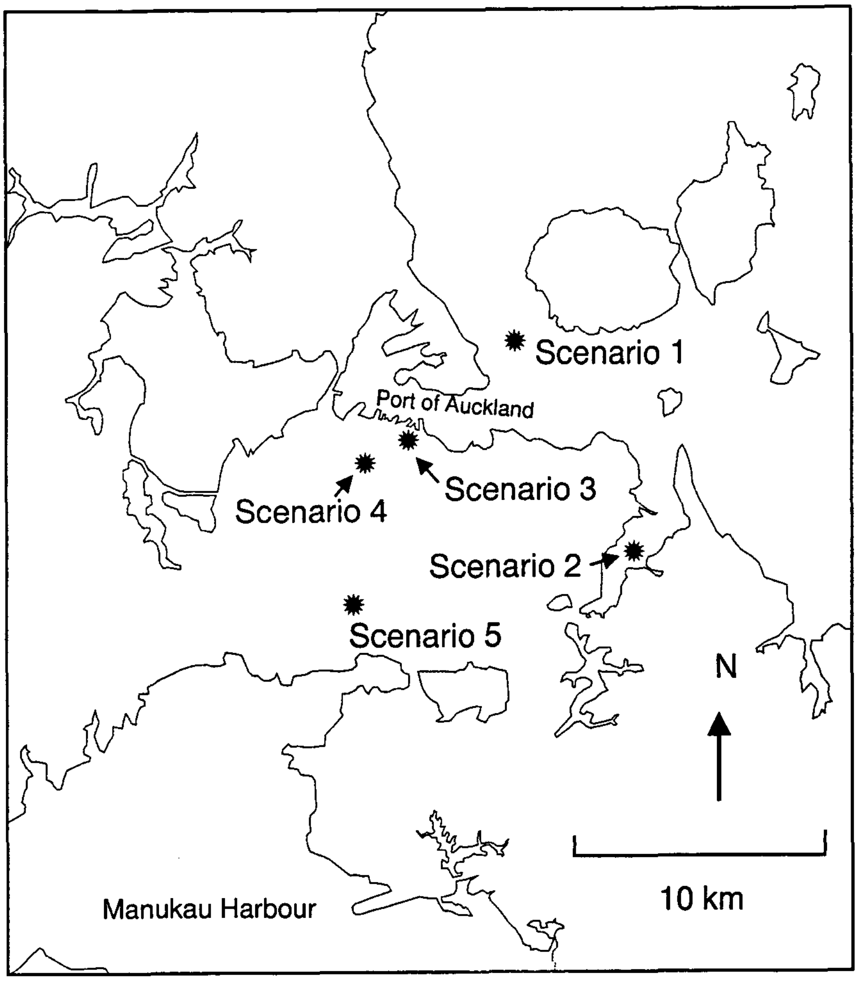

FIGURE 1.1: Map showing the location of the five eruption scenarios.

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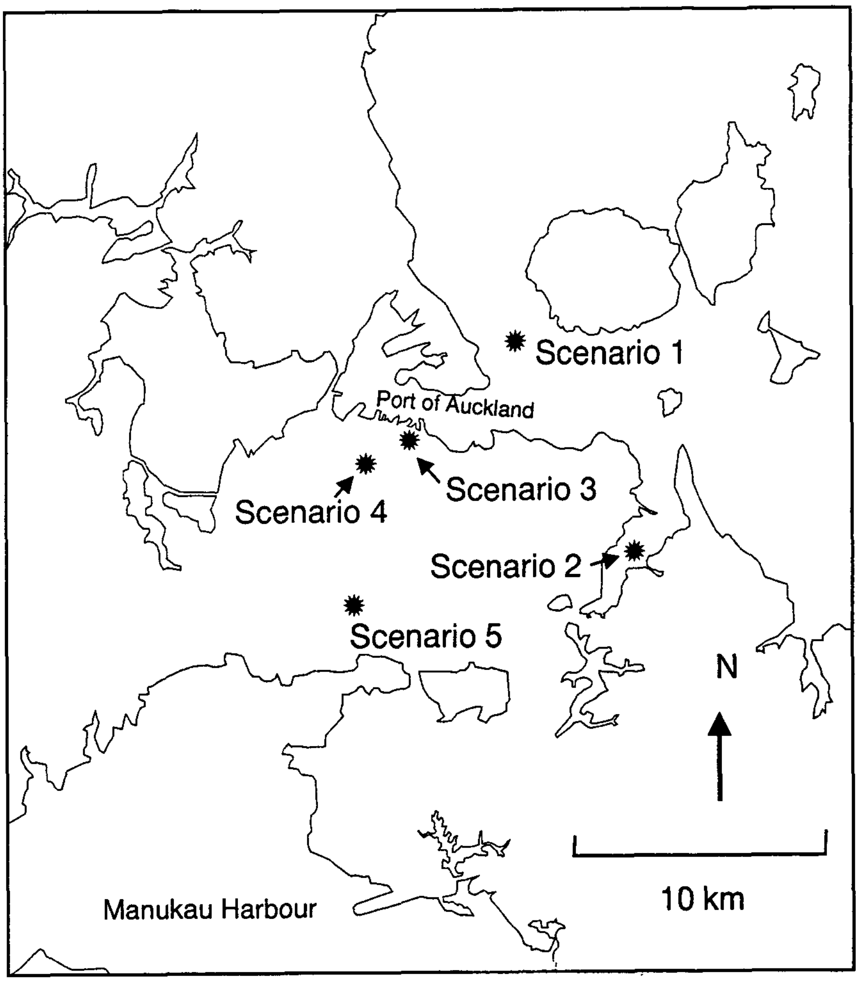

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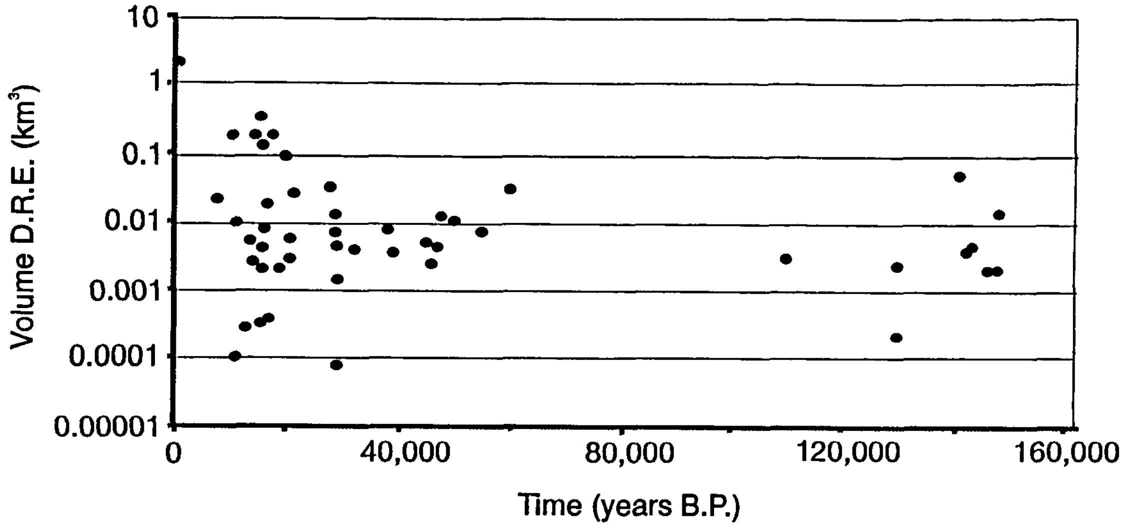

FIGURE 1.3: Volumes of Auckland volcanoes, and their ages. Note that all the larger eruptions (>0.1 km^3) have occurred in the last 20 000 years. From Allen and Smith (1994).

1.3 SCENARIO DEVELOPMENT

A scenario provides an imagined but logical sequence of events. Scenarios allow consideration of a range of possible events which may occur in the future. In developing the scenarios described in this report a number of assumptions have been made as to size of the scenario eruptions, their locations, durations, wind velocities at the time, and so on. The purpose of the scenarios is not to predict what the next eruption at Auckland will be like, but to identify some of the processes and effects that could be expected in a likely eruption. The parameters used in these scenario eruptions are based on evidence from the geological record of the Auckland Volcanic Field, plus observed eruptions at similar volcanoes overseas. However, a future Auckland eruption will not necessarily be similar to any of the scenario events, in sequence, size, duration, or vent location. Note that the effects of pyroclastic surges and tephra falls in the scenario eruptions are more widespread than those preserved in the geological record at Auckland. We have been influenced by the recent (1945, 1995, 1996) eruptions of Ruapehu

(and other recently active volcanoes), where thin but socially- and economically-significant tephra falls have already been lost from the geological record of distal areas.

The scenarios do not include actions that might be taken by responding agencies (eg. police and civil defence). These are for the appropriate agency to determine, and are outside the scope of this report.

1.4 SCENARIO ERUPTION PARAMETERS

Precursors

Seismicity in the upper crust (0-20 km depth) is a common precursor to volcanic eruptions. The Auckland Volcano-Seismic Network (Fig. 1.4), which is currently under development, is designed to detect such earthquakes. Cassidy *et al.* (1986) suggest that the ascent rate for basalt magma in the Auckland Volcanic Field may range from 1 to several tens of centimetres per second, from a source at 75-125 km depth. This implies that it may only take days to a few months for magma to reach the surface once upward movement is initiated.

There are few recorded observations of eruptions in monogenetic volcanic fields, and even fewer detailed accounts of the seismicity preceding such eruptions. The 1943 eruption of Paricutin volcano, Mexico (Yokoyama & de la Cruz-Reyna 1990), provides one of the best examples. The first instrumentally detected earthquake occurred 45 days before the eruption. Earthquakes were first felt two weeks prior to the outbreak of surface activity, and increased until the eruption occurred. Steam and gases were emitted 4.5 hours before the first magmatic ejecta reached the surface.

We have devised a general precursory seismic sequence for the Auckland Volcanic Field, and used it in each of the 5 eruption scenarios, modified to suit the different vent location of each scenario. This is (a) a result of lack of knowledge as to the actual precursory seismic sequences of previous Auckland eruptions (there being no evidence preserved); and (b) to illustrate that the same magma body generated at depth could erupt in very different ways, determined by vent location, near-surface geology, and topography. However, the use of a general precursory seismic sequence does not indicate that we expect the next eruption to follow this pattern. Eruptions may follow only a short precursory sequence (days) or longer periods (weeks).

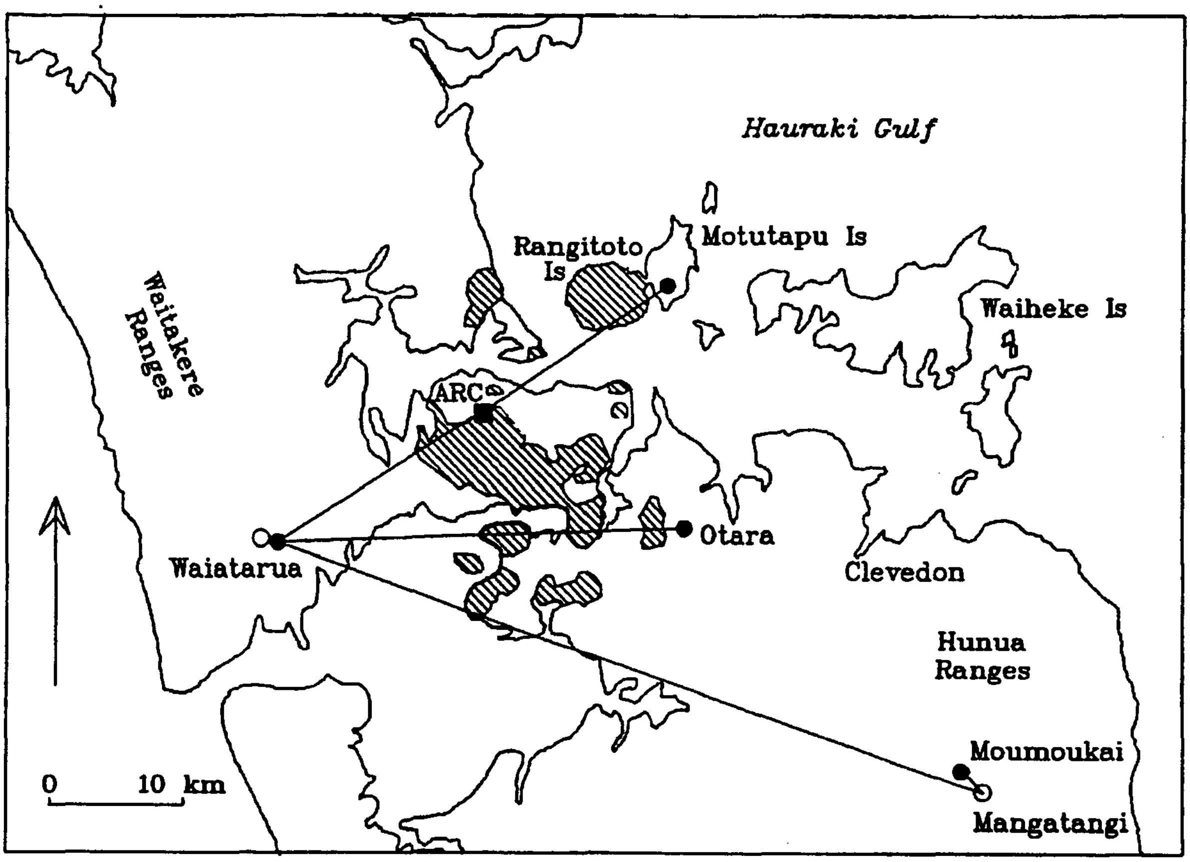

FIGURE 1.4: The Auckland Volcano-Seismic Network. Otara (OTAz), Motutapu (MTAz), Waiatarua (WTAz) and Moumoukai (MKAz) seismometers (solid circles) are telemetered via relay sites (open circles) to the Auckland Regional Council. The Auckland Volcanic Field is hatched.

Eruption Dynamics

The style of eruptions in the Auckland Volcanic Field is largely controlled by whether the vent is on land or within the sea, and by the near-surface occurrence of water-saturated sediments. Past eruptions have covered a range from phreatomagmatic ("wet"), caused by explosive interaction of magma and external water (see below), to purely magmatic ("dry") in which involvement of external water is not significant.

During the course of an eruption, changes in the water/magma ratio (see below) may lead to changes in the style of the activity. These changes may be either "short-term" oscillations in eruption style, or a long term evolution towards a "drier" or "wetter" eruption. Evidence for changes in style during an eruption are seen in many of the eruption deposits in the Auckland Volcanic Field (Searle 1981 and Kermode 1992), and have been well documented at Crater Hill (Houghton *et al.* 1996).

Phreatomagmatic eruptions

Phreatomagmatic ("wet") eruptions in the Auckland Volcanic Field involve the interaction of high temperature basaltic magma and external water (which may be surface water or groundwater). Phreatomagmatic eruptions are complex and dependent on a set of interrelated factors including: (a) the magma supply rate and physical properties (temperature, gas content, viscosity etc); (b) the supply rate and pressure (depth) of available external water; (c) vent geometry and structure; and (d) basement geology. The key feature in phreatomagmatic eruptions is the rapid heating of liquid water to magmatic temperatures (~1000°C). At low confining pressures, magmatic heating causes water to flash into steam, so that the water phase volume increases by up to 6000 times (at 1b atmospheric pressure). This explosive expansion of the water phase enhances fragmentation of the basaltic magma and adjacent country rock. Fragmentation very efficiently transfers the heat energy of the magma into kinetic energy driving the steam explosions. Efficiency of the explosive heat exchange process is related to the ratio of water to magma (Fig. 1.5), with the highest efficiency at a water:magma ratio of ~0.3, (Wohletz 1983, Wohletz and Sheridan 1983). Efficiency falls off at higher or lower water:magma ratios.

Phreatomagmatic explosions can occur in a number of situations including: (a) when rising magma encounters shallow ground water or surface water, (b) when vent wall rocks containing abundant groundwater collapse onto the magma column, (c) when retreat of a magma column allows rapid inflow of groundwater into the vent.

Phreatomagmatic explosions commonly produce rapidly rising, steam-rich vertical eruption columns surrounded by ground-hugging turbulent mixtures of steam and solid ejecta that flow out laterally from the base of the eruption column. Such lateral flows are termed "base surges" (Moore 1967). Surges range from wet and cool, to dry and hot. Initial velocities can be as high as 100 ms^{-1} at the vent, and surges can flow at velocities of 15 to 30 ms^{-1} (55 to 100 km/hr) out over 3 km from the vent (Moore *et al.* 1966). Historic examples of phreatomagmatic eruptions producing base surges the 1957 Capelinhos eruptions (Azores) in which surges travelled up to 2 km from the vent (Waters & Fisher 1971), the 1965 Taal eruption (Philippines) in which surges travelled 6 km from the vent (Moore 1967) and the 1977 eruptions at Ukinrek Maars (Alaska) where surges reached 3 km from the vent (Self *et al.* 1980). In the Auckland Volcanic Field preserved surge deposits are found up to 1 km from vents but would have almost certainly been deposited beyond that distance. Near-vent, where deposits are significantly thick (>0.2 m) surges are non-survivable and will destroy all but strongly-constructed structures. Surge thickness, density and speed will decrease towards the limits of flow, but will still prove fatal to people in the open, and will damage weakly-constructed buildings. Within the Auckland Volcanic Field, a 5 km radius is assumed to be a minimum safe distance to avoid the impacts of surges.

The fragmentation associated with phreatomagmatic eruptions produces a high proportion of fine material (ash and lapilli). Steam condensation in the eruption plume commonly produces ash rainout and promotes aggregation of ash into small clusters and accretionary lapilli. In the 1977 eruptions at Ukinrek Maars, the ash plume rose in excess of 6 km and fine ash fell up to 125 km from the vent (Self *et al.* 1980). The 1963 Surtsey eruption produced an ash plume to 12-15 km altitude and ash fell to >20 km downwind (Thorarinsson 1965, 1969).

A range of crater landforms is produced by phreatomagmatic eruptions, reflecting the dynamics of the eruption, and principally the ratio of explosion energy to ejecta mass (this parameter is sometimes termed "eruption violence"). The greater the energy content of a (subaerial) explosion, the greater the eruption velocities produced, and the more widely ejecta is dispersed. Three main crater types are maars, tuff rings and tuff cones, in order of decreasing energy content of eruption. **Maars** are usually vertical-walled volcanic craters that have been cut (largely by collapse) into pre-eruption country rocks, and are surrounded by low ejecta rims. **Tuff rings** are constructional craters that lie mostly on or above the pre-eruption surface. The crater rims usually dip at a low angle both outwards and inwards. **Tuff cones** (including scoria cones) have smaller craters than tuff rings and higher rims, with steeply dipping beds produced by the deposition of most ejecta close to the vent.

Magmatic (dry) eruptions

"Dry" eruptions of basaltic magma in Auckland Volcanic Field exhibit styles of activity termed hawaiian and strombolian. Both types of eruption are driven by the escape of magmatic gases from the venting lava. Hawaiian activity is characterised by the continuous and voluminous discharge of highly fluid lavas, often with gas-driven "fire fountaining" of scoria to hundreds of metres above the vent. Strombolian eruptions are characterised by a series of discrete explosions as large gas bubbles burst through the magma surface at intervals between 0.1 s to several hours (Blackburn *et al.* 1976). Both types of eruption commonly produce scoria cones, along with lava flows.

Wood (1980) summarises observations of 48 basaltic cone-forming eruptions. The eruptions usually start along a fissure, with initial weak venting of gases followed by intense eruption of scoria. Eruption usually becomes concentrated at one or more locations along the fissure. The near-continuous explosions can produce fire fountaining of incandescent lava to 200 -500 m in height. High accumulation rates of material falling back to ground often produces fountain-fed lava flows. Scoria cones are the most visible result of these eruptions and reach near final heights within a few days. The cone usually represents the least significant fraction of material produced, with lava flows and pyroclastic fall deposits (tephra) the dominant products. Lava flows are commonly fed by lava tubes at the base of the cones. Alternatively lava can flow from a breach in the cone when lava ponds in the vent. With time, explosions become less frequent and lava effusion becomes the main activity. The mean duration of observed cone-forming eruptions is 30 days.

Blackburn *et al.* (1976) describe the dynamics of strombolian explosive eruptions. Observations of the 1973 Heimaey (Iceland) eruption showed that large clasts (>20 cm) follow ballistic trajectories from the vent; intermediate-sized clasts (5-20 cm) are commonly released from the eruption column at 100-500 m heights; small particles (0.1-5 cm) are carried up 200-1000 m in the convecting eruption plume, with finer material (<1 mm) reaching heights of 6-10 km (Self *et al.* 1974). Subsequent dispersal is influenced by wind velocity. Most of the coarse material is deposited on or near the vent, but a small proportion of fine material can be deposited hundreds of kilometres downwind.

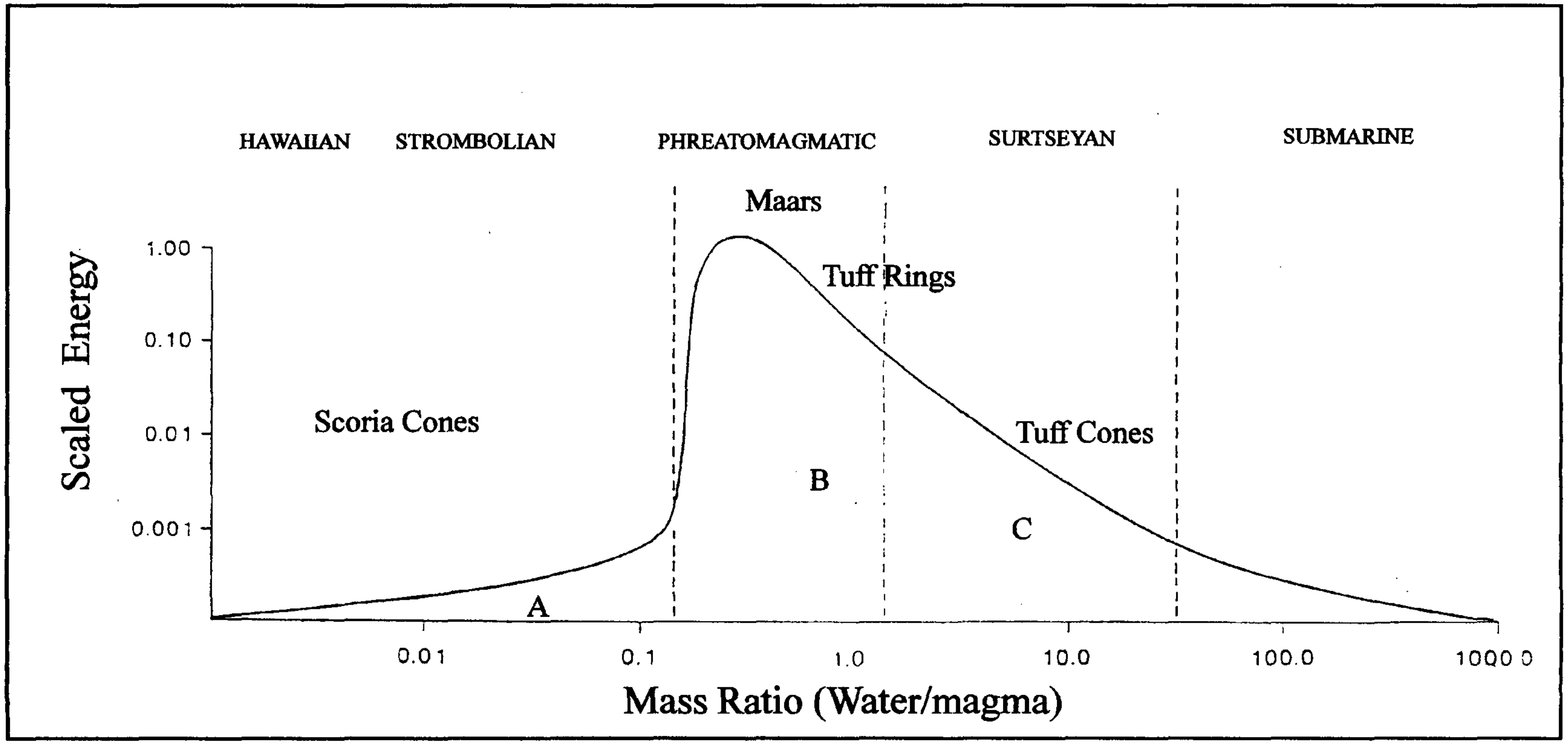

FIGURE 1.5: Plot of explosive energy (scaled to maximum yield) against water/magma mass ratios for volcanic eruptions. The sharp rise in the curve within the surtseyan field marks the onset of dynamic mixing between magma and water. From Wohletz (1983).

Wind direction

The wind direction in Auckland is variable (Fig. 1.6) but the predominant directions are from the west and southwest. In modelling tephra fall distribution for each scenario eruption the ASHFALL program (Hurst 1994) has been used, with the following wind speed profile with elevation.

Elevation (km)	Wind Speed (ms^{-1})
1	9
2	11
3	12
4	13
5	14
6	16
7	17

Wind directions for each scenario have been chosen to produce tephra fall patterns desired or required for the scenario brief and/or the subsequent impact study (e.g. we have not been constrained by the most frequently-occurring wind directions).

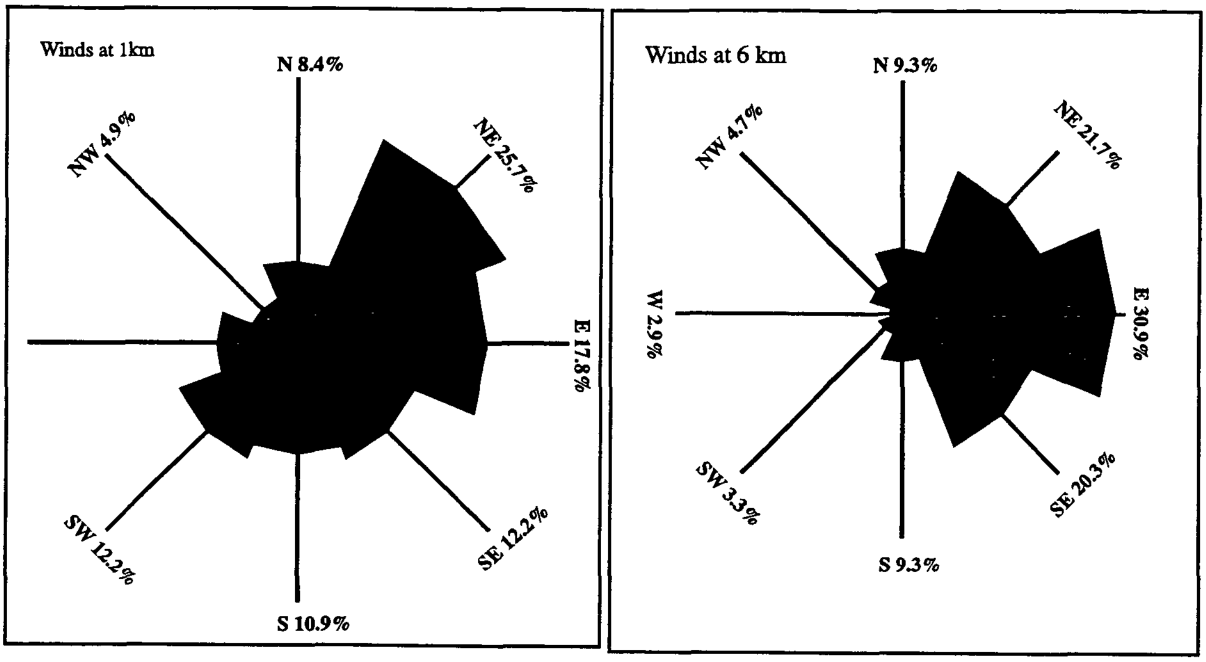

FIGURE 1.6: The frequency of wind directions at 1 and 6 km above Auckland Airport.

SCENARIO 1

Vent location:	Offshore (at R11/730860) in Rangitoto Channel
Magma type:	Basalt
Underlying country rock:	Sea floor sediments over Waitemata Group flysch (sandstones and mudstones).
Erupted volumes:	Tephra - 10^7 m^3; lava -10^8 m^3
Water depth:	$\leq$20 m

In this offshore, surtseyan-style phreatomagmatic "Rangitoto-type" eruption scenario, the first instrumentally-recorded high-frequency earthquake is set at -25 days (25 days before the start of eruptive activity). The eruption dynamics and products are modelled, in part, on the 1963 Surtsey eruption in Iceland (Thorarinsson 1965, 1969) with modifications as required by the shallower-water setting of the Auckland scenario eruption. Tephra dispersal patterns for this scenario are shown in Figs. 1.7 and 1.8, and the extent of base-surges and lava flows in Fig. 1.9.

CHRONOLOGY OF THE SCENARIO 1 ERUPTION

Day 1(-25) A M_L 5.1 high frequency tectonic earthquake occurs at ~100 km depth beneath Auckland. It is recorded by the Auckland Volcano-Seismic Network (AVSN - Fig. 3) and by most North Island stations of the National Seismic Network, although only weakly felt in the Auckland area.

Day 6 (-20) Two high-frequency earthquakes (M_L 2.5 and 3.2) are recorded by the AVSN, with first arrivals on the Motutapu (MTAz) instrument; sequentially later at the Otara (OTAz), Waiatarua (WTAz) and Moumoukai (MKAz) stations. These events are not felt, and are regarded as aftershocks of the M_L 5.1 event 5 days earlier. No action is taken.

Day 8 (-18) Four high-frequency earthquakes (M_L 2.4 to 2.9) are recorded by the AVSN, with sequential arrival times on MTAz, OTAz, WTAz and MKAz seismographs, similar to those of Day 6. GNS is contacted at 1800 h and the recent seismic events are discussed. ARC deploys a smoked-paper portable seismograph at North Head during the evening.

Day 9 (-17) GNS staff travel to Auckland and install a portable seismometer at Musick Point. Five high-frequency earthquakes similar to those of the previous days are recorded by the Auckland net instruments. **Scientific Alert Level 1 is declared**[1]**,** as a result of the unusual seismicity.

Day 10 (-16) Five high-frequency earthquakes (M_L 3.1 to 3.4) are recorded by the Auckland network and portable seismographs; the largest event is weakly felt across central Auckland. Analysis of these (and some of the earlier) events indicates they are approximately located beneath the Rangitoto-Takapuna-Devonport area, at 30-40 km depths. A further portable seismometer is installed near Flax Point on Rangitoto Island.

Day 16 (-10) Two high-frequency earthquakes (both M_L 3.1) are recorded by the AVSN and portable seismographs.

Day 19 (-7) 25 high-frequency earthquakes (M_L 2.4 to 3.7) are recorded by the AVSN and portable seismographs. Locations are similar to the earlier events, with possible shallowing to ~10-20 km depths. Two apparent long-period small earthquakes are poorly recorded. **Scientific Alert Level 2 is declared,** after recognition of the apparent shallowing of epicentres and the possible occurrence of long-period events. An additional portable seismograph is installed at Takapuna Head, although the site is very noisy and the instrument gain has to be set at very low level. A RSAM tremor monitoring system is installed on the volcano-seismic network at the ARC Building recording centre.

Day 20 (-6) 10 high-frequency earthquakes (M_L 2.3 to 3.9) are recorded by the AVSN. Epicentral locations of the best-recorded events suggest that they originate at about 15 km depth.

Day 21(-5) 8 high-frequency earthquakes (M_L 2.4 to 3.7), and 4 (uncertain) long period earthquakes are recorded by the volcano-seismic network. Refinement of the seismic analysis shows that most of the well-recorded high-frequency shallower events of the last 12 days have been located within a 3 km diameter area centred within the Rangitoto Channel, between Rangitoto Island and Takapuna. Tilt-levelling sites are installed at Takapuna Head and North Head, and initial

[1]See Appendix 4 for description of the Science Alert levels

surveys performed.

Day 22 (-4) 150 high-frequency earthquakes (M_L 2.2 to 4.1) and 10 long period volcanic earthquakes are recorded by the AVSN and portable seismographs; the two largest high-frequency events are strongly felt by people in the Takapuna-Devonport area, and on the western side of Rangitoto Island. The high-frequency events are estimated to be centred at 5-10 km depths. Some minor shaking damage (cracking of facades, plastered walls, and a few windows) occurs in older buildings within the epicentral area, with some items falling from shelves. Felt intensities are MM III to V. Low-frequency volcanic tremor (1-2 Hz) appears on MTAz, OTAz and adjacent portable seismographs, occurring as short bursts of 30-60 s duration over a two hour period from 1600h. The **Scientific Alert Level** remains at 2 (e.g. 2+ ?) although the further shallowing of epicentres and the occurrence of volcanic tremor is recognised as indicating an increased probability of an eruption actually occurring. A further tilt-levelling site is hastily installed near Flax Point on Rangitoto Island.

Day 23 (-3) 45 high-frequency earthquakes are recorded by the AVSN; 25 of these earthquakes are felt (M_L 3.9 to 4.3), including 5 which are locally audible. 60 long-period volcanic earthquakes are recorded. Bursts of low-frequency tremor are occurring more often, with increasing amplitudes, and the appearance of higher frequency spectra. Relevelling of the Takapuna tilt-level sites finds that significant inflation (~200 microradians) has occurred, up towards the centre of the Rangitoto Channel. Crude tide gauges (metal pipes driven into the beaches about 1 m below low tide level) are installed on Takapuna and Rangitoto beaches, and height scales attached. Aerial infrared survey locates a 100 m wide patch of water with slightly elevated (+3 C) surface temperature at R11/730860.

Day 24 (-2) 30 high-frequency earthquakes are recorded by the AVSN seismographs; 4 of these earthquakes were felt (M_L 3.8 to 4.1) but seismicity is generally less than on the previous few days. Tremor levels and numbers of long-period events are also lower than on the previous day. No further inflation is detected by relevelling of tilt sites.

Day 25 (-1) High-frequency earthquakes increase dramatically to over 1100 events instrumentally recorded in the 16 hrs prior to 1200h today. At least 200 of these

events are felt (M_L 3.8 to 4.6), with widespread minor shaking damage to buildings in the Takapuna-Devonport epicentral area. Near-continuous volcanic tremor, with mixed low and higher frequencies, starts at 0300h, overloading MTAz and the local portable seismographs. Relevelling finds highly significant inflation (~1000 microradians up towards focal area), with ongoing inflationary tilt detectable during the survey. Discrete level changes accompany some of the larger felt earthquakes, which are heard as sharp bangs. Sulphurous gas smells are detected by scientists working at the Rangitoto tilt-levelling site. **Scientific Alert Level 3 is declared at 1200h** as an eruption appears imminent. Helicopter inspection of the Rangitoto Channel finds areas of gas bubbles, upwellings of hot water, high (80-90°C) spot surface water temperatures, and some dead fish around R11/730860. Water samples are taken using a sampling device lowered from the helicopter. Felt earthquakes continue throughout the day and into the night.

Day 26 (0) (Eruption day)

0400h Seismic activity (felt and instrumentally recorded) peaks around this time, before decreasing again. Continuous and intense volcanic tremor with mixed low to high-frequency spectra, is accompanied by large high-frequency earthquakes occurring at 0.5 to 3 minute intervals. Gas smell is again noted on Rangitoto.

0600h Ground shaking intensifies, causing structural damage to some buildings in the Takapuna-Devonport area. Isolated waves (1.5 m amplitude) are seen breaking on Devonport beaches at dawn, and appear to be related to the largest earthquakes.

0700h Intense seismic activity continues. At 0720h the tide gauge installed at Takapuna Head is observed (from a helicopter) to have totally emerged from the low-tide sea level, and ~0.5 m uplift of the adjacent sea floor is clearly visible as exposed mudflats and rock platforms. Steam clouds begin to rise above the sea surface as small white jets break through near the centre of the channel. Steam discharge rates steadily increase, accompanied by volcanic gas emission now very noticeable on Rangitoto Island. Wind is blowing from SW carrying the white steam/gas plume to NE at low elevations. Intermittent local updoming of the sea surface causes waves (amplitude ~ 2 m) to spread from the channel centre and break on the Takapuna beaches.

0745h Subaerial eruption begins with low (initially ~10 m height) jetting of black ejecta plumes above the sea along a 300 m line centred at R11/730860. Volcanic tremor levels remain very high but discrete sharp-onset high- frequency large earthquakes are decreasing, being replaced by smaller volcanic earthquakes which accompany the larger jetting eruptions. The eruptions are almost silent, but generate waves larger than any of the previous examples, with vertical runup of 3-5 m on Takapuna and Rangitoto beaches. By 0810h a voluminous white steam column is vigorously convecting to 2-3 km elevation above the active area, expanding into a large steam cloud drifting downwind above Rangitoto Island. **Alert Level 4 is declared.**

0830h Activity is becoming focused at a single main vent with frequent (near-continuous) discrete surtseyan explosions increasing in size. Black plumes and jets rise 200-300 m above the sea surface, falling back into outwardly expanding steam-rich base-surges flowing over the violently agitated sea surface. Metre-size bombs are falling into the sea out to 0.4 km from the active vents. Large waves generated by the eruptions are now flooding onto Takapuna and Rangitoto beaches, and arriving with diminished amplitude on the Orakei-Mission Bay-St Heliers shore to south. Here the waves are funnelled into the Tamaki river estuary and metre-high surges pass up the river. Fine ejecta separating from the falling eruption plumes is being carried up in a vigorously convoluting grey eruption column now rising to 6-7 km, with sparse fallout of mm-size ash occurring across Rangitoto Island. Frequent lightning pulses within the eruption column are causing some interference with radio-linked communications including the radio-telemetered seismographs.

0900h Base-surges generated by the largest of the increasingly violent eruptions (the largest plumes are now being ejected to 1000 m vertically and bombs are falling out to 1 km laterally) just reach the Rangitoto (downwind) shore by 0900h and the Takapuna shore shortly afterwards (see Fig. 1.8). Here the dilute wet surges flow inland a few hundred metres beyond the wave-affected areas adjacent to the beaches, to carry away some unsubstantial structures and break glass doors and windows. Ash is plastered onto solid structures causing considerable abrasion damage, and carried into buildings through broken doors and windows. About 10^6 m^3 of tephra has been erupted to this time, with distribution as shown in Fig. 1.7.

0930h Discrete eruptions become increasingly frequent before merging into the continuous uprush of pyroclastic material, steam and gas, accompanied by the most intense volcanic tremor of the entire eruption episode. The enlarging eruption column rises to 8-10 km in a decreasing SW wind. Large ejecta in the column are visibly incandescent for several hundred metres above the sea surface. Less frequent fall back of column material (beyond the vent area) causes the generation of large waves and base-surges to become less frequent. As the wind decreases, the eruption cloud expands at high elevation (>10 km) over the Devonport peninsula, with fallout of mm-size ash and scoria clasts commencing in this area.

1020h Wind direction is veering to NW and freshening, while the continuous uprush eruption continues. Fine scoria and ash commences to fall in the Mission Bay-St Heliers urban area. Volcanic gas becomes detectable here during the early afternoon.

1315h The continuous uprush eruption abruptly diminishes, being replaced by frequent intermittent eruptions similar to those which occurred prior to 0930h.

This style of activity continues at fluctuating intensity during the remainder of the day, broken by occasional periods of quiescence. An aerial inspection during a quiescent period finds a tuff cone rising a few metres above the sea surface at the active vent. Carried by an incoming tide, rafts of floating scoria are spreading across the Rangitoto Channel and into the Waitemata Harbour. Similar eruptions continue during the night and into the next day.

Day 27 (+1) Similar eruptions build up a small tuff cone to about 20 m above sea level by midday. Water still has free access to the rising magma and typical surtseyan activity continues. Another continuous uprush eruption commences about 1300 h, with column height increasing to ~10 km, and subsequent heavy tephra fall (50-20 mm) occurring downwind to SE, in the Mission Bay-St Heliers-Howick areas. Rapid growth of the cone occurs during this eruption, to reach 40 m above sea level, forming an elongated island with 200 x 150 m lateral dimensions. A total of about 10^7 m^3 of tephra has been erupted over the last 24 hours, with distribution as shown in Fig. 1.8.

Days 28-40 Tuff cone growth is continued by similar eruptions of fluctuating size, but with less water gaining access to the vent. As the eruption dries out, surtseyan-style

intermittent eruptions diminish, to be replaced by more frequent episodes of continuous uprush, and later by near-hawaiian fire-fountaining and strombolian explosive episodes. These become common beyond Day 35 by when the tuff cone has grown to 100 m high, and is subcircular - about 800 m across at sea level (Fig. 1.9). Little tephra is widely dispersed by these later eruptions.

Day 45 -- Lava flows commence from a central vent on the new island and flow across the tuff cone into the sea. Minor explosive activity accompanies these effusive eruptions, building a small summit scoria cone. Boiling of sea water by the inflowing lava creates voluminous dense white clouds of hydrochloric acid aerosols ("laze") which are carried downwind at low elevation as an acid haze.

Later...............

Lava flows continue for several months, accompanied by occasional fire fountaining episodes and explosive eruptions which generate tephra falls for a few km downwind. The continuous voluminous discharge of SO_2 gas from the vent, plus the laze generated at the lava inflows to the sea, give rise to acid rains and considerable corrosion problems in downwind areas, where returning inhabitants experience breathing difficulties, nausea, skin irritations and other deleterious health effects. The lava outpourings build up a small lava shield to ~1.5 km diameter at sea level on the axis of the Rangitoto Channel (Fig. 1.9), until the eruption ceases about 8 months after commencement. Growth of the lava shield has blocked the Rangitoto Channel to all shipping requiring more than 5 m water depth.

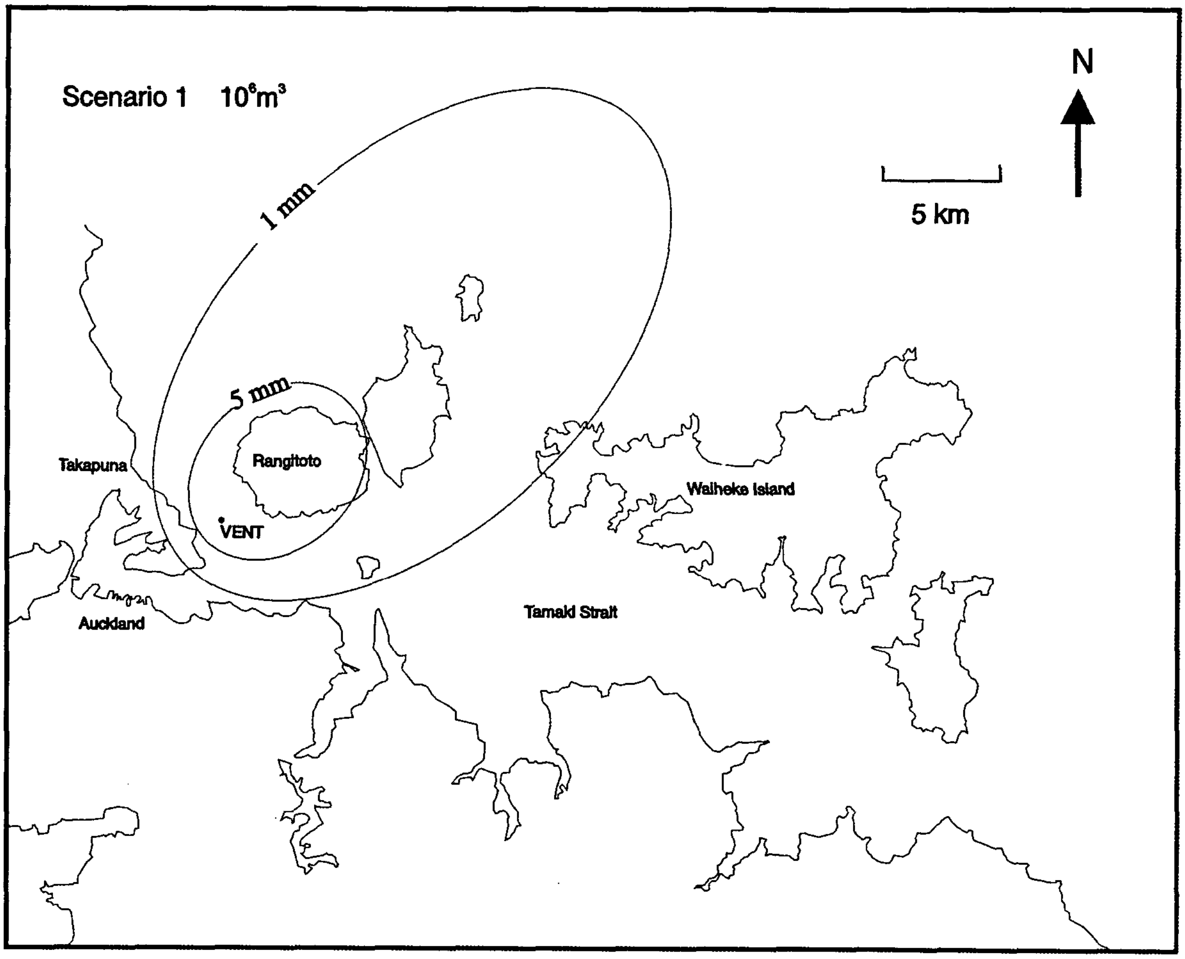

FIGURE 1.7: Initial (10^6 m^3) tephra fall distribution in Scenario 1 eruption to about 0900h on Day 26.

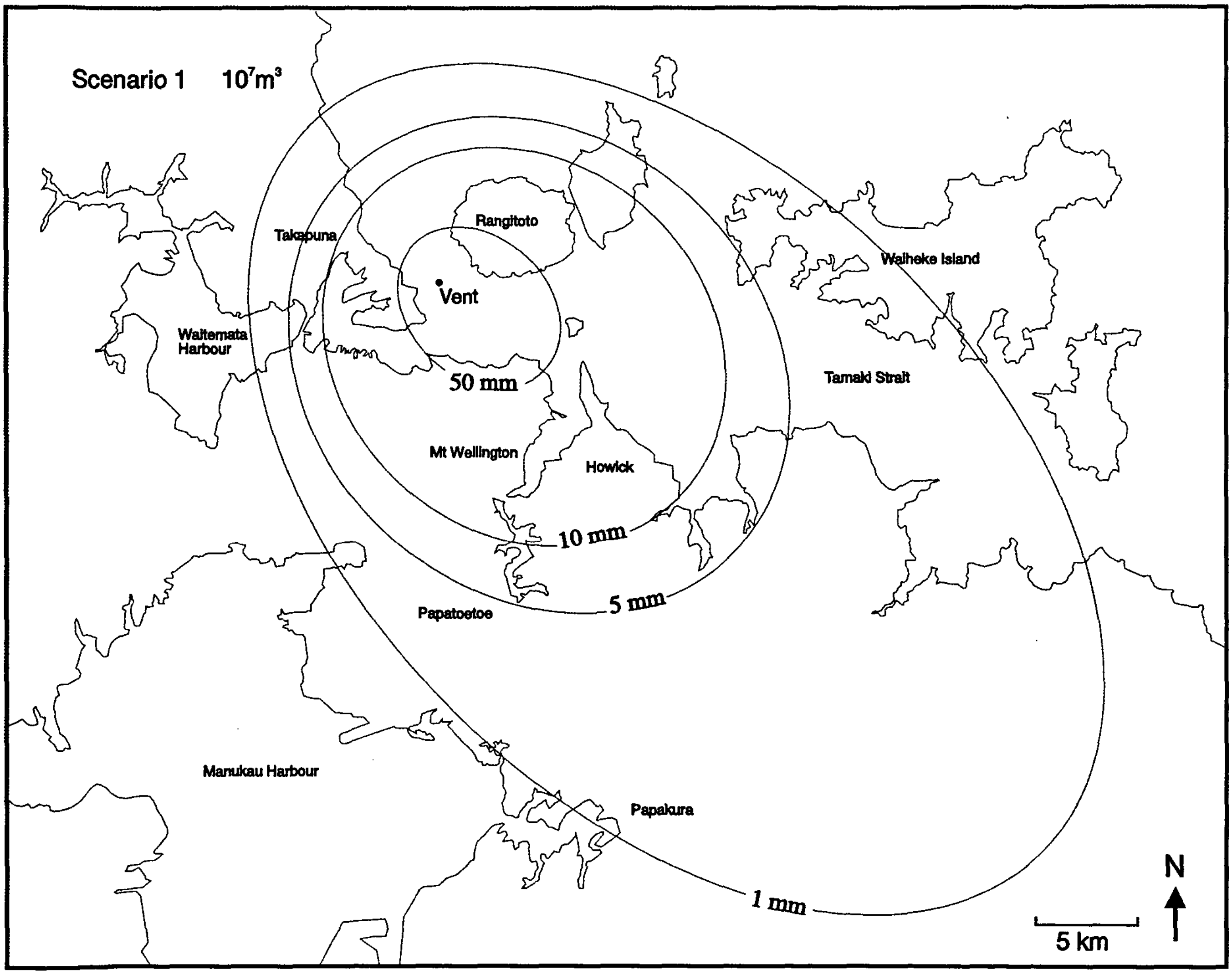

FIGURE 1.8: Tephra fall distribution (10^7 m^3) in Scenario 1 eruption to end of Day 26.

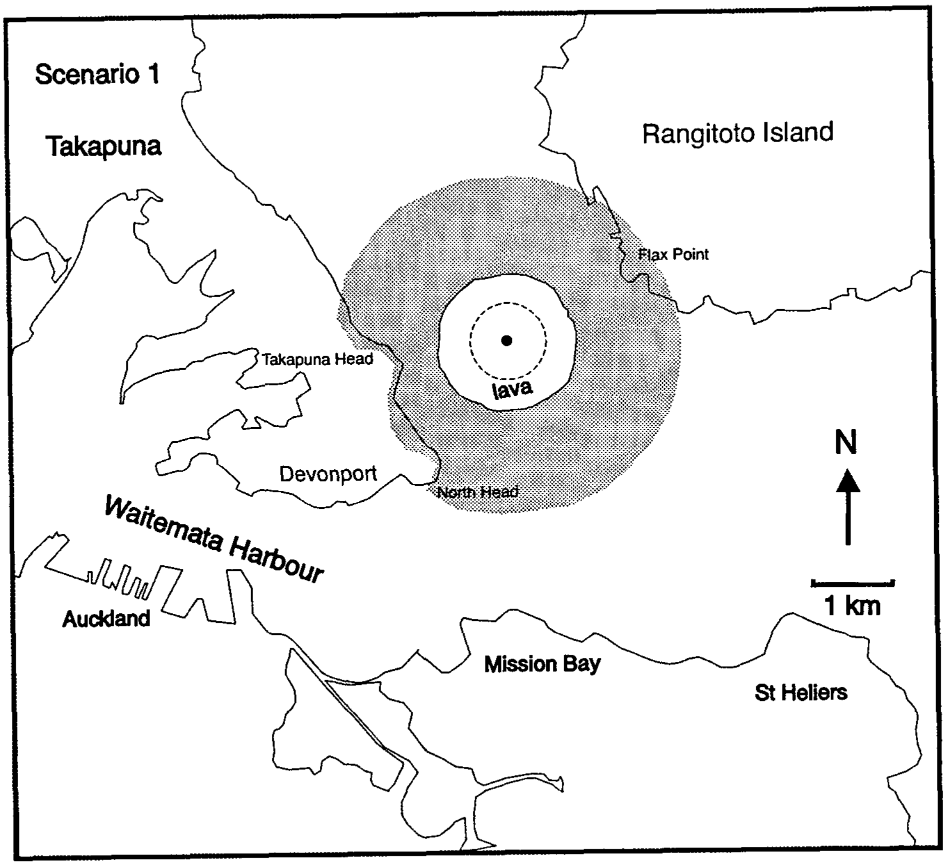

FIGURE 1.9: Final extent of lava shield (at sea level), surmounting the tuff cone (dashed line). Extent of base-surge deposits is shown by stippled area.

PHOTOGRAPHS TO ILLUSTRATE SCENARIO 1

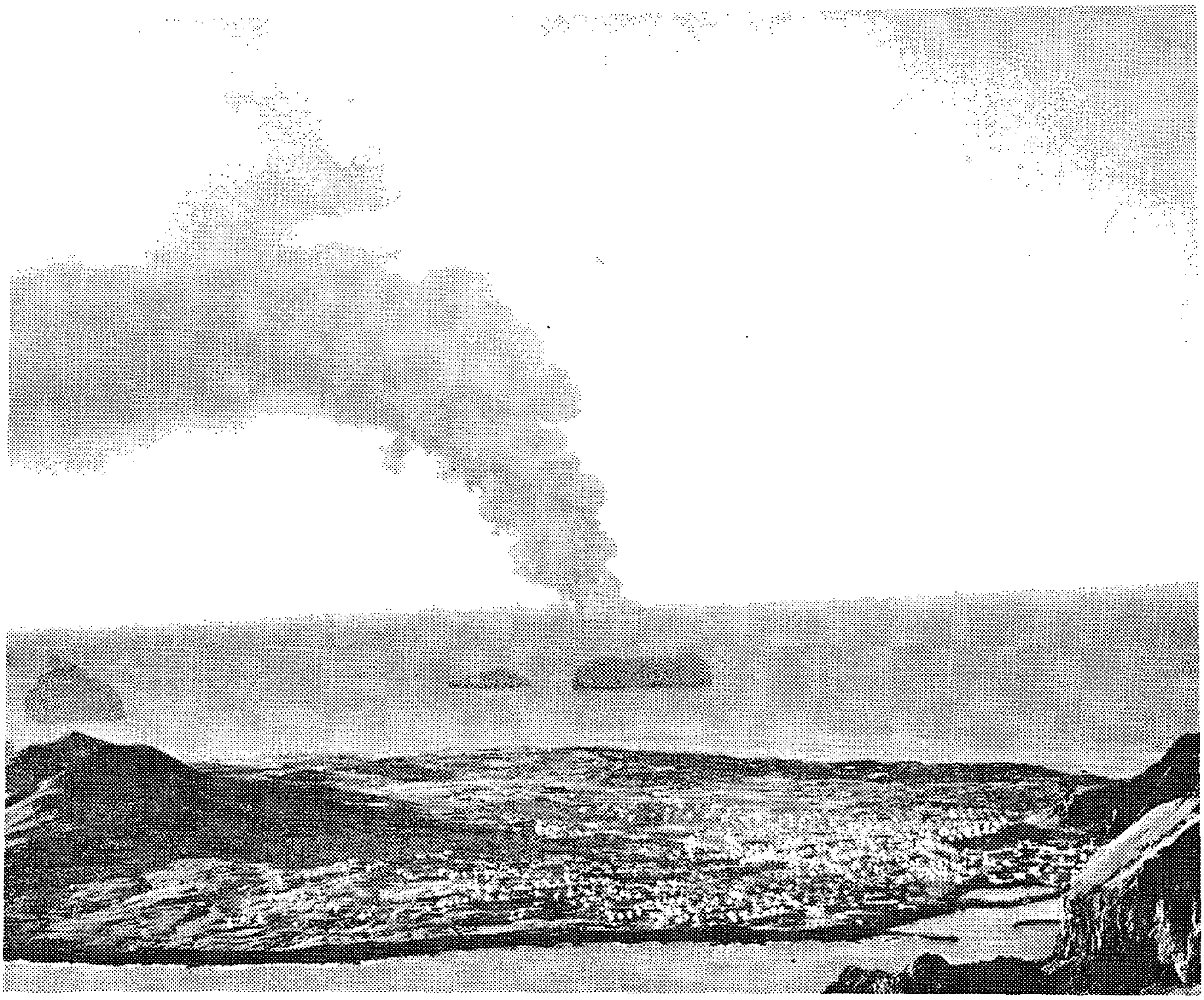

FIGURE 1.10: Ash plume emerging from the ocean on the first day of the 1963 eruption of Surtsey, Iceland (November 14). (photography by S. Einarsson and courtesy of S.Thorarinsson and Cassell & Company)

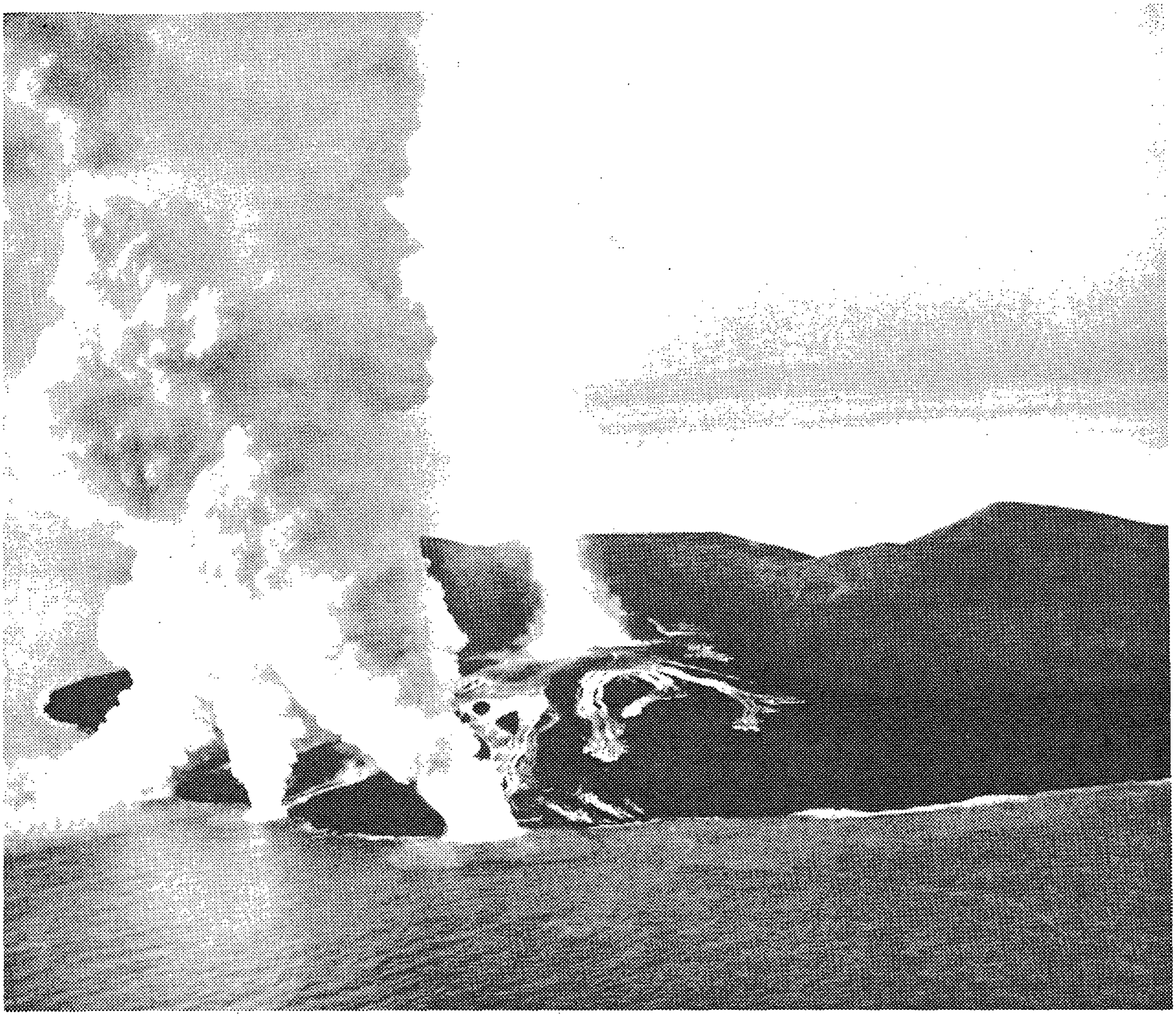

FIGURE 1.11: Lava flowing from the vent to the sea on the island of Surtsey, Iceland, on April 20,1964. The high ground behind the vent is the tuff cone formed during the initial phreatomagmatic phases of the eruption. (Photography by G. Elisson and courtesy of T. Einarsson).

SCENARIO 2

Vent location:	Tamaki Estuary (R11/780780)
Magma type:	Basalt
Underlying country rock:	Micaceous sand of tidal mud flats, over Waitemata Group flysch (sandstones and mudstones).
Erupted volume:	Tephra fall - 10^7 m^3, base surge deposits - $5x10^7$ m^3.
Water depth:	<5 m

In this phreatomagmatic eruption scenario affecting residential and industrial areas, the first instrumentally-recorded high-frequency earthquake is set at -25 days (25 days before the start of eruptive activity). For scenario 2, the eruption dynamics and products are in part modelled on the 1957/58 Capelinhos eruption in the Azores (Machado *et al.* 1962) and the 1965 Taal eruption in the Philippines (Moore *et al.* 1966). A tuff-ring, similar to the Panmure or Orakei basins (Kermode 1992), is produced. Vent location for this scenario is shown in Fig. 1.12 along with the radial distances affected by base-surges and ballistic ejecta. Tephra fall distribution is shown in Fig. 1.13.

CHRONOLOGY OF THE SCENARIO 2 ERUPTION

Day 1(-25) A M_L 5.1 high frequency tectonic earthquake occurs at ~100 km depth beneath Auckland. It is recorded by the Auckland Volcano-Seismic Network (AVSN - Fig. 3) and by most North Island stations of the National Seismic Network, although only weakly felt in the Auckland area.

Day 6 (-20) Two high-frequency earthquakes (M_L 2.5 and 3.2) are recorded by the AVSN, with first arrivals at the Otara (OTAz) station; sequentially later at the Motutapu (MTAz), Waiatarua (WTAz) and Moumoukai (MKAz) stations. These events are not felt, and are regarded as aftershocks of the M_L 5.1 event 5 days earlier. No action is taken.

Day 8 (-18) Four high-frequency earthquakes (M_L 2.4 to 2.9) are recorded by the AVSN, with sequential arrival times on OTAz, MTAz, WTAz and MKAz seismographs, similar to those of Day 6. GNS is contacted at 1800 h and the recent seismic events are discussed. ARC deploys a smoked-paper portable seismograph at Musick Point during the evening.

Day 9 (-17) GNS staff travel to Auckland and install a portable EARSS seismometer at Musick Point. Five high-frequency earthquakes similar to those of the previous days are recorded by the AVSN. **Scientific Alert Level 1 is declared**[2], as a result of the unusual seismicity.

Day 10 (-16) Five high-frequency earthquakes (M_L 3.1 to 3.4) are recorded by the Auckland network and portable seismographs; the largest event is weakly felt across the Eastern Suburbs. Analysis of these (and some of the earlier) events indicates they are approximately located beneath the Glen Innes-Pakuranga area, at 30-40 km depths. A further portable seismometer is installed on Mt Wellington, although the site is very noisy and the instrument has to be operated at a low gain.

Day 16 (-10) Two high-frequency earthquakes (both M_L 3.1) are recorded by the AVSN and portable seismographs.

Day 19 (-7) 25 high-frequency earthquakes (M_L 2.4 to 3.7) are recorded by the AVSN and portable seismographs. Locations are similar to the earlier events, with possible shallowing to ~10-20 km depths. Two apparent long-period small earthquakes are poorly recorded. **Scientific Alert Level 2 is declared,** after recognition of the apparent shallowing of epicentres and the possible occurrence of long-period events. An additional telemetered seismograph is installed on Brown's Island. A RSAM tremor monitoring system is installed on the volcano-seismic network at the ARC Building recording centre.

Day 20 (-6) 10 high-frequency earthquakes (M_L 2.3 to 3.9) are recorded by the AVSN, with locations in the same general area as the previous events. Epicentral locations of the best recorded events suggest they originate at about 15 km depth.

Day 21(-5) 8 high-frequency earthquakes (M_L 2.4 to 3.7), and 4 (uncertain) long period earthquakes are recorded by the volcano-seismic network. Refinement of the seismic analysis shows that most of the well-recorded high-frequency shallower events of the last 12 days have been located within a 3 km diameter area centred within the Tamaki River estuary between Farm Cove and Glen Innes. Tilt-levelling sites are installed in the Pt England Reserve, Pakuranga College and

[2]See Appendix 4 for description of the Science Alert levels

the Half Moon Bay School, and initial surveys performed.

Day 22 (-4) 150 high-frequency earthquakes (M_L 2.2 to 4.1) and 10 long period volcanic earthquakes are recorded by the AVSN and portable seismographs; the two largest high-frequency events are strongly felt by people in the Glen Innes and Howick areas, and less strongly in the surrounding suburbs. The high-frequency events are estimated to be centred at 5-10 km depths. Some minor shaking damage (cracking of facades, plastered walls, and a few windows) occurs in older buildings within the epicentral area, with some items falling from shelves. Felt intensities are MM III to V. At 1600h, low-frequency volcanic tremor (1-2 Hz) appears on OTAz, MTAz and the Brown's Island seismographs (but not on the other portable seismographs - which are operating at too low a gain to detect it), occurring as short bursts of 30-60 s duration over a two hour period. The **Scientific Alert Level** remains at **2** (e.g. 2+ ?) although the further shallowing of epicentres and the occurrence of volcanic tremor is recognised as increasing the probability that an eruption will actually occur.

Day 23 (-3) 45 high-frequency earthquakes are recorded by the volcano-seismic network; 25 of these earthquakes are felt (M_L 3.9 to 4.3); 5 were locally audible. 60 long-period volcanic earthquakes are recorded. Bursts of low-frequency tremor are occurring more often, with increasing amplitudes, and appearance of higher frequency spectra. Relevelling of the tilt-level sites finds significant inflation (~100 microradians) has occurred, up towards the Tamaki River estuary epicentral area.

Day 24 (-2) 30 high-frequency earthquakes are recorded by the volcano-seismic network seismographs; 4 of these earthquakes were felt (M_L 3.8 to 4.1) but seismicity is generally less than during the previous few days. Tremor levels and numbers of long-period events are also lower than on the previous day. No further inflation is detected by relevelling of tilt sites.

Day 25 (-1) High-frequency earthquakes increase dramatically to over 1100 instrumentally-recorded in the 16 hrs prior to 1200h today. At least 200 of these events are felt (M_L 3.8 to 4.6), with widespread minor shaking damage to buildings in the Glen Innes-Howick-Pakuranga epicentral area. Near-continuous volcanic tremor, with mixed low and higher frequencies, starts at 0300h, overloading OTAz and the Brown's Island seismographs, and intense on the MTAz record. Relevelling

finds increased inflation (~400 microradians up towards focal area), with ongoing inflation detectable during the survey. Discrete level changes accompany some of the larger felt earthquakes, which are heard as sharp bangs. Sulphurous gas smells are detected by scientists working at the tilt-levelling sites. **Scientific Alert Level 3 is declared at 1200h** as an eruption appears imminent. At low tide, a helicopter search locates a zone of hot water emission with gas bubbles extending for 200 m NE across the Tamaki River estuary. Felt earthquakes continue throughout the day and into the night.

Day 26 (0) Eruption

0400h Seismic activity (felt and instrumentally recorded) peaks around this time, before decreasing again. Continuous volcanic tremor with mixed low to high frequency spectra, is accompanied by large high frequency earthquakes occurring at 0.5 to 3 minute intervals. Strong gas smells are detected within the (now largely evacuated) Pakuranga-Howick area.

0600h Ground shaking intensifies, causing severe damage to buildings on both sides of the Tamaki River. At dawn the emergence of an NE-elongated area of uplifted mudflats is observed, centred on R11/780780 in the Tamaki River estuary.

0715 Steam appears from three locations along a fissure crossing the uplifted mudflats. Steam discharge rates steadily increase, accompanied by volcanic gas emission with strong smell of SO_2. Wind is blowing from SW carrying the steam/gas plume to NE at low elevations.

0804h The eruption begins with initially small explosions throwing mostly lithic ejecta ~100 m into the air in vertically-directed dark plumes. Explosions rapidly increase in violence and ejected volume, and spread 300 m along a fissure. Volcanic tremor levels remain very high but discrete sharp-onset high-frequency large earthquakes are decreasing, being replaced by smaller volcanic earthquakes which accompany the larger eruptions. The volcanic earthquakes contain airwave phase sharp arrivals which correlate with loud detonations accompanying the most explosive eruptions. **Scientific Alert Level 4 is declared.**

0820h A voluminous white and grey eruption column is vigorously convecting to 2-3 km elevation above the increasingly active vent area, expanding into a large steam cloud drifting downwind over Bucklands Beach and out towards Waiheke Island. Some fine ash fallout occurs from this cloud.

0840h Explosions are now larger and occurring more frequently, some explosions generating air shock waves strong enough to break large windows in buildings out to 2 km from the vent (see Fig. 1.12). A coherent eruption column is now rising to 8 km, spreading into an expanding eruption cloud at 10 to 12 km elevation.

0850h The eruption fissure has extended NE into shallow water beyond the emergent area, and some sea water is flooding into the fissure which is being continually enlarged and deepened by removal of estuary floor material. With widening of the fissure, explosions are becoming more divergent, and steam-rich small base-surges are spreading from base of the eruption column, carrying lithic material from the estuary floor plus a minor component of basaltic magma. These initial surges travel out to 1 km across the estuary, to just reach the shoreline areas at Pt England and Farm Cove. Wet ash and scoria is falling out of the eruption cloud, in some places as rains of mud, with accretionary lapilli. The tephra dispersal axis extends across the Bucklands Beach area and into the Tamaki Strait. Metre-sized ballistic clasts are falling out to 1.6 km from the vent; most fall into the estuary but some land on buildings and structures causing considerable damage and starting fires. Frequent lightning pulses within the eruption column and cloud are causing some interference with radio-linked communications including the radio-telemetered seismographs.

0900h The explosions continue to grow in size as the eruption intensifies, with excavation of the crater to deeper levels. The larger explosions throw massive plumes to >1km above the surface. Lateral components of these explosions send spear-headed plumes out to 600 m laterally from the vent, where they collapse to generate locally-directed primary surges which flow into restricted sectors of both the Glen Innes and Half Moon Bay areas. However, these surges are overridden by the larger and faster moving annular surges formed by bulk collapse of the vertical eruption columns. These secondary surges ride over low coastal cliffs to travel out to ~2 km radially from the vent (Fig. 1.12), destroying or partially burying all structures within this distance, and damaging others

beyond by steam/gas cloud turbulence. Ash is plastered onto solid structures with considerable abrasion damage, and carried into buildings through broken glass doors and windows. The ash is not hot enough to ignite wooden materials. Tephra fall is now occurring across Waiheke Island with the eruption cloud being carried across the Hauraki Gulf towards northern Coromandel Peninsula and Great Barrier Island. The largest base-surges pass down the Tamaki River channel towards Bucklands Beach, where they drive tsunami waves (~2-4 m amplitude) out into the harbour towards Devonport, Brown's Island and Rangitoto. **Scientific Alert Level 5 is declared.**

0930h Discrete eruptions become increasingly frequent and are being concentrated into a single main vent being excavated in the centre of the Tamaki Channel. Some collapse of the vent walls is occurring, enlarging the crater to ~500 m diameter, with collapsed material ejected in the explosions. Almost continuous large explosions and base surges are accompanied by the most intense seismic activity of the entire eruption episode. The enlarging eruption column rises to 8-10 km in a decreasing SW wind, before expanding at higher elevation (>10 km) over the eastern suburbs (Mt Wellington to Howick). Fallout of mm-cm size ash and scoria clasts, and some larger (low density) bombs, commences in this area, along with wet ash aggregates and accretionary lapilli.

1100h Activity continues with only slight fluctuations in intensity. Heavy tephra fall (to >5 mm thickness) is now occurring in the whole eastern suburbs area, with total darkness beneath the eruption cloud. Base-surges continue to destroy and then bury large areas of the surrounding suburbs, with surge deposits >0.3 m thick now extending out to 3 km from the vent. Beyond this surge-devastated zone, wet tephra fall loadings are causing collapse of some flat-roofed buildings in the Bucklands Beach area. About 10^7 m^3 of tephra fall deposits have been erupted to this time, with dispersal shown in Fig. 1.13.

1300h Wind direction is veering to the NNW and freshening, so that scoria and ash is commencing to fall towards the south in the Otara and Manurewa areas which are on the periphery of the tephra dispersal fan. Height of the eruption column diminishes during the afternoon and into the night, while continuing surge deposition builds a low tuff ring rampart at about 500 m distance around the vent.

Day 27 (+1) Eruptions become less frequent during the early morning. The eruption of 5×10^7 m^3 of tephra in the surge deposits has built a 0.8 km diameter, 50 m high tuff-ring (Fig. 1.12) with shape rather similar to the Panmure basin. Smaller vertical explosions commence to build a scoria cone within the crater. Voluminous clouds of volcanic gas and steam pour from the crater. Light rainfall through the gas clouds brings down acid rain on areas downwind of the vent.

Day 28 (+2) Heavy rainfall on the thick and muddy tephra deposits within about 5 km of the crater causes considerable erosion where increased runoff is concentrated. Erosion cuts through into the underlying soils and deep gullies are rapidly formed. Eroded material accumulates in depressions, blocking drains, and flows into buildings where it sets into concrete-like masses. The new tuff-ring largely blocks the Tamaki River channel to inflowing tides, and outflowing drainage.

Day 29 (+3) Steam explosions, possibly induced by the previous heavy rainfall and runoff into the (now blocked) estuary channel, generate small base surges but no high eruption column.

Later..................

Small, dominantly magmatic eruptions continue intermittently for several weeks, building a small scoria cone in the new crater. Little tephra is dispersed by these eruptions. The Tamaki River is now dammed behind the new tuff cone. Catchment drainage over the next few months ponds behind the dam, causing local flooding of upstream shorelines before overflow cuts a new channel through the tuff deposits.

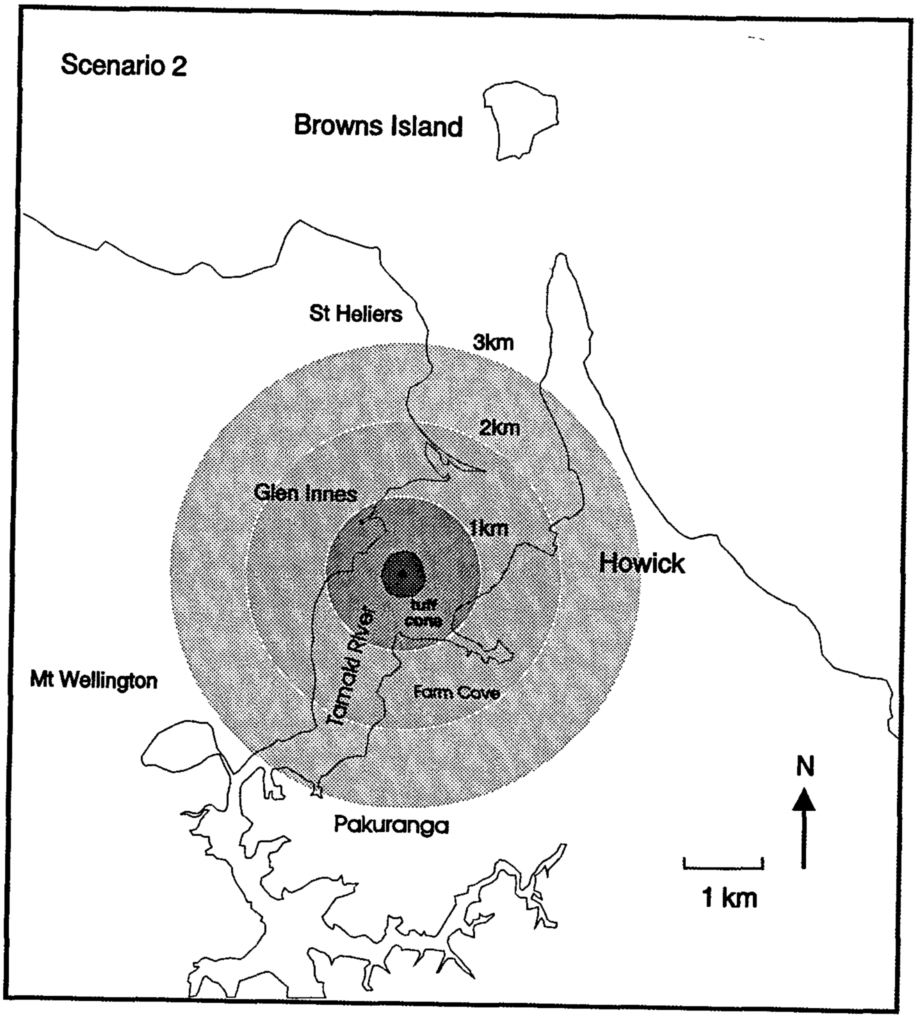

FIGURE 1.12: Vent location for Scenario 2 eruption, extent of tuff cone, and the 1, 2, 3 km zones affected by base-surges and ballistic clasts (see text for details).

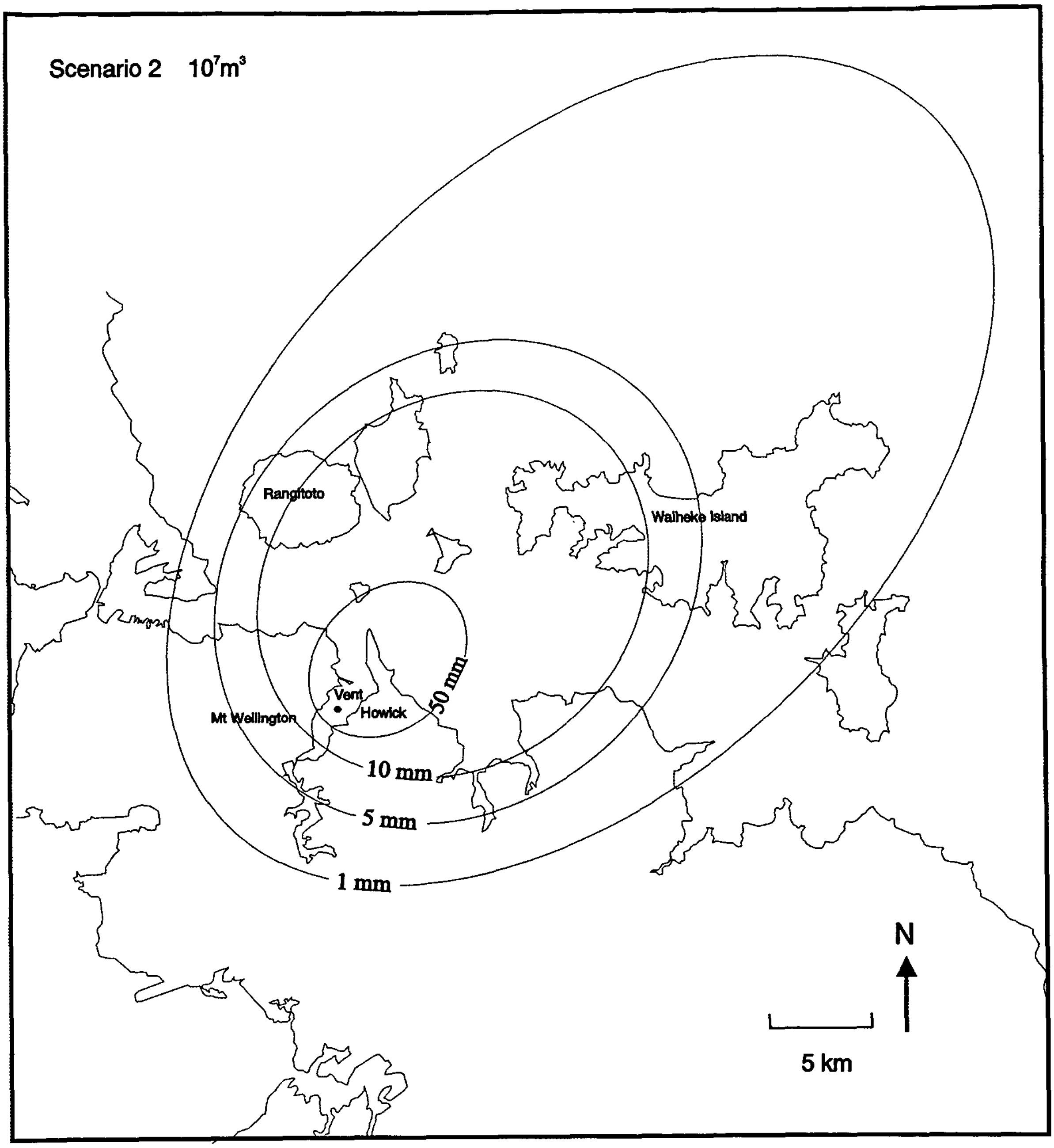

FIGURE 1.13: Tephra fall distribution pattern (10^7 m^3) for Scenario 2 eruption.

PHOTOGRAPHS TO ILLUSTRATE SCENARIO 2

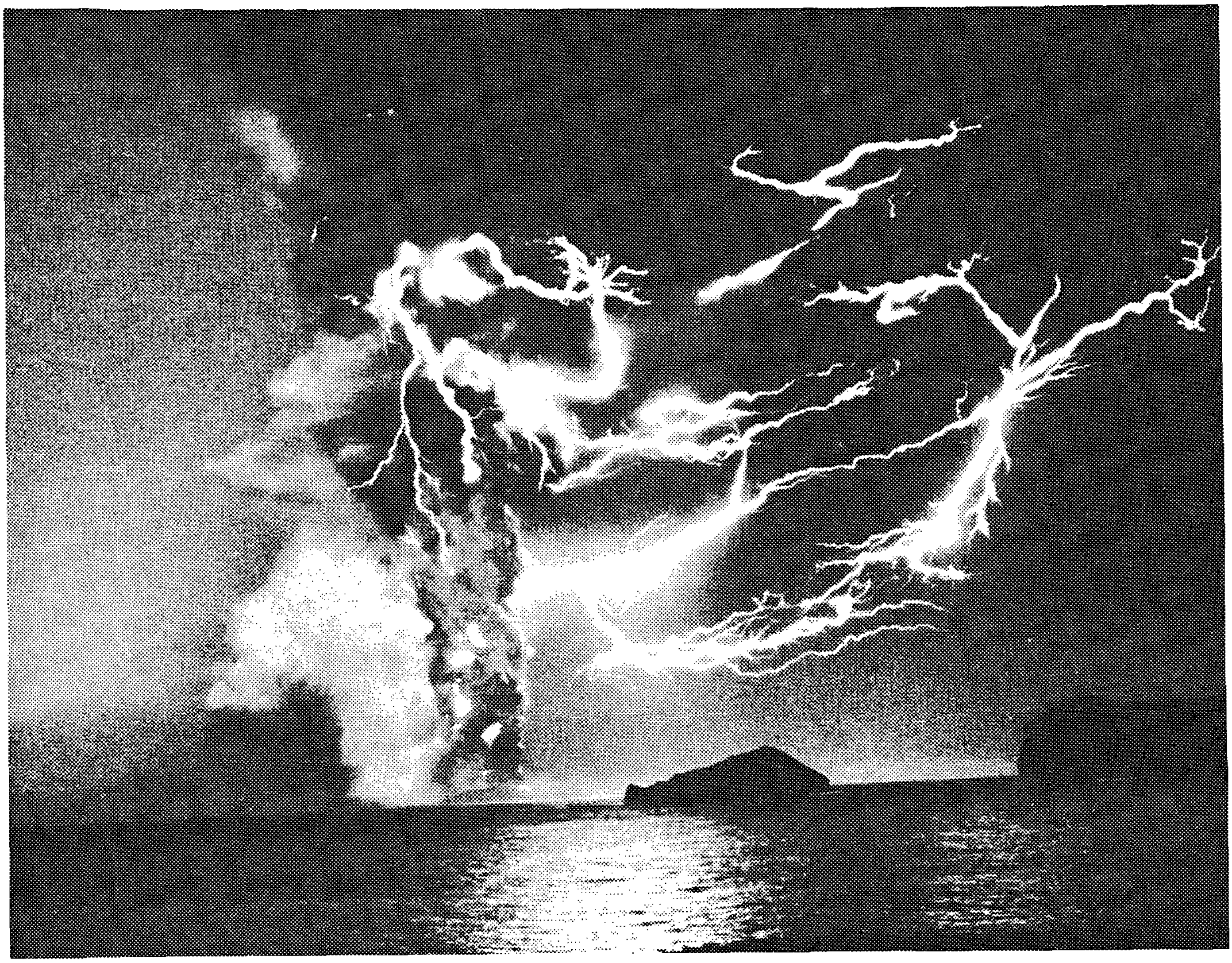

FIGURE 1.14: Lightning flashes produced in the ash column during the eruption of Surtsey, Iceland on December 1, 1963. (photography by S. Jonasson and courtesy of S.Thorarinsson and Cassell & Company).

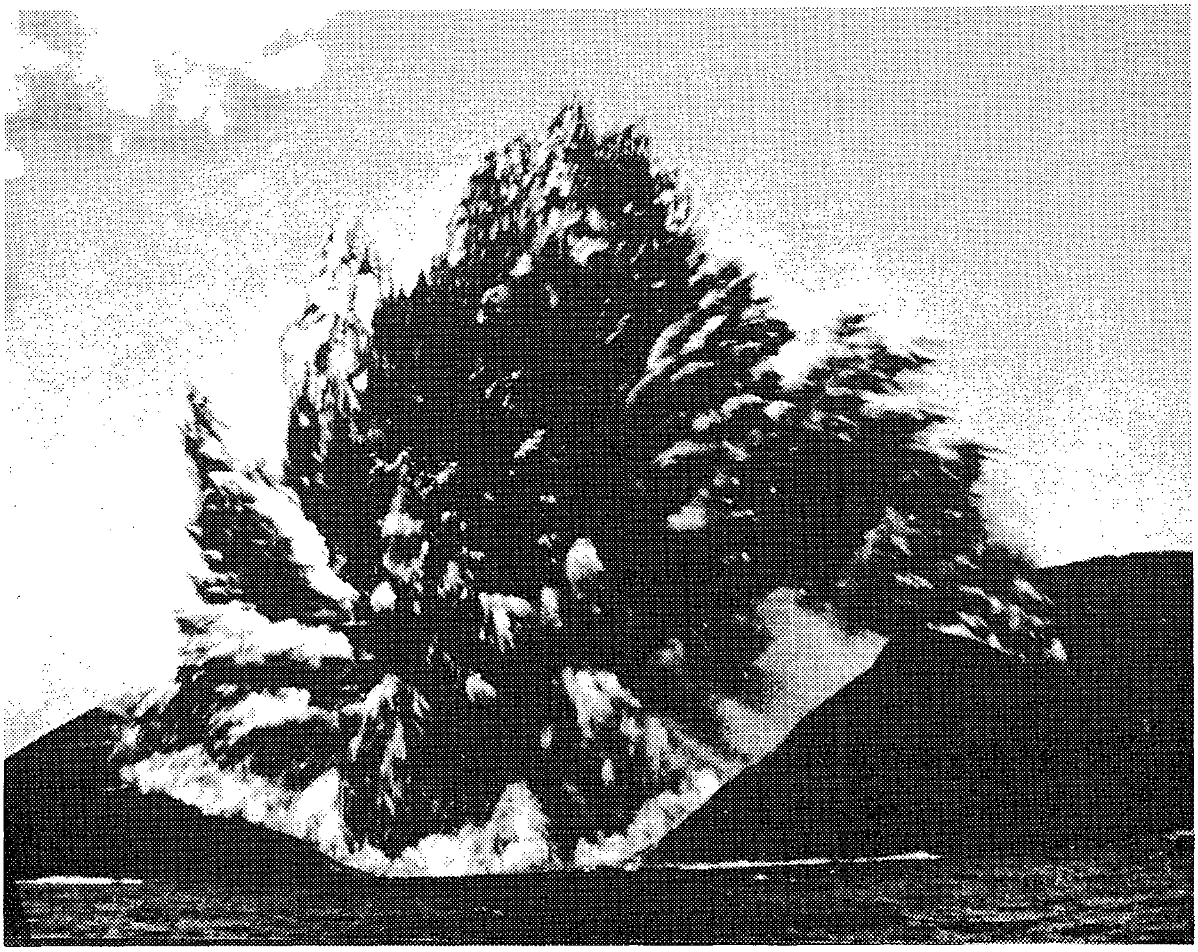

FIGURE 1.15: Phreatomagmatic explosions from Surtsey, Iceland on February 19, 1964. (photography by S. Einarsson and courtesy of S.Thorarinsson and Cassell & Company)

SCENARIO 3

Vent location:	Auckland Rail Yards, downtown Auckland City (R11/690824)
Magma type:	Basalt
Underlying country rock:	Waitemata Group flysch (sandstones and mudstones).
Erupted volume:	Tephra - 10^7 m^3; lava - 10^8 m^3.

In this CBD and port/residential waterfront-located phreatomagmatic/magmatic eruption scenario, the first instrumentally-recorded high-frequency earthquake is set at -25 days (25 days before the start of eruptive activity). For scenario 3, the eruption dynamics and products are in part modelled on the 1957/58 Capelinhos eruption in the Azores (Machado *et al.* 1962), and on the eruption which produced Rangitoto Island. Vent location is shown in Fig. 1.16.

CHRONOLOGY OF THE SCENARIO 3 ERUPTION

Day 1(-25) A M_L 5.1 high frequency tectonic earthquake occurs at ~100 km depth beneath Auckland. It is recorded by the Auckland Volcano-Seismic Network (AVSN - Fig. 1.4), and by most North Island stations of the National Seismic Network, although only weakly felt in the Auckland area.

Day 6 (-20) Two high-frequency earthquakes (M_L 2.5 and 3.2) are recorded by the AVSN, with first arrivals on the Motutapu (MTAz) instrument; sequentially later at the Otara (OTAz), Waiatarua (WTAz) and Moumoukai (MKAz) stations. These events are not felt, and are regarded as aftershocks of the M_L 5.1 event 5 days earlier. No action is taken.

Day 8 (-18) Four high-frequency earthquakes (M_L 2.4 to 2.9) are recorded by the AVSN, with sequential arrival times on MTAz, OTAz, WTAz and MKAz seismographs, similar to those of Day 6. GNS is contacted at 1800 h and the recent seismic events are discussed. ARC deploys a smoked-paper portable seismograph at North Head during the evening.

Day 9 (-17) GNS staff travel to Auckland and install a portable seismometer at Kauri Point. Five high-frequency earthquakes similar to those of the previous days are recorded by the Auckland net instruments. **Scientific Alert Level 1 is**

declared[3], as a result of the unusual seismicity.

Day 10 (-16) Five high-frequency earthquakes (M_L 3.0 to 3.2) are recorded by the AVSN and portable seismographs; the largest event is weakly felt across central Auckland. Analysis of these (and some of the earlier) events indicates they are approximately located beneath the Auckland City-Devonport area, at 30-40 km depths. A further portable seismometer is installed at Cornwall Park (with a very low gain setting as the site is very noisy).

Day 16 (-10) Two high-frequency earthquakes (both M_L 3.1) are recorded by the AVSN and portable seismographs.

Day 19 (-7) 25 high-frequency earthquakes (M_L 2.4 to 3.7) are recorded by the AVSN and portable seismographs. Locations are similar to the earlier events, with possible shallowing to ~10-20 km depths. Two apparent long-period small earthquakes are poorly recorded. **Scientific Alert Level 2 is declared,** after recognition of the apparent shallowing of epicentres and the possible occurrence of long-period events. A portable EARSS seismograph (replacement) is installed at North Head, although the site is very noisy and the instrument gain has to be set at very low level. A RSAM tremor monitoring system is installed on the volcano-seismic network at the ARC Building recording centre.

Day 20 (-6) 10 high-frequency earthquakes (M_L 2.3 to 3.9) are recorded by the Auckland volcano-seismic network. The best-located events appear to originate at about 15 km depth.

Day 21(-5) 8 high-frequency earthquakes (M_L 2.4 to 3.7), and 4 long period earthquakes are recorded by the volcano-seismic network. Refinement of the seismic analysis shows that most of the well-recorded high-frequency shallower events of the last 12 days have been located within a 3 km diameter area centred between Devonport and the Auckland Central Business District. A tilt-levelling site and tide gauge are installed in the Container Wharf area, with the initial tilt survey carried out during the night.

[3]See Appendix 4 for description of the Science Alert levels

Day 22 (-4) 150 high-frequency earthquakes (M_L 2.2 to 4.1) and 10 long period volcanic earthquakes are recorded by the volcano-seismic network and portable seismographs; the two largest high-frequency events are most strongly felt by people in the Devonport-CBD area. The high-frequency events are estimated to be centred at 5-10 km depths. Some minor shaking damage (cracking of facades, plastered walls, and a few windows) occurs in older buildings within the epicentral area, with some items falling from shelves. Felt intensities are MM III to V. Low-frequency volcanic tremor (1-2 Hz) appears on MTAz, OTAz and adjacent portable seismographs, occurring as short bursts of 30-60s duration over a two hour period from 1600h. The **Scientific Alert Level** remains at 2 (e.g. 2+ ?) although the further shallowing of epicentres and the occurrence of volcanic tremor is recognised as indicating an increased probability of an eruption actually occurring. A further tilt-levelling site is hastily installed at North Head.

Day 23 (-3) 45 high-frequency earthquakes are recorded by the volcano-seismic network; 25 of these earthquakes are felt (M_L 3.9 to 4.3), including 5 locally audible. 60 long-period volcanic earthquakes are recorded. Bursts of low-frequency tremor are occurring more often, with increasing amplitudes, and the appearance of higher frequency spectra. Relevelling of the tilt-level sites finds no significant tilt, but initial data from the crude tide gauge at the Container Wharf suggests that some uplift may be occurring here.

Day 24 (-2) 30 high-frequency earthquakes are recorded by the volcano-seismic network seismographs; 4 of these earthquakes were felt (M_L 3.8 to 4.1) but seismicity is generally less than on the previous few days. Tremor levels and numbers of long-period events are also lower than on the previous day. No inflation is detected by relevelling of tilt sites.

Day 25 (-1) High-frequency earthquakes increase dramatically to over 1100 events instrumentally recorded in the 24 hrs prior to 0800h today. At least 200 of these events are felt (M_L 3.8 to 4.6), with widespread minor shaking damage to buildings in the Devonport-CBD epicentral area. Near-continuous volcanic tremor, with mixed low and higher frequencies, starts at 0300h, overloading MTAz and the local portable seismographs. Discrete level changes of the Container Wharf tide gauge appear to accompany some of the larger felt earthquakes, which are heard as sharp bangs. Sulphurous gas smells are detected by scientists working in the Mechanics Bay area. **Scientific Alert Level 3 is**

declared at 1200h as an eruption appears imminent. Felt earthquakes continue throughout the day and into the night.

Day 26 (0) Eruption

0400h Seismic activity (felt and instrumentally recorded) peaks around this time, before decreasing again. Continuous volcanic tremor with mixed low to high frequency spectra, is accompanied by large (M_L 4-4.5) high frequency earthquakes occurring at 0.5 to 3 minute intervals. Shaking damage occurs to buildings and structures in the CBD and Wharf area. Ground cracking is observed in the Auckland Rail Yards-Container Wharf area around R11/690824, where continuous ground shaking is being felt.

0600h Ground shaking intensifies, causing severe damage to local buildings and structures. Ground cracks widen and coalesce into a 300 m long zone of branching fissures, partially collapsing structures which are undermined. Steam appears from five vents along the fissure. Steam discharge rates steadily increase, accompanied by detectable volcanic gas emission with strong smell of SO_2. Wind is blowing from SW carrying the steam/gas plume NE towards Devonport at low elevations.

0804h The eruption begins with initial small explosions throwing mostly lithic ejecta ~100 m into the air in vertically-directed dark plumes. Explosions rapidly increase in violence and ejected volume, and spread along the 300 m long fissure. Volcanic tremor levels remain very high but discrete sharp-onset high-frequency large earthquakes are decreasing, being replaced by volcanic earthquakes which accompany the larger jetting eruptions. Some of the larger explosions generate visible shock waves associated with loud detonations. Some large windows are broken by overpressures out to 2 km from the fissure. The eruption column is convecting to 2-3 km elevation above the active area, expanding into a large steam cloud drifting downwind over the Harbour and towards Devonport. **Scientific Alert Level 4 is declared.**

0840h Explosions are now larger and occurring more frequently, with the eruption column rising to 8 km, spreading into an expanding eruption cloud carried to NE and E by winds at this elevation. The eruption fissure has extended 200 m NE into the harbour and sea water is flooding into the fissure which is being continually enlarged and deepened by removal of material. With widening of

the fissure, explosions are becoming more divergent, and steam-rich small base-surges are spreading from base of the eruption column, carrying mixed lithic material with a minor component of basaltic magma. These surges travel out to 1 km across the low-lying areas adjacent to the wharves, and into the harbour (Fig. 1.16). Ash and scoria is falling out of the eruption cloud across the main harbour channel and Devonport. Ballistic clasts up to metre-size are falling out to 2 km from the vent; those falling on buildings and structures causing considerable damage including the starting of fires. Smoke from burning buildings contributes to the eruption column. Frequent lightning pulses within the eruption column are causing some interference with radio-linked communications including the radio-telemetered seismographs.

0900h The explosions continue to grow in size as the eruption intensifies. The larger explosions throw massive plumes to >1 km above the surface. Lateral components of these explosions send spear-headed plumes out to 400 m horizontally, where they collapse to generate locally-directed primary base-surges, some of which flow into restricted sectors of the Parnell and CBD areas as well as out into the harbour. However, these primary surges are overridden by larger and faster moving base-surges formed by bulk collapse of the vertical eruption columns. These secondary surges destroy all the Mechanics Bay wharf structures, and travel 2-3 km to north across the harbour to the Devonport shoreline (Fig. 1.16) where lesser damage occurs. Somewhat controlled by the rising topography to south of the vent, the surges travel 1-2 km in this direction, where they infill the flat area to south of the vent and destroy, bury or damage all structures. Strongly-constructed large buildings remain standing, but are damaged by sand blasting and breakage of glass doors and windows, and partly buried. The surges cause considerable damage inside the buildings they enter. Steam/gas cloud turbulence causes considerable further damage beyond the surge limits. Heavy tephra fall is now occurring across Devonport, Rangitoto, Orakei, Mission Bay and St Heliers (Fig. 1.17). The large surges passing into the harbour drive large waves (~4-6 m amplitude) northward towards Northcote, Takapuna and Devonport, where they flood onto the beaches causing considerable damage to near shore structures and roads. The largest explosions are accompanied by strongly felt earthquakes, the largest of M_L 4.6, with shaking causing further damage to structures. **Scientific Alert level 5 is declared.**

0930h Discrete eruptions become increasingly frequent and are becoming concentrated into a single main vent being excavated in the centre of the rail yards. Some collapse of the vent walls is occurring, enlarging the crater to ~500 m diameter, with collapsed material ejected in the explosions. Almost continuous large explosions and base- surges are accompanied by the most intense seismic activity of the entire eruption episode. The enlarging eruption column rises to 8-10 km in a decreasing W wind. Large ejecta in the column are visibly incandescent for several hundred metres above the surface. The eruption cloud expands at high elevation (~10 km) over Devonport-Mission Bay as the wind continues to decrease, with fallout of mm-cm size ash and scoria clasts, and some larger bombs, commencing in these areas.

1100h Activity continues with only slight fluctuations in intensity while the wind dies. Heavy tephra fall (>1 cm accumulation) is now occurring in the whole CBD, Devonport area (including Northcote and Takapuna), and the eastern suburbs (Fig. 1.17), with total darkness beneath the eruption cloud. Base surges continue to devastate and then bury large areas, with ~1 m thick surge deposits now extending out to 3 km from the vent (Fig. 1.16). Beyond this surge-devastated zone, 5-10 cm thick wet tephra fall loadings are causing partial collapse of some weakly-constructed flat-roofed buildings. Surges which flowed into the harbour have partly infilled the <20 m deep, 1 km wide channel between the wharf area and Devonport, while thick rafts of floating scoria have covered the entire channel.

1300h Wind direction is veering to the WNW and freshening, so that scoria and ash is commencing to fall towards the south in the Newmarket, Remuera, Ellerslie and Mt Wellington areas. The eruptions continue during the day and into the night, building a low tuff ring rampart at about 500 m distance around the vent, completely burying the previously flat area at foot of the Parnell and Albert Park hills.

Day 27 (+1) Eruptions diminish during the early morning and only minor activity occurs during this day. Voluminous clouds of volcanic gas and steam pour from the crater, with occasional minor ash emissions.

During the next 3 months similar but somewhat smaller phreatomagmatic eruptions occur frequently. The eruption of 5 x 10^7 m^3 of tephra has built a 1 km diameter, 50 m high tuff-ring (Fig. 1.16) with shape and structure rather similar to the Orakei Basin (Allen *et al.* 1996). Areas

within 5 km downwind of the crater are affected by >5 cm thick tephra falls, depending on wind directions at time of the larger eruptions. Emission of a continuous gas plume causes considerable gas and acid rain problems in downwind areas during attempts at tephra clearing operations.

Day 156 Strong seismic activity recommences with a vigorous swarm of M_L 2.0-3.6 high-frequency shallow events with sharp onsets, occurring at several hundred per day over three days. These events are located in a linear zone extending from 1 to 4 km SSW of the new crater (Fig. 1.18). Ground cracking occurs in two subparallel alignments on each margin of the seismic zone, which subsides by up to 0.4 m during the swarm. Buildings located within and adjacent to the seismic zone, and which had survived the thick tephra fall, suffer considerable shaking damage, some collapsing. Roads are blocked by collapsed material and displacement cracks.

Day 159 Hawaiian/strombolian-style eruptions commence as low (10 m height) explosive fire fountaining within the new crater. Gas clouds (including SO_2) spread across central Auckland as fire fountaining increases in height to 200 m. Large (~0.6 m) incandescent bombs are falling out to 500 m from the vent. Most of the ejecta consists of 1 to 50 cm scoria clasts and this is being deposited around the vent (where a small scoria cone is forming) and in a fallout apron extending out 1 km downwind to the NE. A small amount of fine material is being convected up to 5 km and drifts to the NE. Volcanic gas clouds are extending over a wider area, with SO_2 gas becoming noticeable in Devonport. The largest explosions are accompanied by strongly felt earthquakes, the largest of M_L 4.6. A small lava flow emerges from the base of the newly forming scoria cone and flows across the floor of the tuff-ring crater. Fire fountaining continues with fluctuating intensity, as the largest fire fountains reach 300 m above the vent and the cone grows in height. The eruption column becomes more collimated and rises to 8 km, with fine ash being carried across Rangitoto Island. Wind changes to the west, carrying gas clouds, scoria and fine ash over the eastern suburbs (Orakei, Mission Bay and Glen Innes areas).

Day 170 The scoria cone has grown to 100 m height and often contains a lava lake. Lava flows from the cone, as strombolian and hawaiian eruptions continue with fire fountaining frequently to 200-300 m height. Lava flows and intercalated scoria deposits have partly filled the new tuff ring crater, and lava has flowed into the

harbour from new vents which have broken out on the north side of the tuff ring. These flows threaten to block the channel to shipping. Vigorous strombolian eruptions continue, with downwind effects as previously described......

Day 200 The scoria cone continues to grow, reaching 140 m in height, and scoria and lavas have now entirely filled the tuff ring crater and are spilling over the lower northern sides (Fig. 1.18). As the cone increases in height, lava outbreaks are more frequently occurring from its base, and lava tunnels carry voluminous flows into the harbour to north. White clouds of hydrochloric acid aerosols (laze) are produced where lava flows into the sea. No shipping has entered Auckland Harbour since the eruption commenced 6 months earlier.

Day 250 Lava eruptions continue without break, most flowing out to the north, as a substantial lava shield is being constructed (Fig. 1.18). Occasional explosive eruptions generate eruption columns to 500-1000 m, and minor tephra falls occur downwind. Some littoral explosions have been occurring on the northern edge of the lava shield, where the inflowing lavas have trapped sea water. These littoral explosions have thrown hot ejecta to a few hundred metres from the "rootless" vents, and discouraged attempts to slow northward progress of the lava flow by pumping water on it from nearby boats.

Day 295 Lava shield growth has extended across the harbour channel to the Devonport Naval Base area, blocking the channel with lava.

Day 360++ Continuing lava outpouring builds a smaller version of Rangitoto cone. Fire fountaining and lava overflow occur, and a massive lava shield now joins the Parnell hills to Devonport. The previous Waitemata Harbour is now a lake, dammed behind the new lava cone. Heavy winter and spring rainfalls are causing a slow rise in Waitemata lake level, flooding onto shorelines. Plans are being made to cut a new drainage channel to the sea through the Takapuna area...........

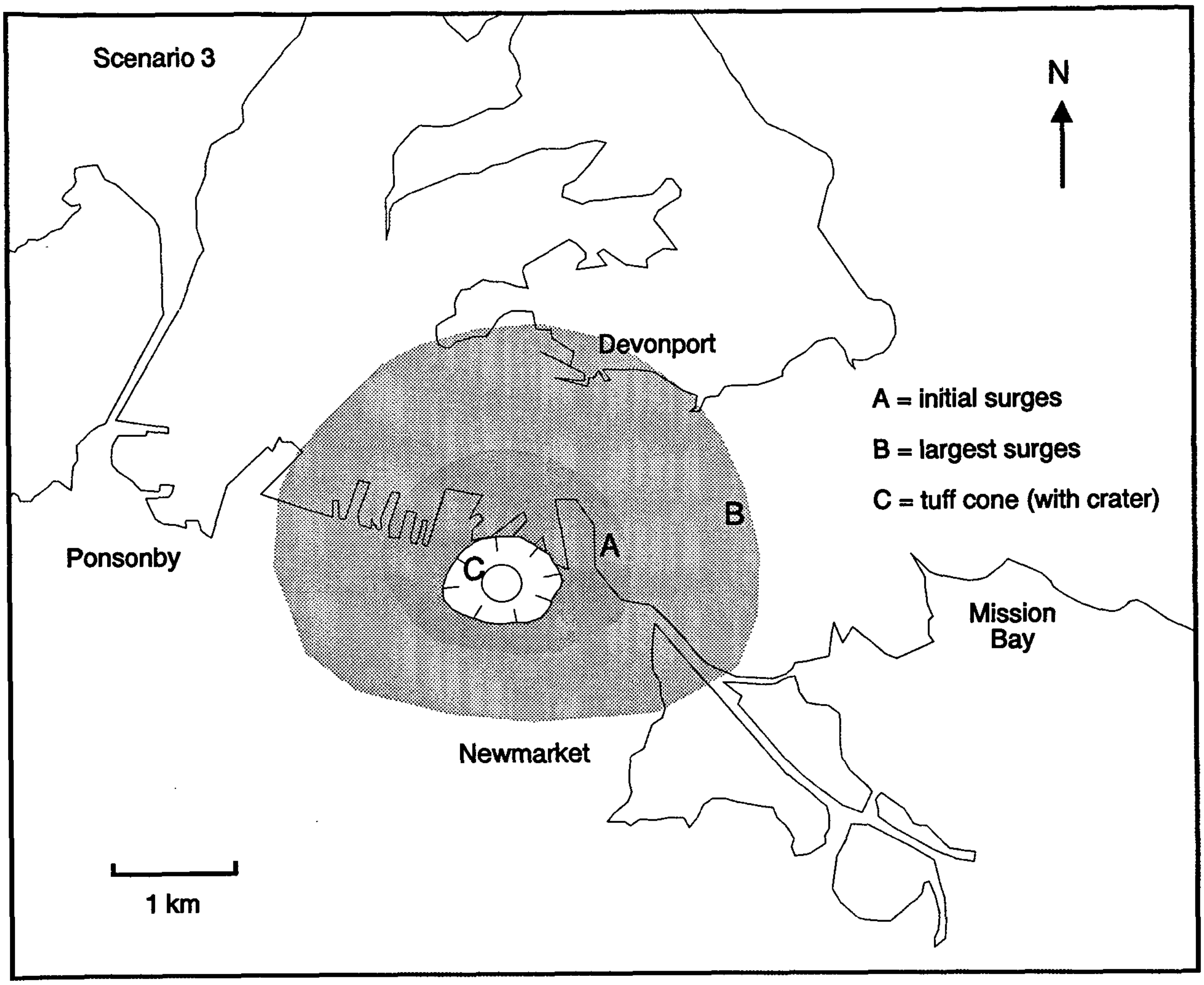

FIGURE 1.16: Vent location and extent of initial, and largest, base-surges (stippled) during early stage of the Scenario 3 eruption. The tuff cone is also shown.

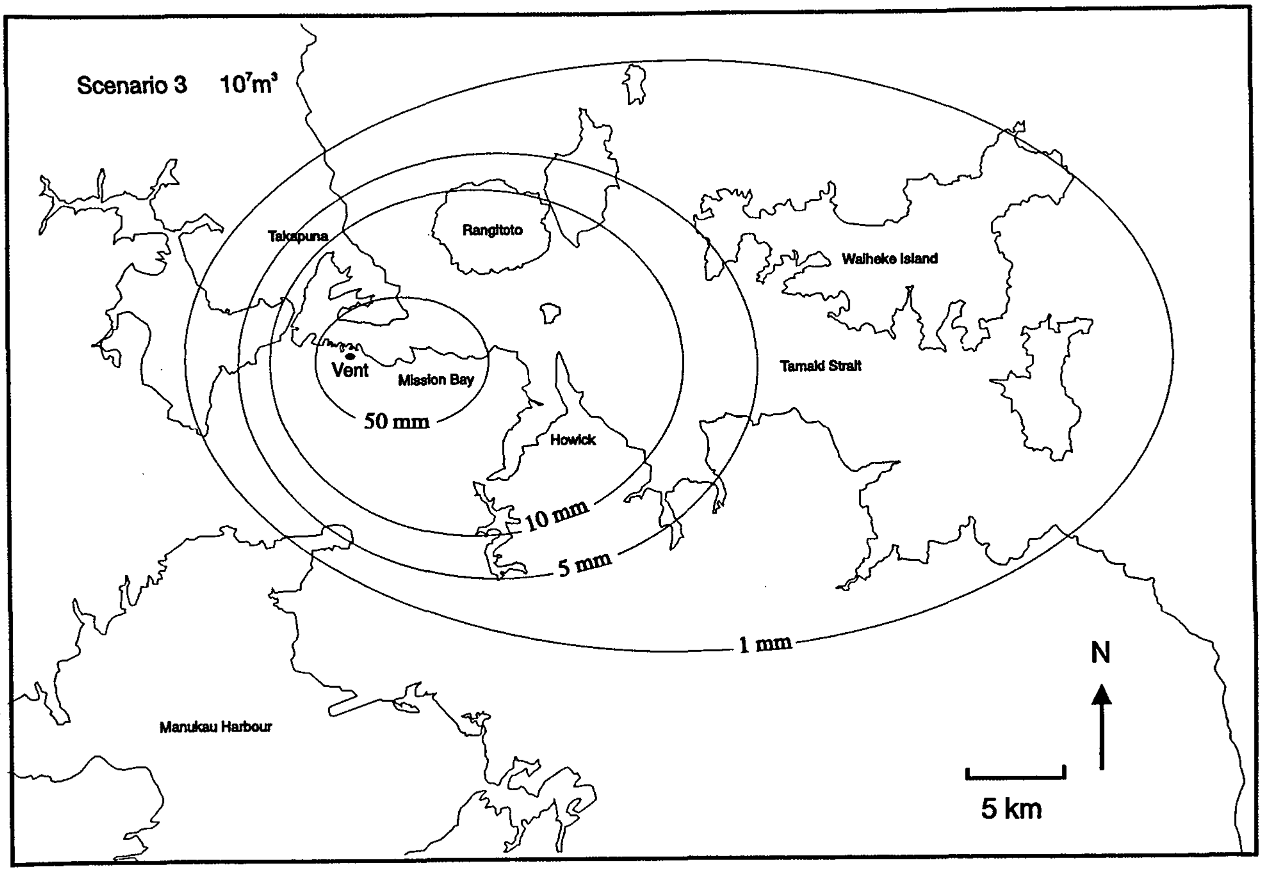

FIGURE 1.17: Tephra fall distribution (10^7 m^3) resulting from the Scenario 3 eruption.

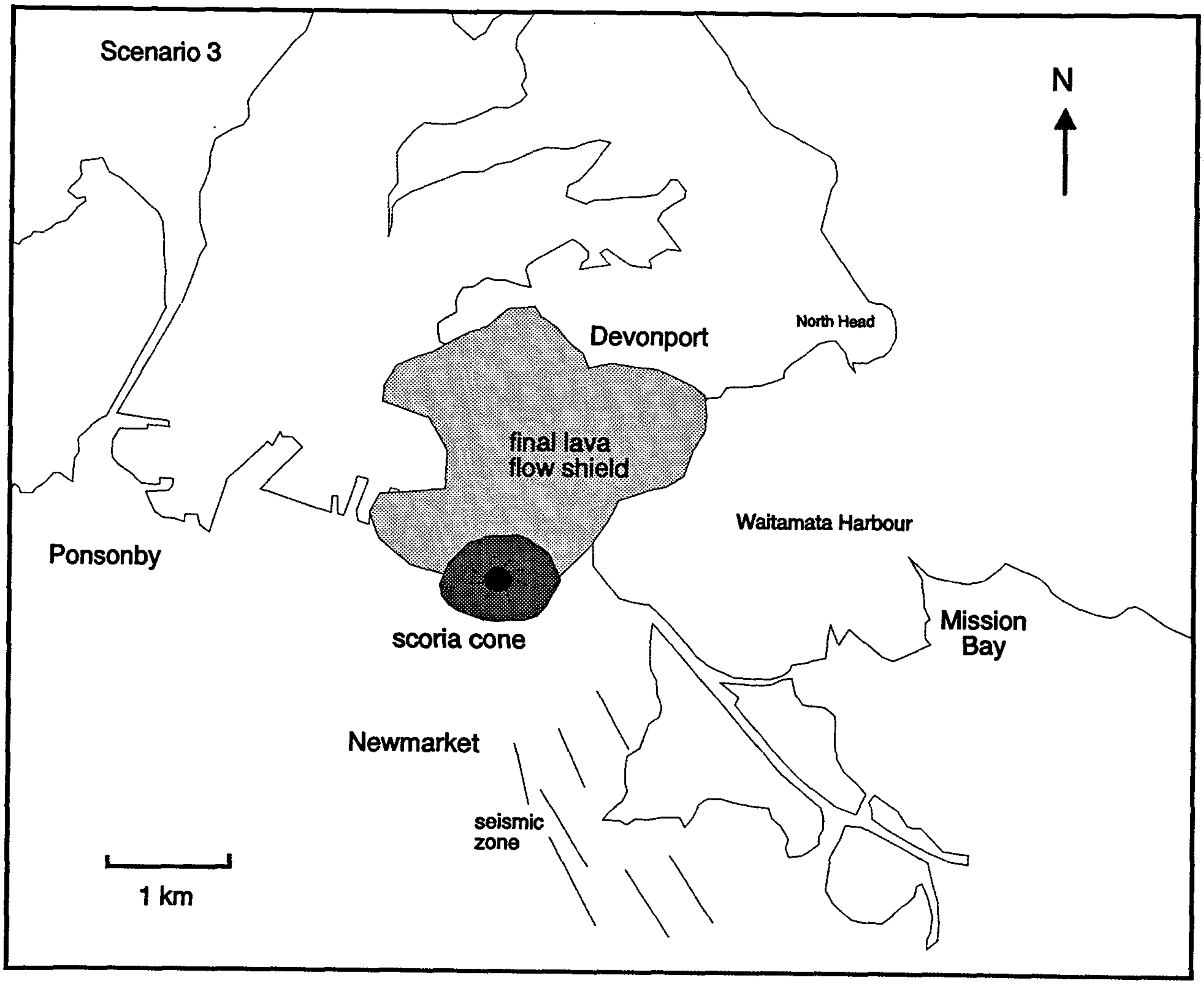

FIGURE 1.18: Scoria cone and lava shield constructed during the final stage of the Scenario 3 eruption. Zone of precursory seismicity and ground cracking is also shown.

PHOTOGRAPHS TO ILLUSTRATE SCENARIO 3

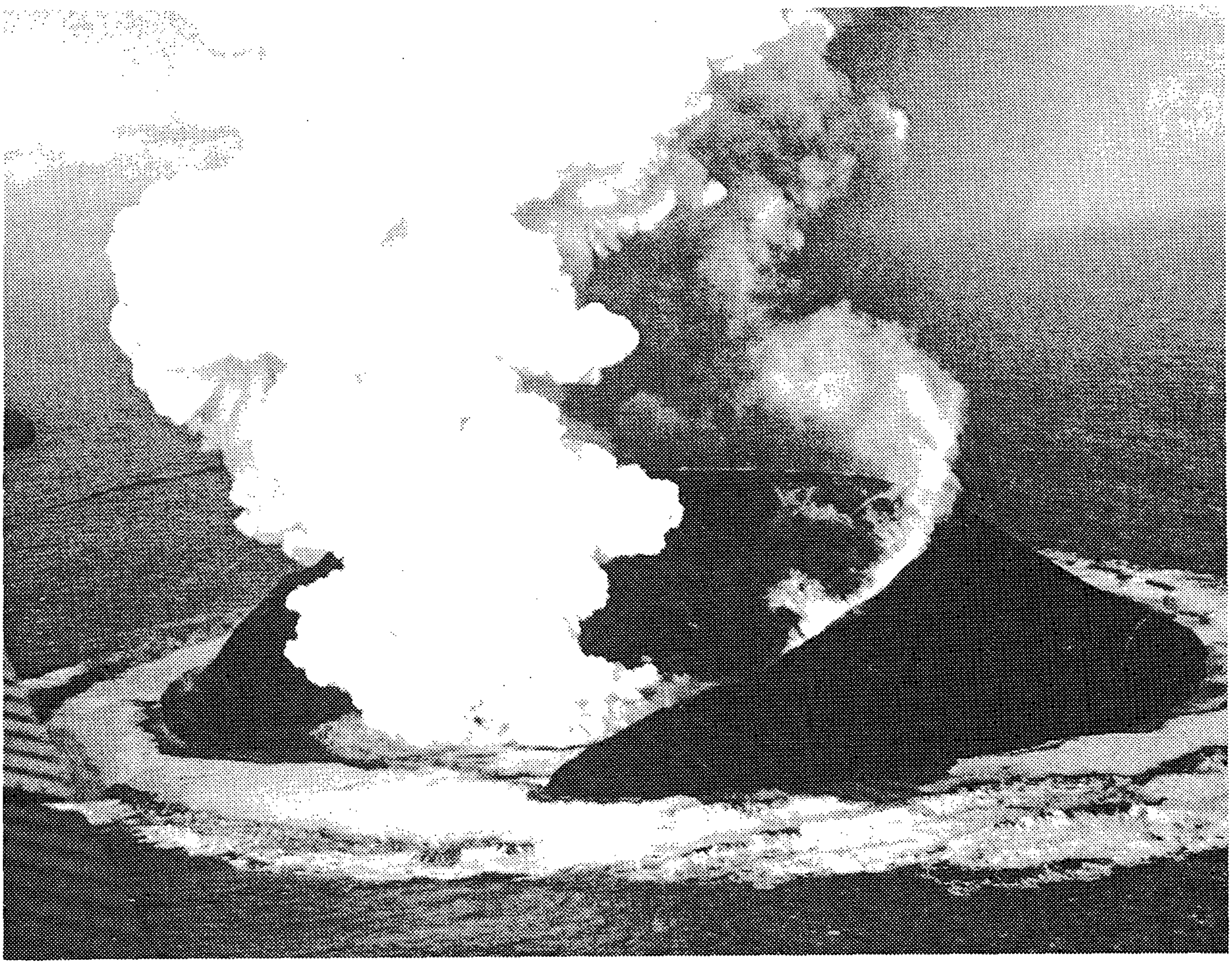

FIGURE 1.19: The tuff cone of Surtsey, Iceland, viewed from the air on November 30, 1963. The eruption began 16 days earlier. (Photograph courtesy of S.Thorarinsson and Cassell & Company)

FIGURE 1.20: An aerial view looking across the fishing port of Vestmannaeyjar on the island of Heimaey, Iceland, partly covered by tephra and lava from the 1973 eruption. Note the newly formed scoria cone at the top of the picture. (Photography BY S. Einarsson and courtesy of T. Einarsson).

SCENARIO 4

Vent location:	Top (south) end of Queen Street, Auckland City (R11/675 812)
Magma type:	Basalt
Underlying country rock:	Waitemata Group flysch (sandstones and mudstones)
Erupted volumes:	Tephra - 10^7 m^3, lava - 10^6 m^3

In this magmatic eruption within the CBD scenario, the first instrumentally-recorded high-frequency earthquake is set at -25 days (25 days before the start of eruptive activity). The eruption dynamics and products are in part modelled on the 1973 Heimaey eruption in Iceland (Self *et al.* 1974, Thorarinsson *et al.* 1973), plus effusive phases of the 1963 Surtsey eruption (Thorarinsson 1965, 1969), and the 1990 Kalapana (Kilauea) eruption in Hawaii (Mattox *et al.* 1993). Vent location and eruption parameters are shown in Fig. 1.21. Tephra distribution is shown in Fig. 1.22.

CHRONOLOGY OF THE SCENARIO 4 ERUPTION

Day 1(-25) A M_L 5.1 high frequency tectonic earthquake occurs at ~100 km depth beneath central Auckland. It is recorded by the Auckland Volcano-Seismic Network (AVSN- Fig. 1.4) and by most North Island stations of the National Seismic Network, although only weakly felt in the Auckland area.

Day 6 (-20) Two high-frequency earthquakes (M_L 2.5 and 3.2) are recorded on Waiatarua (WTAz), Otara (OTAz) and Motutapu (MTAz) seismographs of the Auckland net with near-simultaneous arrival times; somewhat later on Moumoukai (MKAz). These events are not felt and regarded as aftershocks of the M_L 5.1 event 5 days earlier. No action is taken.

Day 8 (-18) Four high-frequency earthquakes (M_L 2.4 to 2.9) are recorded by the AVSN, with near-simultaneous arrival times on WTAz, OTAz and MTAz seismographs. GNS is contacted at 1800h and the recent seismic events are discussed. ARC deploys a smoked-paper portable seismograph at Kauri Point during the evening.

Day 9 (-17) GNS staff travel to Auckland and install a portable seismometer at Cornwall Park (with a very low gain setting as the site is very noisy). Five high-frequency earthquakes similar to those of the previous days are recorded by the Auckland

net instruments. **Scientific Alert Level 1 is declared**[4]**,** as a result of the unusual seismicity.

Day 10 (-16) Five high-frequency earthquakes (M_L 3.1 to 3.4) are recorded by the Auckland network and portable seismographs; the largest event is weakly felt across central Auckland. Analysis of these (and some earlier) events indicates they are approximately located beneath the Newmarket-Ponsonby area, at 30-40 km depth. A further portable EARSS seismometer is installed at Kauri Point

Day 16 (-10) Two high-frequency earthquakes (both M_L 3.1) are recorded by the AVSN and portable seismographs.

Day 19 (-7) 25 high-frequency earthquakes (M_L 2.4 to 3.7) are recorded by the Auckland network and portable seismographs. Locations are similar to the earlier events, with possible shallowing to ~10-20 km depths. Two apparent long-period small earthquakes are poorly recorded. **Scientific Alert Level 2 is declared,** after recognition of the apparent shallowing of epicentres and the possible occurrence of long-period events. Two additional portable seismographs are installed at Mt Eden and Western Springs, although sites are very noisy and instrument gains have to be set at very low levels. A RSAM tremor monitoring system is installed on the volcano-seismic network at the ARC Building recording centre.

Day 20 (-6) 10 high-frequency earthquakes (M_L 2.3 to 3.9) are recorded by the AVSN network. The best-recorded appear to originate at about 15 km depth.

Day 21 (-5) 8 high-frequency earthquakes (M_L 2.4 to 3.7) and 4 long period earthquakes are recorded by the volcano-seismic network. Refinement of the seismic analysis shows that most of the well-recorded high-frequency shallower events of the last 12 days have been located within a 3 km diameter area centred on the Queen Street/Karangahape Road intersection. Tilt-levelling sites are installed on Upper Queen Street, Karangahape Road, and Symonds Street, with the initial surveys carried out during the night, when these streets are closed to traffic.

[4]See Appendix 4 for description of the Science Alert levels

Day 22 (-4) 150 high-frequency earthquakes (M_L 2.2 to 4.1) and 10 long period volcanic earthquakes are recorded by the volcano-seismic network and portable seismographs; the two largest high-frequency events are felt, most strongly by people in the Central Business District. The high-frequency events are estimated to be centred at 5-10 km depths. Some minor shaking damage (cracking of facades, plastered walls, and a few windows) occurs in older buildings within the epicentral area, with some items falling from shelves. Felt intensities are MM III to V. Low-frequency volcanic tremor (1-2 Hz) appears on WTAz, OTAz, MTAz and adjacent portable seismographs, occurring as short bursts of 30-60 s duration over a two hour period from 1600h. The **Scientific Alert Level** remains at 2 (e.g. 2+ ?) although the further shallowing of epicentres and the occurrence of volcanic tremor is recognised as indicating an increased probability of an eruption actually occurring.

Day 23 (-3) 45 high-frequency earthquakes are recorded by the volcano-seismic network; 25 of these earthquakes are felt (M_L 3.9 to 4.3); including 5 locally audible. 60 long-period volcanic earthquakes are recorded. Bursts of low-frequency tremor are occurring more often, with increasing amplitudes, and the appearance of higher frequency spectra. Relevelling of the tilt-level sites finds detectable inflation (50 microradians) has occurred, up towards the Queen St/Karangahape Rd intersection.

Day 24 (-2) 30 high-frequency earthquakes are recorded by the volcano-seismic network seismographs; 4 of these earthquakes were felt (M_L 3.8 to 4.1) but seismicity is generally less than on the previous few days. Tremor levels and numbers of long-period events are also lower than on previous day. No further inflation is detected by relevelling of tilt sites.

Day 25 (-1) High-frequency earthquakes increase dramatically to over 1100 events instrumentally recorded in the 24 hrs prior to 0800h today. At least 200 of these events are felt (M_L 3.8 to 4.6), with widespread minor shaking damage to buildings in the epicentral area centred on the Newton-Grafton district. Near-continuous volcanic tremor, with mixed low and higher frequencies, starts at 0300h, overloading WTAz, OTAz, MTAz, and the local portable seismographs. Relevelling finds increased inflation (up towards focal area), with ongoing inflation detectable during the survey. Discrete level changes accompany some of the larger felt earthquakes, which are heard as sharp bangs. Sulphurous gas

smells are detected by scientists carrying out the relevelling. **Scientific Alert Level 3 is declared at 1200h** as an eruption appears imminent. Felt earthquakes continue throughout the day and into the night.

Day 26 (0) (Eruption day)

0400h Ground cracking is observed around the top end of Queen Street, where continuous ground shaking is being felt. Seismic activity peaks around this time, before decreasing again. Continuous and intense volcanic tremor, with mixed low to high frequency spectra, is accompanied by large high frequency earthquakes occurring at 0.5 to 3 minute intervals.

0600h Ground shaking intensifies, causing severe damage to local buildings. Ground cracks widen and coalesce into a 300 m long branching fissure, partially collapsing buildings which are undermined.

0650h Steam appears from five vents along the fissure. Steam discharge rates steadily increase, accompanied by detectable volcanic gas emission with strong smell of SO_2. Wind is blowing from SW carrying the steam/gas plume to NE at low elevations. Intense seismic activity continues.

0804h Eruption begins with initially low (~10 m height) but rapidly increasing lava fountaining occurring along a 200 m fissure length. Structures within 50 m of the fissures are partially buried, burnt, and impact-damaged by incandescent ejecta. Gas clouds (including SO_2) are carried NE across Remuera-Orakei into the harbour. Lava flows (fountain-fed) commence to flow downslope into Queen Street. Volcanic tremor levels remain very high but discrete sharp-onset high-frequency large earthquakes are decreasing, being replaced by smaller volcanic earthquakes.

0830h Lava fountaining has become intense, reaching 100 m heights above the fissure, and feeding a pahoehoe lava flow into Queen Street. This fissure activity continues until 2 hours after commencement of the eruption.

1000h Activity has become concentrated at one location (R11/675812). Fire-fountaining has become somewhat discontinuous, and occasionally reaches heights of 200 m. Large incandescent bombs are falling out to 500 m from the

vent, breaking windows in buildings and starting many fires. Smoke from burning buildings and their contents contributes to the eruption column. Most of the ejecta consists of 1 to 50 cm scoria clasts falling around the vent (where a scoria cone is growing) and forming an apron extending out 1 km to the NE. A small amount of finer material is being carried up in the convective eruption column to 5 km where an expanding cloud is drifting to the NE. Volcanic gas clouds are extending over a wider area, with SO_2 gas becoming noticeable in Devonport. Lava flow discharge has decreased slightly but lava is now emerging from the base of the growing scoria cone and flowing downslope.

1100h Fire-fountaining continues with the progressive growth of a scoria cone (Fig. 1.21) now 30 m high. Tephra continues to be deposited to the northeast, between fallout margins at Westhaven and Orakei Basin.

1200h Activity continues with fluctuating intensity. Highest fire fountains reach 250 m above the vent as the cone grows in height. The convective eruption column becomes more collimated and rises to 8 km, with fine ash now falling across Rangitoto Island. The lava flow continues to move downslope (Fig. 1.21), flowing back into Queen St from the Myers Park gully to west. Frequent lightning pulses within the eruption column are causing some interference with radio-linked communications, including the radio-telemetered seismographs.

1300h Activity continues.

1800h Wind swings to the west, carrying gas clouds, scoria and fine ash over the Newmarket, Remuera, Mission Bay and Glen Innes areas. Magma discharge rates slowly begin to decrease. The ~900 m long lava flow is slowly advancing down Queen Street, where the flow front is 1-2 m high and 50 m wide. All inflammable objects in or adjacent to its path are burnt, and weakly constructed buildings destroyed. Strongly constructed (reinforced concrete) buildings remain standing but the fluid lava flow enters via basement and ground level windows and doorways, igniting inflammable contents. The flow thickens and widens behind the flow front, as the flow is inflated by the arrival of later erupted magma. Lateral outbreaks of new lava lobes spread into adjacent topographic lows, as the flow ponds and thickens behind the front.

2200h Fire-fountaining continues, with further advance of the lava flow which is now 1600 m long. Growth of the scoria cone and apron to NE and E has largely or partially buried the remains of adjacent buildings, in which all inflammable contents have been burnt.

Day 27(+ 1) Activity continues with lower fire-fountaining (to 200 m), feeding a diminishing eruption column. Wind shifts back to a light southwesterly, with gas and ash dispersal into the same areas as on the previous day. About 10^7 m^3 of tephra has been emitted over the last 2 days (Fig. 1.22). Lava continues to issue from the base of the cone, and the lava delta continues to widen (Fig. 1.21), ponding at Customs Street and spreading into adjoining side streets before overflowing into the wharf area and entering the harbour at the end of this day. White clouds of hydrochloric acid aerosol are formed where the lava flows enter the sea, and are carried downwind at low elevation across the wharf area.

Day 28 (+2) Continuous fire fountaining has ceased, replaced by intermittent (every few seconds) violent strombolian explosions which eject scoria bombs, smaller clasts and ash to several hundred metres above the cone. Metre-size ballistic bombs fall out to 1.5 km from the crater. Lava continues to flow from base of the scoria cone which is now 100 m in height and 500 m across. The convective eruption column fed by the continuous and explosive gas release is rising to 3-4 km, carrying a small amount of ash which is dispersed to a few kilometres downwind.

Day 29 (+3) and continuing..................

Similar strombolian activity continues until 6 days after commencement of the eruption, when lava emission ceases, having built a substantial delta in the harbour area (Fig. 1.21). About 10^6 m^3 of lava flow has been emitted since the eruption began. Occasional bursts of explosive activity occur every few days during the next 4 months, before the eruption episode comes to an end.

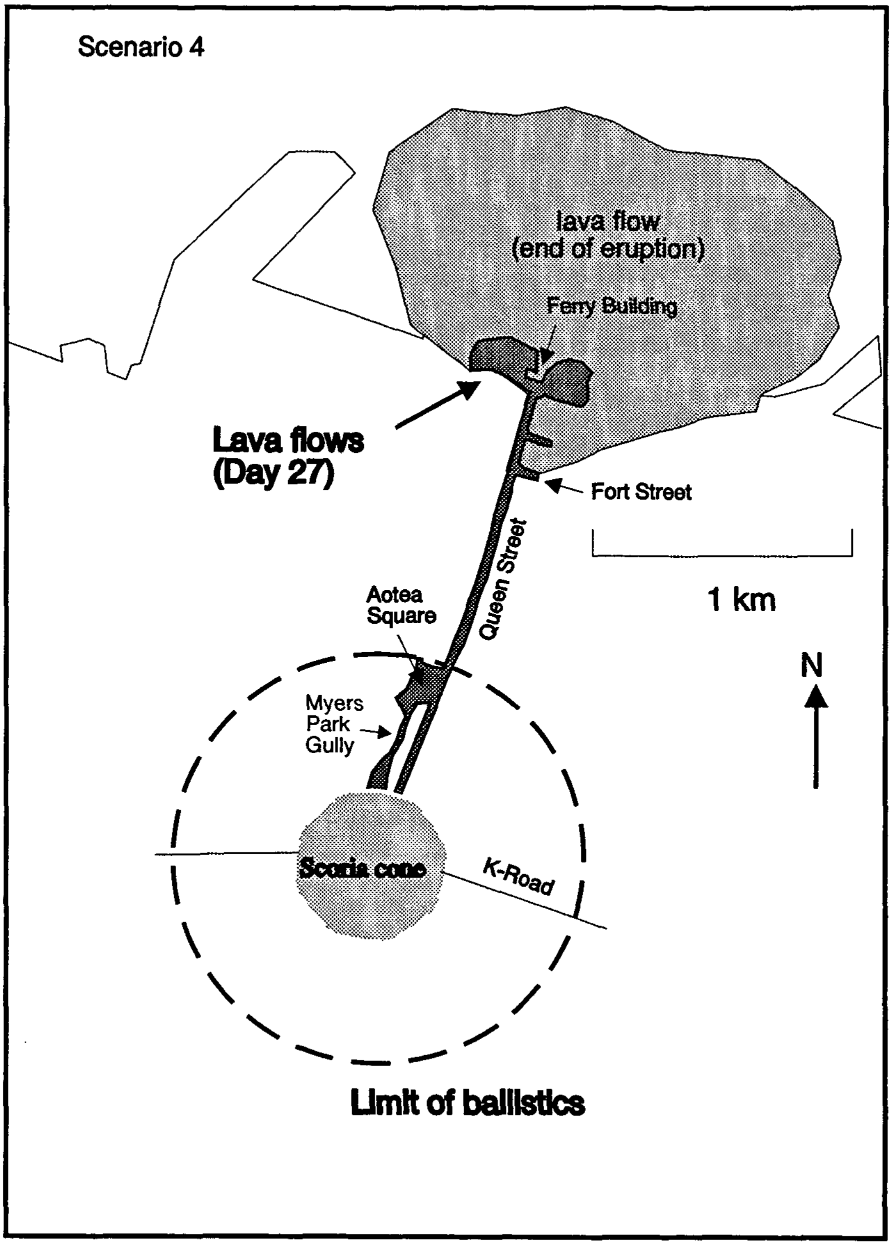

FIGURE 1.21: Vent location and eruption parameters for Scenario 4 eruption. Extent of lava flows shown for end of Day 27 (dark stipple), and at end of eruption (light stipple).

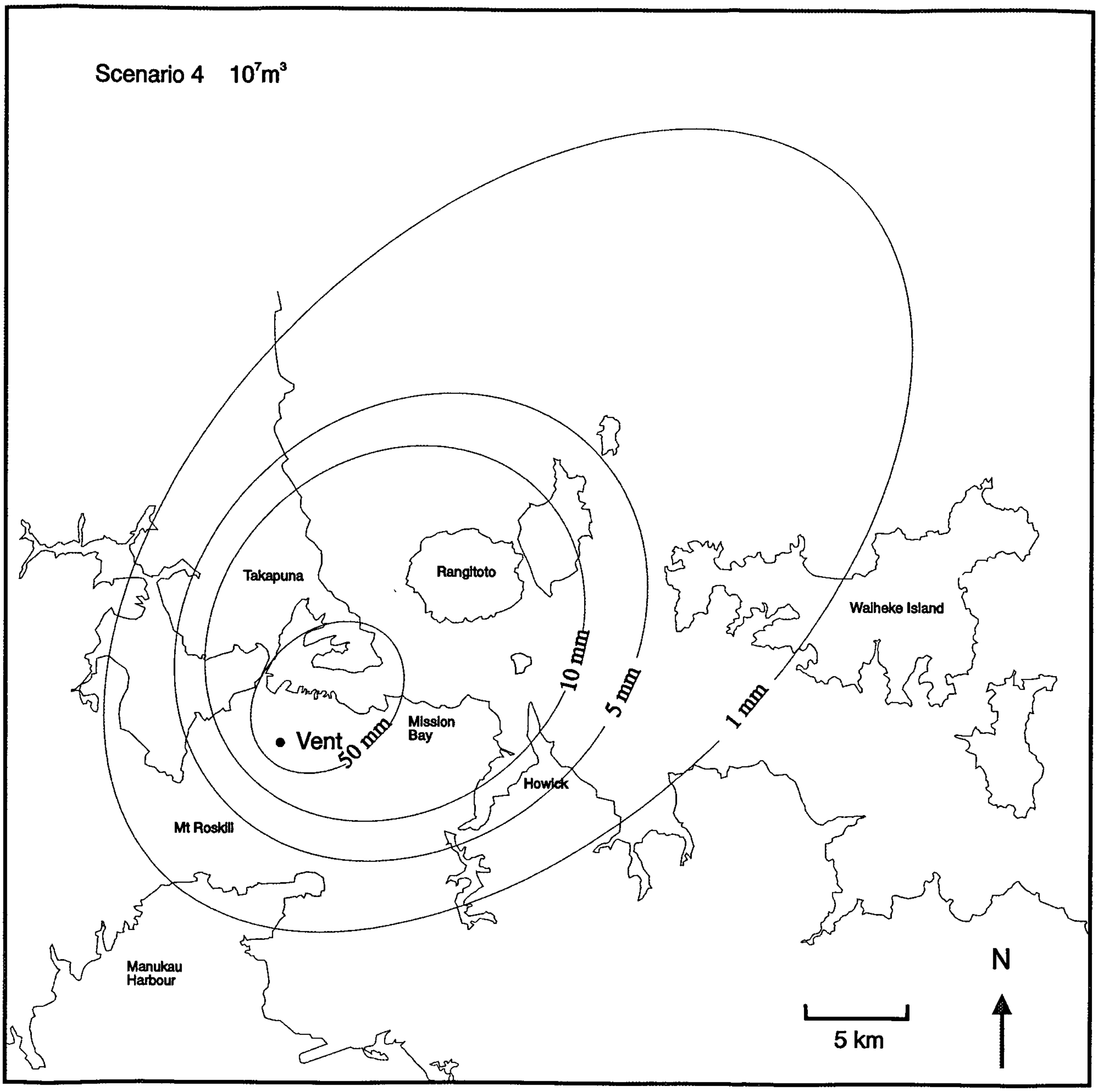

FIGURE 1.22: Tephra fall distribution (10^7 m^3) for Scenario 4 eruption.

PHOTOGRAPHS TO ILLUSTRATE SCENARIO 4

FIGURE 1.23: Houses in the town of Vestmannaeyjar inundated by lava from the 1973 eruption of Heimaey, Iceland. (Photograph by V. Olafsdottir and courtesy of T. Einarsson)

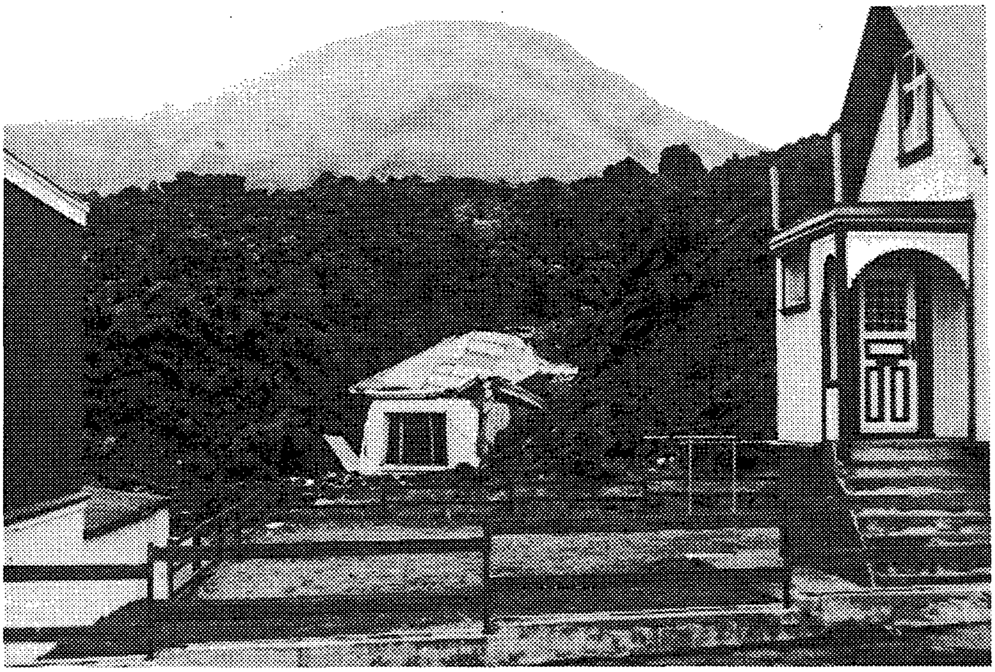

FIGURE 1.24: The front of the 1973 Heimaey lava flow in eastern part of the town of Vestmannaeyjar, showing the ruins of one the many houses that were over run by lava. The photo was taken 9 years after the eruption. The houses on either side of the lava flow were not seriously damaged and are now occupied by families. (Photograph by Thor Thordarson in 1982).

SCENARIO 5

Vent location: Intersection of Mt Eden/Mt Albert roads (R11/671755)
Magma type: Basalt
Underlying country rock: Waitemata Group flysch (sandstones and mudstones).
Erupted volumes: Tephra - 10^7 m^3, lava - 10^6 m^3

In this magmatic eruption scenario affecting residential and commercial areas, the first instrumentally-recorded high-frequency earthquake is set at -25 days (25 days before the start of eruptive activity). The eruption dynamics and products are in part modelled on the 1973 Heimaey eruption in Iceland (Self *et al.* 1974, Thorarinsson *et al.* 1973), plus effusive phases of the 1963 Surtsey eruption (Thorarinsson 1965, 1969), and the 1990 Kalapana (Kilauea) eruption in Hawaii (Mattox *et al.* 1993). Vent location and lava flows are shown in Fig. 1.25. Tephra distribution is shown in Fig. 1.26.

CHRONOLOGY OF THE SCENARIO 5 ERUPTION

Day 1(-25) A M_L 5.1 high frequency tectonic earthquake occurs at ~100 km depth beneath central Auckland. It is recorded by the Auckland Volcano-Seismic Network (AVSN - Fig. 1.4), and by most North Island stations of the National Seismic Network, although only weakly felt in the Auckland area.

Day 6 (-20) Two high-frequency earthquakes (M_L 2.5 and 3.2) are recorded on the AVSN, with first arrival on the Otara (OTAz) seismograph, near-simultaneous arrival times at the Waiatarua (WTAz) and Motutapu (MTAz) stations, and somewhat later on Moumoukai (MKAz). These events are not felt and regarded as aftershocks of the M_L 5.1 event 5 days earlier. No action is taken.

Day 8 (-18) Four high-frequency earthquakes (M_L 2.4 to 2.9) are recorded by the AVSN, with arrival times similar to those of Day 6. GNS is contacted at 1800h and the recent seismic events are discussed. ARC deploys a smoked-paper portable seismograph at Kauri Point during the evening.

Day 9 (-17) GNS staff travel to Auckland and install a portable seismometer at Cornwall Park (with a very low gain setting as the site is very noisy). Five high-frequency earthquakes similar to those of the previous days are recorded by the Auckland net instruments. **Scientific Alert Level 1 is declared,** as a result of the unusual seismicity.

Day 10 (-16) Five high-frequency earthquakes (M_L 3.1 to 3.4) are recorded by the AVSN and portable seismographs; the largest event is weakly felt across central Auckland. Analysis of these (and some of the earlier) events indicates they are approximately located beneath the Three Kings area, at 30-40 km depth. A portable EARSS seismometer is installed at Cape Horn (R11/645722).

Day 16 (-10) Two high-frequency earthquakes (both M_L 3.1) are recorded by the AVSN and portable seismographs.

Day 19 (-7) 25 high-frequency earthquakes (M_L 2.4 to 3.7) are recorded by the AVSN and portable seismographs; the four largest are weakly felt in central Auckland. Locations are similar to the earlier events, with possible shallowing to ~10-20 km depths. Two apparent long-period small earthquakes are poorly recorded. **Scientific Alert Level 2 is declared,** after recognition of the apparent shallowing of epicentres and the possible occurrence of long-period events. Two additional portable seismographs are installed at Mt Eden and Western Springs, although sites are very noisy and instrument gains have to be set at very low levels. A RSAM tremor monitoring system is installed on the volcano-seismic network at the ARC Building recording centre.

Day 20 (-6) 10 high-frequency earthquakes (M_L 2.3 to 3.9) are recorded by the augmented AVSN volcano-seismic network. Five events are felt, the best-recorded appear to originate at about 15 km depth.

Day 21(-5) 8 high-frequency earthquakes (M_L 2.4 to 3.7) and 4 (uncertain) long period earthquakes are recorded by the volcano-seismic network. Refinement of the seismic analysis shows that most of the well-recorded high-frequency shallower events of the last 12 days have been located within a 3 km diameter area centred on the Auckland City Council Eden-Roskill office. Tilt-levelling sites are installed on Mt Albert and Mt Eden Roads with the initial surveys carried out during the night, when these streets are closed to traffic.

Day 22 (-4) 150 high-frequency earthquakes (M_L 2.2 to 4.1) and 10 long period volcanic earthquakes are recorded by the volcano-seismic network; the two largest high-frequency events are felt, most strongly by people in the central Auckland area. The high-frequency events are estimated to be centred at 5-10 km depths. Some minor shaking damage (cracking of facades, plastered walls, and a few

windows) occurs in older buildings within the epicentral area, with some items falling from shelves. Felt intensities are MM III to V. Low-frequency volcanic tremor (1-2 Hz) appears on OTAz and adjacent portable seismographs, occurring as short bursts of 30-60 s duration over a two hour period from 1600h. The **Scientific Alert Level** remains at 2 (e.g. 2+ ??) although the further shallowing of epicentres and the occurrence of volcanic tremor is recognised as indicating an increased probability of an eruption actually occurring.

Day 23 (-3) 45 high-frequency earthquakes are recorded by the volcano-seismic network; 25 of these earthquakes are felt (M_L 3.9 to 4.3); including 5 which are locally audible. 60 long-period volcanic earthquakes are recorded. Bursts of low-frequency tremor are occurring more often, with increasing amplitudes, and the appearance of higher frequency spectra. Relevelling of the tilt-level sites finds significant inflation (50 microradians) has occurred, up towards the Mt Albert/Mt Eden Road intersection.

Day 24 (-2) 30 high-frequency earthquakes are recorded by the volcano-seismic network; 4 of these earthquakes were felt (M_L 3.8 to 4.1) but seismicity is generally less than on the previous few days. Tremor levels and numbers of long-period events are also lower than on previous day. No further inflation is detected by relevelling of tilt sites.

Day 25 (-1) High-frequency earthquakes increase dramatically to over 1100 events instrumentally recorded in the 16 hrs prior to 1200h today. At least 200 of these events are felt (M_L 3.8 to 4.6), with widespread minor shaking damage to buildings in the epicentral area centred on the Three Kings Mall. Near-continuous volcanic tremor, with mixed low and higher frequencies, starts at 0300h, overloading OTAz and local portable seismographs, and intense on WTAz and MTAz. Relevelling finds continuing inflation (520 microradians up towards focal area), with ongoing inflation detectable during the survey. Discrete level changes accompany some of the larger felt earthquakes, which are heard as sharp bangs. Sulphurous gas smells are detected by scientists carrying out the relevelling. **Scientific Alert Level 3 is declared at 1200h** as an eruption appears imminent. Felt earthquakes continue throughout the day and into the night.

Day 26 (0) Eruption day

0400h Ground cracking is observed around the Mt Albert/Mt Eden Roads intersection where continuous ground shaking is being felt. Seismic activity peaks around this time, before decreasing again. Continuous and intense volcanic tremor, with mixed low to high frequency spectra, is accompanied by large high frequency earthquakes occurring at 0.5 to 3 minute intervals.

0600h Ground shaking intensifies, causing severe damage to local buildings. Ground cracks widen and coalesce into a 300 m long branching fissure, partially collapsing buildings which are undermined.

0650h Steam appears from five vents along the fissure. Steam discharge rates steadily increase, accompanied by detectable volcanic gas emission with strong smell of SO_2. Wind is blowing from NNW carrying the steam/gas plume to SE at low elevations.

0804h Eruption begins with initially low (~10 m height) but rapidly increasing lava fountaining occurring along a 200 m fissure length. Structures within 50 m of the fissures are partially buried, burnt, and impact-damaged by incandescent ejecta. Gas clouds (including SO_2) are carried SSE across Hillsborough and Onehunga towards Mangere. Lava flows (fountain-fed) commence to flow downslope away from the fissure vents. Volcanic tremor levels remain very high but discrete sharp-onset, high-frequency large earthquakes are decreasing, being replaced by smaller volcanic earthquakes. **Scientific Alert Level 4 is declared.**

0830h Lava fountaining has become intense, reaching 100 m heights above the fissure, and feeding a pahoehoe lava flow. This fissure activity continues for 2 hours after commencement of the eruption.

1000h Activity has become concentrated at one location (R11/671755). Fire fountaining has increased in height to 200 m. Large incandescent bombs are falling out to 500 m from the vent, breaking windows in buildings and starting many fires. Smoke from burning buildings contributes to the eruption column. Most of the ejecta consists of 1 to 50 cm scoria clasts and this is being deposited around the vent (where a small cone is forming) and in an apron extending out 1 km to the S. A small amount of fine material is being convected up to 5 km and drifts to the S. Volcanic gas clouds are extending over a wider area, with SO_2 gas becoming noticeable in Mangere and Papatoetoe, where fallout of mm-size

ash has commenced. A pahoehoe lava flow emerges from the base of the newly-forming scoria cone and flows downslope to north where it eventually ponds in the Three Kings quarry area (Fig. 1.25).

1100h Fire-fountaining continues with the progressive growth of a scoria cone now 30 m high. Tephra dispersal extends further to SE, with mm-size ash now falling over the Mangere oxidation ponds, Auckland International Airport, and Manurewa.

1200h Activity continues with fluctuating intensity. Highest fire fountains reach 500 m above the vent as the cone grows in height. The convective eruption column becomes more collimated and rises to 6 km in a freshening NW wind. Tephra is being dispersed in a narrow plume being carried to SSE by strong winds at 3 to 6 km altitudes. Tephra accumulation is now 1.5 cm thick in Hillsborough and Onehunga; 8 mm in Mangere, and 5 mm at Auckland International Airport and Papatoetoe. Frequent lightning pulses in the eruption column are causing some interference with radio-linked communications, including the radio-telemetered seismographs. A second lava flow moves downslope E into Mt Albert Road, towards Mt Smart Road.

1300h Activity continues at fluctuating but generally similar levels. Tephra accumulation is now >3 cm in the Onehunga area, >1 cm in Mangere, and 8 mm at the Airport. Fine ash is reported falling in Hamilton.

1730h The strong NNW wind has decreased in speed and is shifting towards the west. 15 mm of ash has accumulated at the Airport, with more than 2 cm on the Mangere oxidation ponds. About 1 cm of ash has fallen in Manurewa, and on the Southern Motorway between Otara and Takanini (Fig. 1.26).

1800h The westerly wind change is now carrying gas clouds, scoria and fine ash over the Onehunga, Ellerslie, and Mt Wellington areas. Heavy tephra fallout is occurring on the Southern Motorway in the Mt Wellington area, where 15 mm has accumulated. Magma discharge rates slowly begin to decrease. The 800 m long eastern lava flow is slowly advancing down Mt Albert Road where the flow front is 1-2 m high and ~60 m wide. The flow thickens and widens behind the flow front, as the flow is inflated by later erupted magma. Lateral outbreaks of new lava lobes spread into adjacent topographic lows, as the flow thickens

behind the front. All inflammable objects, including houses and other buildings, in or adjacent to its path are burnt.

2200h Fire fountaining continues, with further advance of the eastern lava flow to 1200 m from the vent. Growth of the scoria cone and apron to NE and E (Fig. 1.25) has largely or partially buried the remains of adjacent masonry buildings, in which all inflammable contents have been burnt. Tephra fallout continues across the eastern suburbs, with 2 mm of ash having accumulated in Howick.

Day 27 (+1) Activity continues with lower fire fountaining (to ~200 m) feeding a diminishing eruption column. Lava continues to issue from the base of the cone. Wind has shifted to a light southwesterly, with gas and ash dispersal across One Tree Hill into Ellerslie (3 mm tephra accumulation), Remuera, Mission Bay, St Heliers (2 mm accumulation) areas. About 10^7 m^3 of tephra has been emitted over the last 2 days.

Day 28 (+2) Continuous fire fountaining has ceased, replaced by intermittent (every few seconds) violent strombolian explosions which eject scoria bombs, smaller clasts and ash to several hundred metres above the cone. Metre-size ballistic bombs fall out to 1.5 km from the crater. Lava continues to flow from base of the scoria cone which is now 100 m in height and 500 m across. The convective eruption column fed by the continuous and explosive gas release is rising to 3-4 km carrying a small amount of ash which is dispersed downwind. Light rainfall begins in the evening as a front crosses the Auckland area. Acid rain falls in the Onehunga and Mt Wellington areas. As rain intensity increases, tephra deposits on roofs and roads are remobilised into the storm water system, blocking drains and accumulating to 0.2-0.5 m thicknesses at the foot of some hill roads.

Day 29 (+ 3) and continuing................

Similar strombolian activity continues until 6 days after commencement of the eruption, when lava emission ceases. About 10^6 m^3 of lava flow has been emitted since the eruption began. Occasional bursts of explosive activity occur every few days during the next 4 months, before the eruption episode finally comes to an end.

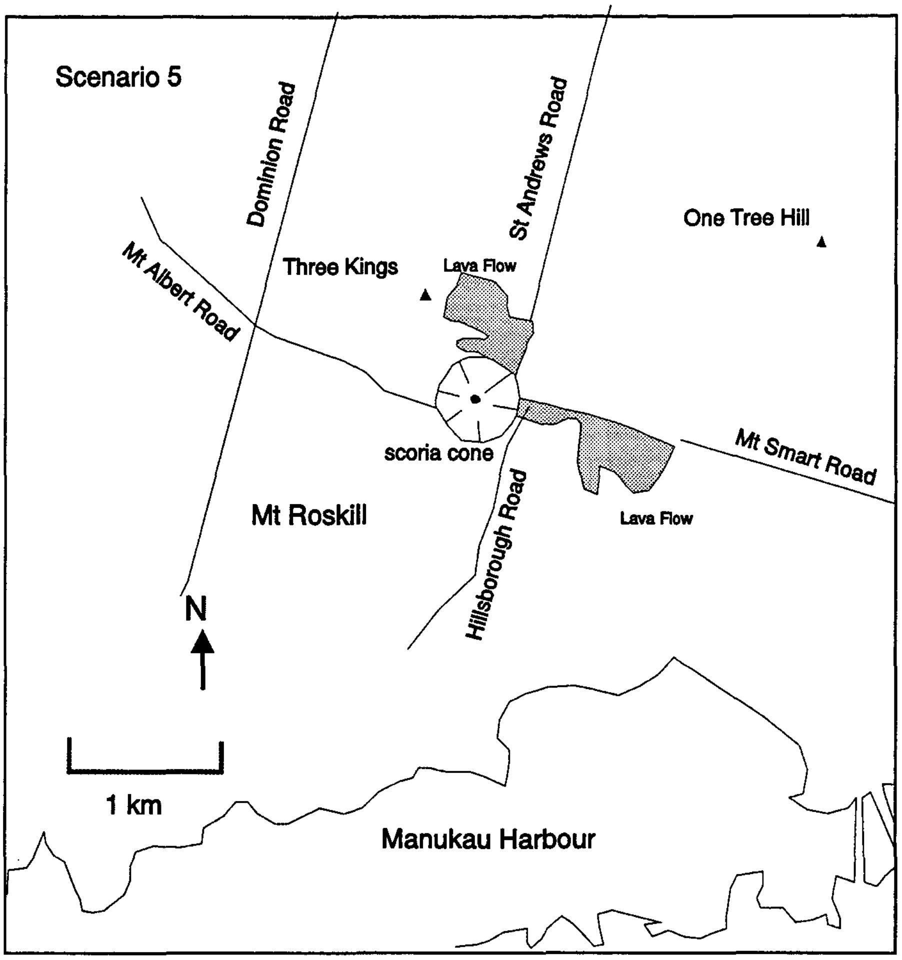

FIGURE 1.25: Vent location, scoria cone and lava flows of the Scenario 5 eruption.

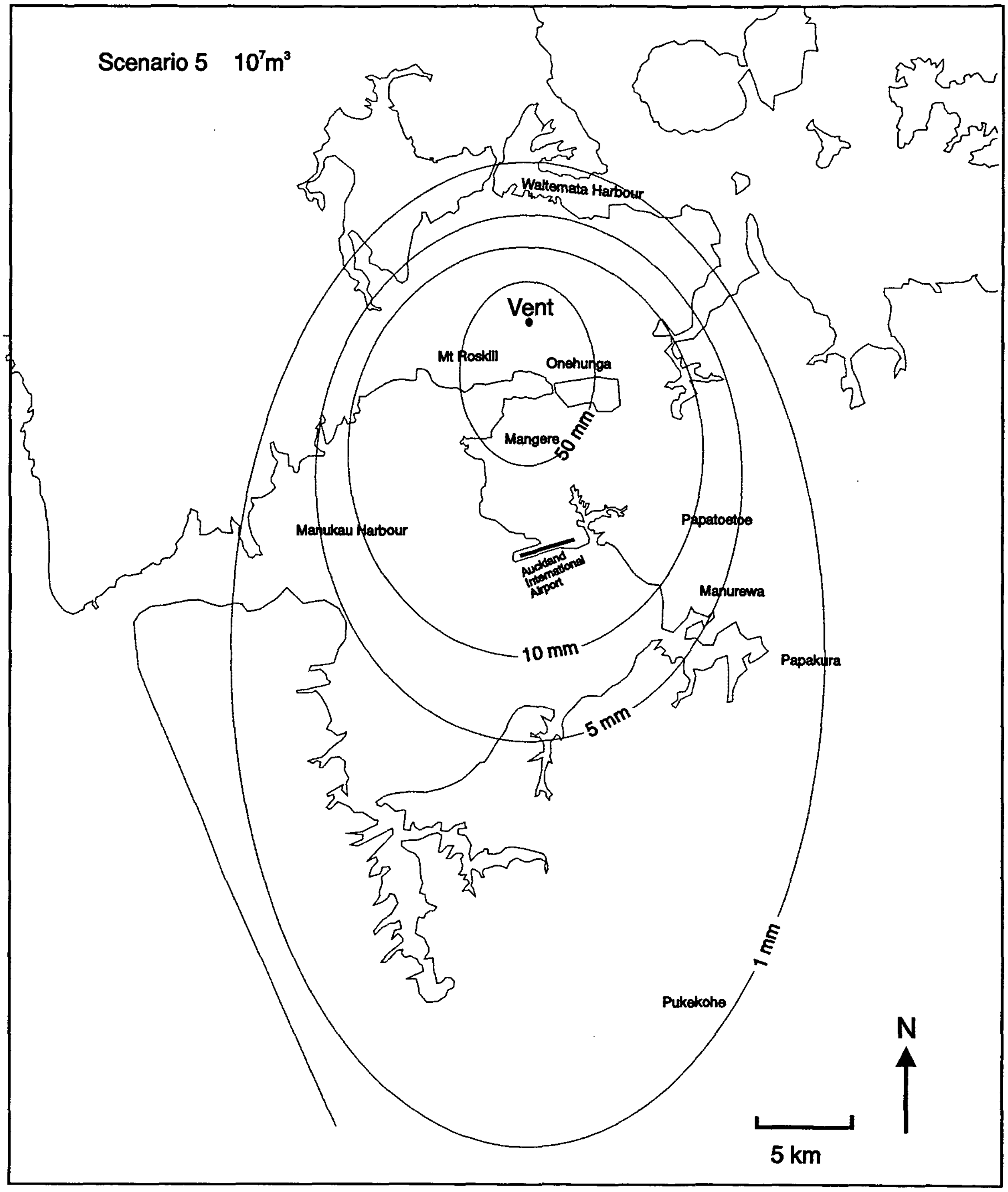

FIGURE 1.26: Tephra fall distribution (10^7 m^3) resulting from the Scenario 5 eruption.

PHOTOGRAPHS TO ILLUSTRATE SCENARIO 5

FIGURE 1.27: The remains of the Mauna Kea Congregational Church (lower centre) and the Painted church (upper centre) after being overrun by lava, Kalapana, Hawaii. Walters store (far right) is just about to be over run by lava. (Photograph courtesy of J. Griggs, HVO, USGS).

FIGURE 1.28: The Wahaula Visitor Centre in flames after lava inundation from an eruption of Kilauea, Hawaii. (Photograph courtesy of J. Griggs, HVO, USGS).

PART 2 - AUCKLAND VOLCANIC FIELD IMPACT ASSESSMENT

D M Johnston, I A Nairn, M Daly

2.1 INTRODUCTION

Part 2 of the report aims to identify the likely impacts of future volcanic eruptions from the Auckland Volcanic Field. The effects of such eruptions on the buildings, main infrastructure, critical facilities, population, economic activities and natural features of the Auckland region are discussed. Because there are few, if any, analogous examples of volcanic eruptions occurring within, or immediately adjacent to, a modern city, our assessment of the likely impacts is somewhat imaginative, and undoubtedly incomplete. Further, information on the infrastructure and facilities of the Auckland region has been obtained from many sources and covers general items only (i.e. first order infrastructure) and therefore detail is lacking. More detailed infrastructure (or higher order) and many topics about specific damage are beyond the expertise of the authors and outside the scope of the report. This report should not be viewed as the final word on the impacts of future eruptions at Auckland. Rather, it should be the starting point for more detailed studies, by the organisations concerned, of potential eruption effects on the population, communications, water and energy supplies, transport and other industries of the Auckland region.

2.2 ELECTRICITY SUPPLY AND RETICULATION

Most electricity used in the Auckland area is produced by the Electricity Corporation of New Zealand Ltd (ECNZ) and Contact Energy Ltd generating facilities (located outside the Auckland Volcanic Field), and distributed by the national grid operated by Transpower Ltd. The grid high voltage lines feed into a number of Auckland region substations (see Fig. 2.1) operated by Transpower Ltd, and then onto Mercury Energy Ltd and Power New Zealand Ltd local substations for distribution to customers. These utilities maintain the local distribution systems.

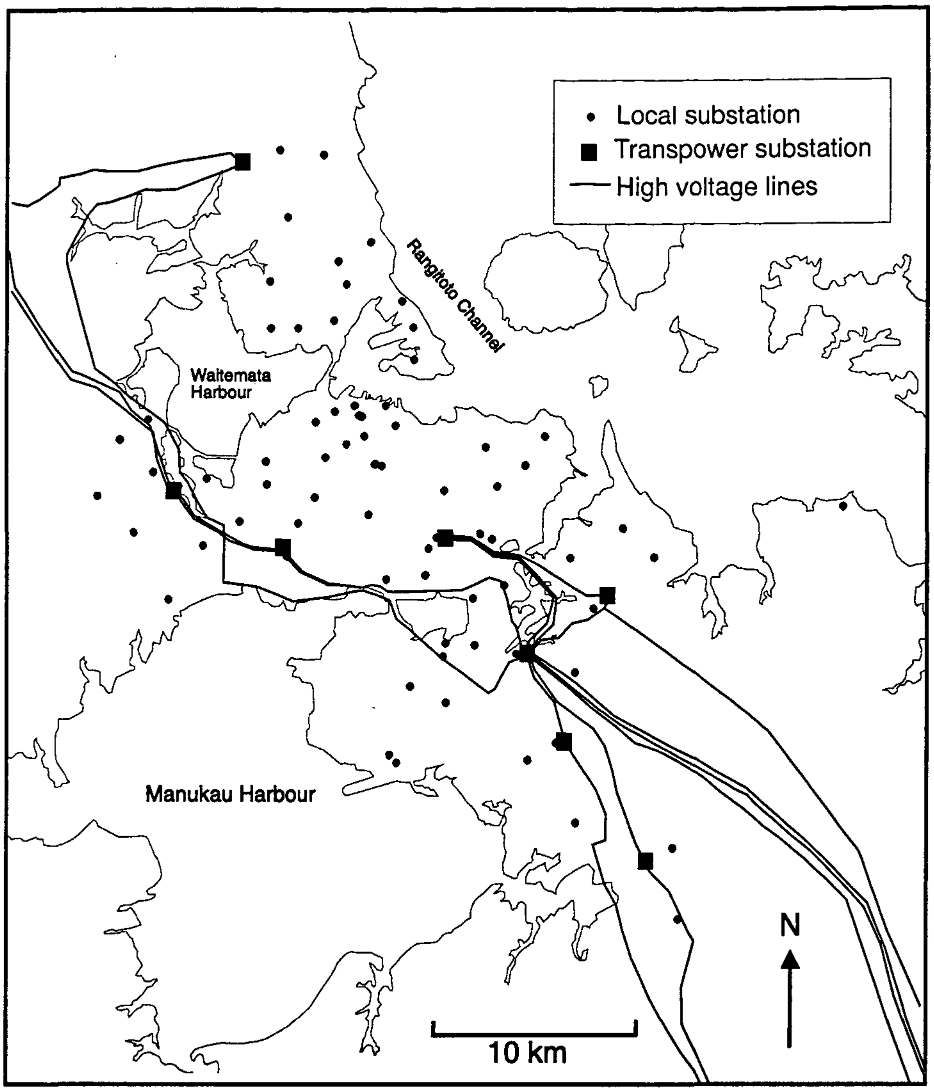

FIGURE 2.1: Electricity distribution substations and high-voltage lines within the Auckland area. (Compiled from information supplied by Transpower Ltd, Mercury Energy Ltd and Power NZ Ltd)

Impacts of the scenario eruptions (see Part 1)

Falls of volcanic ash (tephra) can disrupt electricity supply over wide areas in several ways (see Appendix 1, part A1.2.5). Heavy accumulations of ash on tree limbs can break them onto local distribution lines, shorting-out or breaking the lines. Damp or wet ash-coatings on insulators will induce flashovers. Low-voltage systems are more vulnerable than higher-voltage systems due to the smaller weathersheds on low-voltage insulators. Light rainfalls post-eruption are more likely to induce flashovers than are heavy rainfalls, which will tend to remove ash coatings from insulators. The abrasive nature of ash will cause damage to mechanically moving parts, such as switches and cooling fans. Most tephra-fall induced power outages are of short duration unless the falls are exceptionally thick, or other volcanic hazards prevent clean-up operations.

Immediate ash removal is the best mitigation procedure to prevent widespread outages resulting from tephra-falls.

Lava flows, ballistic block impacts, pyroclastic surges and lightning strikes from ash clouds present a high risk of damage to electricity installations in the affected areas, but the extent of these hazards (in typical Auckland eruptions) is mostly limited to within a few kilometres of the erupting vent. Severe near-vent ground shaking accompanying volcanic earthquakes (and any associated faulting as in Scenario 3 - Part 1) will also topple power poles and rupture underground services, possibly in areas not greatly damaged by eruption products. There are few or no mitigation options available to counteract any of these near-vent hazards, which apply to all structures. Corrosion of metal surfaces will result from acid rain formed from the release of volcanic gases, notably SO_2 and HCl (see Appendix 1, part A1.5).

The consequences of loss of electricity supply are widespread, and many other public utilities (e.g. water supply pumps, radio and telecommunication facilities) will be inoperative without alternative power supplies (batteries and generators) available.

Electricity supply and reticulation

Scenario 1(see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall	North Shore, central and eastern suburbs (5 - 50 mm thick, see fig. 1.6, 1.7 Part 1)	Moderate-high risk of outage if ash is wet. Low risk if ash is dry. Both flashover on insulators and breakage of power lines by ash-laden tree limbs will occur.	Removal of ash from transformer bushings and other substation insulators. Cut back tree branches, repair lines.
	South Auckland (< 5 mm thick)	Low-moderate risk of outage if ash is wet. Low risk if ash is dry.	Removal of ash from transformer bushings and other substation insulators.
Acid Rain	up 10 km downwind from Rangitoto Channel vent	Moderate to minor corrosion, effect decreasing with distance from the vent.	Washing of transformer bushings and other substation insulators.

Scenario 2 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall	Eastern suburbs, western Waiheke Island (5 - 50 mm thick, see fig. 1.13 Part 1)	Moderate - high risk of outage if ash is wet. Low risk if ash is dry. Both flashover on insulators and breakage of power lines by ash-laden tree limbs will occur.	Removal of ash from transformer bushings and other substation insulators. Cut back tree branches, repair lines
	Central Auckland, eastern Waiheke Island (< 5 mm thick)	Low - moderate risk of outage if ash is wet. Low risk if ash is dry.	Removal of ash from transformer bushings and other substation insulators.
Ballistic clasts	out to 1.6 km radius from vent (see fig.1.12 Part 1)	High risk of damage from direct hits on lines, poles etc.	Nil
Surges	out to 3 km radius from vent (see fig.1.12 Part 1)	Destruction of above ground installations	Nil
Lightning strikes	out 2 km from vent.	High risk of damage and outage.	Nil
Acid Rain	up to 10 km downwind from vent	Moderate to minor corrosion, effect decreasing with distance from the vent.	Washing of transformer bushings and other substation insulators.

Electricity supply and reticulation

Scenario 3 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall	North Shore, central and eastern suburbs (5 - 50 mm thick, see fig 1.18 Part 1)	Moderate-high risk of outage if ash is wet. Low risk if ash is dry. Both flashover on insulators and breakage of power lines by ash-laden tree limbs will occur.	Removal of ash from transformer bushings and other substation insulators. Cut back tree branches, repair lines
	South Auckland, Waiheke Island (< 5 mm thick)	Low-moderate risk of outage if ash is wet. Low risk if ash is dry.	Removal of ash from transformer bushings and other substation insulators.
Lava flows	CBD and Devonport (see fig.1.17 Part 1)	Destruction within flow area	N/A
Surges	1.5-3 km from vent (see fig.1.16 Part 1)	Destruction of all above ground installations	N/A
Ground shaking/ faulting	To 5 km SSW from vent (see fig.1.17 Part 1)	Toppled power poles, broken lines, ruptured underground services.	N/A
Lightning strikes	out to 10 km from vent.	High risk of damage and outage.	N/A
Acid Rain	up to 10 km downwind.	Moderate to minor corrosion, effect decreasing with distance from the vent.	Washing of transformer bushings and other substation insulators.

Scenario 4 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall	North Shore, central and eastern suburbs (5 - 50 mm thick, see fig. 1.22 Part 1).	Moderate - high risk of outage if ash is wet. Low risk if ash is dry. Both flashover on insulators and breakage of power lines by ash-laden tree limbs will occur.	Removal of ash from transformer bushings and other substation insulators. Cut back tree branches, repair lines
	South Auckland (< 5 mm thick)	Low - moderate risk of outage if ash is wet. Low risk if ash is dry.	Removal of ash from transformer bushings and other substation insulators.
Ballistic clasts	Out to 1 km from vent (see fig.1.21 Part 1).	High risk of damage from a direct hit to poles, lines etc.	N/A
Lava flows	Flow path from vent to harbour (see fig.1.21 Part 1)	Total destruction in flow area.	N/A
Acid Rain	Up to 10 km downwind from vent and lava flow.	High to minor corrosion,effect decreasing with distance from the vent.	Washing of transformer bushings and other substation insulators.

Electricity supply and reticulation

Scenario 5 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall	South Auckland (5 - 50 mm thick, see fig. 1.26 Part 1	Moderate - high risk of outage if ash is wet. Low risk if ash is dry. Both flashover on insulators and breakage of power lines by ash-laden tree limbs will occur.	Removal of ash from transformer bushings and other substation insulators. Cut back branches, repair lines
	West and East Auckland (< 5 mm thick)	Low - moderate risk of outage if ash is wet. Low risk if ash is dry.	Removal of ash from transformer bushings and other substation insulators.
Ballistic clasts	Out to 1 km radius from the vent (see fig.1.25 Part 1).	High risk of damage from a direct hit to poles, lines, etc.	N/A
Lava flows	Near vent (see fig.1.25 Part 1)	Total destruction in flow area	N/A
Acid Rain	Up to 10 km downwind	Moderate to minor corrosion, effect decreasing with distance from the vent.	Washing of transformers bushings and other substation insulators

2.3 GAS SUPPLY AND RETICULATION

Natural gas is piped from the Maui gas field to the Auckland area by the Natural Gas Corporation Ltd. The pipes are usually buried to more than 0.7 m depth. Automatic shutdown equipment at points along the pipeline is designed to cut off the gas supply if the pipe is ruptured. Gas is supplied to the Enerco Gas Ltd local supply company. A trunk pipeline distributes gas throughout the city, into several branch mains (Fig. 2.2). Gas pressure is reduced at pressure reducing stations for local supply.

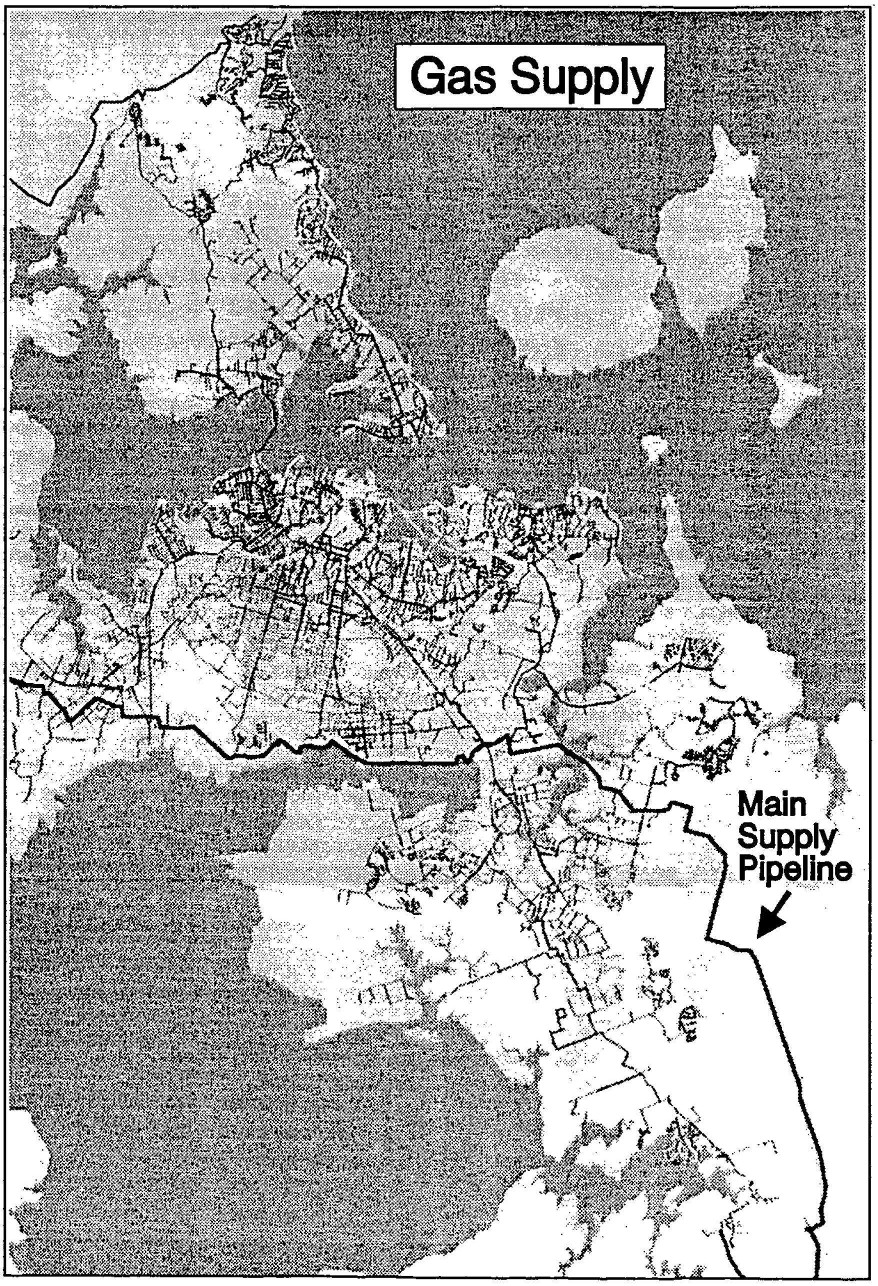

FIGURE 2.2: Gas distribution in Auckland (map supplied by Enerco Gas Ltd).

Impacts of the scenario eruptions (see Part 1)

Most gas pipes are located below-ground and are thus protected from the direct effects of tephra falls, pyroclastic surges, lava flows and the affects of acid rain. Above-ground, pumping stations, pressure reduction facilities, pipeline bridge crossings and gas meters at consumer's sites are vulnerable to damage from a range of volcanic hazards. Any line installations (Fig. 2.2) above ground in the Tamaki area would be severely damaged by surges and possibly ballistic impacts of the Scenario 2 eruption, as would facilities in the surge zone of the Scenario 3 eruption. The trunk pipeline is vulnerable to ballistic block impacts near the Upper Queen street vent of the Scenario 4 eruption. Severe ground deformation would rupture gas pipes near vents (i.e. Scenarios 3, 4 and 5), prior to eruption commencing, and during eruptions in areas of associated faulting (i.e. Scenario 3). Lavas of the Scenario 4 and 5 eruptions would destroy any above-ground distribution and metering facilities the flows encountered. Any damage to facilities or fracture of pipelines may cause ignition of residual gas, even if gas reticulation has been previously shut down.

Gas supply and reticulation

Scenario 1(see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Surges (peripheral zone)	Devonport-Takapuna beach area adjacent to Rangitoto Channel (see fig.1.9 Part 1)	Damage to above-ground gas distribution and metering facilities	Cut off gas supply

Scenario 2

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Surges and ballistic clasts	Within surge/block zone on both banks of Tamaki River (see fig.1.12 Part 1)	Damage to above-ground gas distribution and metering facilities	Cut off gas supply

Scenario 3

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Surges and ballistic clasts	Within surge zone centred on Mechanics Bay vent area (see fig.1.16 Part 1).	Damage to above-ground gas distribution and metering facilities	Cut off gas supply
Lava flows	Within surge-affected area (see fig.1.17 Part 1)	Complete destruction of any facilities which survived surges	Cut off gas supply
Ground deformation and faulting	Near-vent, and in Newmarket-Remuera seismic zone to SSW (see fig.1.17 Part 1)	Fracture of pipelines, before and during the lengthy eruption episode	Cut off gas supply

Gas supply and reticulation

Scenario 4(see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Ground deformation	Around the Upper Queen St vent area (see fig.1.21 Part 1)	Fracture of pipelines, before the eruption	Cut off gas supply
Ballistic clasts	Out to 1-1.5 km from the vent (see fig.1.21 Part 1)	Damage to above-ground facilities	Cut off gas supply
Lava flows	Queen St. area (see fig.1.21 Part 1)	Damage to above-ground gas distribution and metering facilities. Possible residual gas explosions ignited by lava	Cut off gas supply

Scenario 5 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Ground deformation	Around the Mt Albert/ Mt Eden roads intersection (see fig.1.25 Part 1)	Fracture of pipelines, before the eruption	Cut off gas supply
Ballistic clasts	Out to 1-1.5 km from the vent (see fig.1.25 Part 1)	Damage to above ground LP distribution and metering facilities	Cut off gas supply
Lava flows	Mt Smart-St Andrews roads areas (see fig.1.25 Part 1)	Destruction of above-ground gas distribution and metering facilities. Possible residual gas explosions ignited by lava	Cut off gas supply

2.4 WATER SUPPLY AND RETICULATION

Auckland's reticulated water is derived from four main areas: 1) Waitakere Ranges, 2) Onehunga groundwater source, 3) Hays Creek and 4) Hunua Ranges (Fig. 2.3 and Table 2.1). A small stand-alone underground system is also used in Papatoetoe.

TABLE 2.1: Auckland's main water supplies.

Sources	Type	Treatment	% of Auckland Supply
Waitakere Ranges	5 dams	Waitakere, Huia and Nihotupu Filter Stations	31 %
Onehunga	3 wells/ 1 borehole	Onehunga Filter Station	5 %
Hays Creek	1 dam	Hunua Gorge Filter Station	3 %
Hunua Ranges	4 dams	Ardmore Filter Station	61 %

Dams in the Waitakere and Hunua ranges supply 95% of the reticulated water supply (Fig. 2.3). Water is treated at a number of filter stations and supplied by a series of large water mains to 57 service reservoirs. Gravity is the main means of moving water from the filter stations but 20 pumping stations are used where gravity is insufficient. The service reservoirs provide a "buffer" capacity to meet daily demand and have sufficient storage for two and a half days of average demand on the whole system. Reservoirs that supply discrete areas are normally operated between 75-100% full, and others between 50-100% full. Gravity is utilised to supply most areas from the service reservoirs, through local council operated distribution networks. Service reservoirs are completely enclosed except for mesh-covered ventilators. The bulk water supply system is monitored from the Watercare Operations Centre in Onehunga. Water quality is also monitored to ensure that water meets Drinking Water Standards.

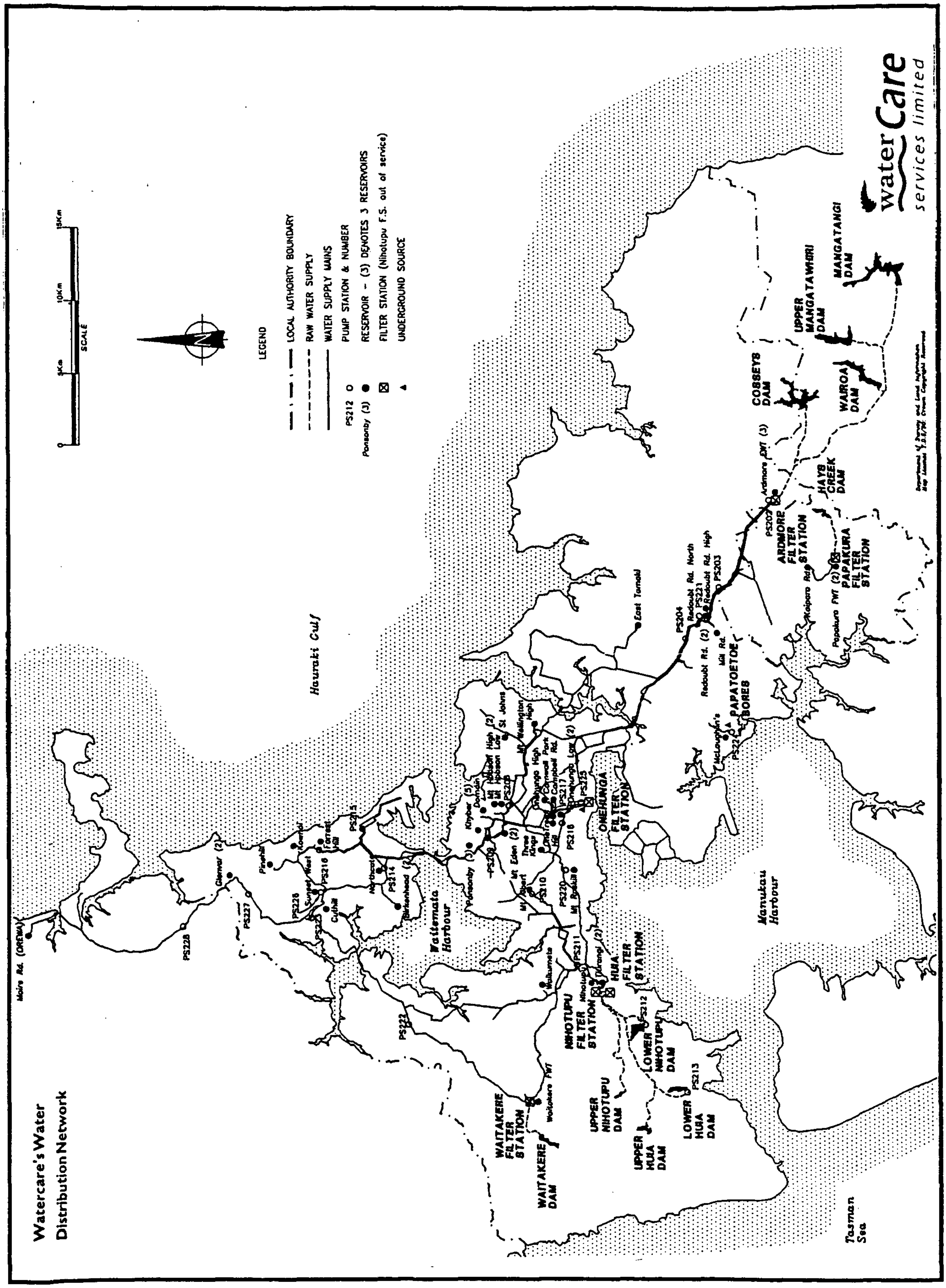

FIGURE 2.3: Water reticulation system in the Auckland region (supplied by Watercare Services Ltd)

Impacts of the scenario eruptions (see Part 1)

Contamination of Auckland's stream-lake-fed reticulated water supplies is possible from even relatively small tephra-producing eruptions, and is likely to restrict or prevent water intake from these sources for some time during and after an eruption episode. It is at just this time that increased demand for water can be expected for ash and acid rain clean-up operations.

Both turbidity and acidity of storage lakes will increase with tephra infall, but these parameters are likely to return to normal levels within a few days-weeks after tephra-falls cease and suspended ash settles out of the water column. However, intense rainfalls will wash further ash into lakes from their catchments, and ash-laden stormwater inflows can continue for months after an eruption has ended. Filter beds at the lake water treatment stations could be blocked by high loadings of suspended ash, and water intake at the treatment stations would likely be stopped until the lakes had cleared. Hazardous changes in lake water chemistry induced by toxic trace elements (including selenium, mercury, arsenic, fluorine and boron) contained in condensates on infalling ash are possible but unlikely due to the dilution and buffering properties of the relatively large volumes of lake water.

Water supply installations in near-vent areas directly affected by lava flows, ballistic blocks and pyroclastic surges will be destroyed. Water supply pipes in areas of severe ground deformation and/or faulting (e.g. Scenario 3) will be broken. Heat from lava flows can pressurise water remaining in underlying shallow buried pipes, possibly causing local explosions.

In outlying areas without reticulated water supply, household tank water may be collected from roof catchments. Within tephra-fall areas, downpipes should be disconnected from storage tanks so that ash is not washed into the tanks, and only reconnected after ash has been removed from roofs and gutters.

Water supply and reticulation

Scenario 1 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall (direct)	North Shore, central and eastern suburbs (5-50 mm thick, see figs.1.7, 1.8 Part 1).	Low - moderate risk to service reservoirs from ash infiltration	Cover ventilators, monitor water quality
	Hunua Dams (~1 mm thick)	Low risk to storage lakes from minor ash contamination.	Cover reservoir ventilators, monitor water quality in lakes
(indirect)	all ash fall and acid rain areas	High risk to supply capacity due to excessive demand during clean-up operations.	Initiate water management procedures

Scenario 2 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall (direct)	Eastern suburbs, western Waiheke Island (5-50 mm thick, see fig 1.13 Part 1)	Low - moderate risk to reservoirs from ash infiltration. Contamination of roof/tank supplies	Cover ventilators, monitor water quality. Disconnect roof/tank pipes
	Central Auckland, eastern Waiheke Island (< 5 mm thick)	Low risk to reservoirs from ash infiltration. Contamination of roof/tank supplies	Cover reservoir ventilators, monitor water quality. Disconnect roof/tank pipes
(indirect)	all ash fall and acid rain areas	High risk to supply capacity due to excessive demand during clean-up operations.	Initiate water management procedures

Water supply and reticulation

Scenario 3 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall (direct)	North Shore, central and eastern suburbs (5-50 mm thick, see fig.1.18 Part 1)	Low - moderate risk to reservoirs from ash infiltration	Cover reservoir ventilators, monitor water quality
	South Auckland, Waiheke Island (< 5 mm thick)	Low risk to reservoirs from ash infiltration. Contamination of roof/tank supplies.	Cover reservoir ventilators, monitor water quality. Disconnect roof/tank pipes
(indirect)	all ash fall and acid rain areas	High risk to supply capacity due to excessive demand during clean-up operations.	Initiate water management procedures
Ground shaking/ faulting	Near-vent and 5 km to SSW (see fig.1.17 Part 1)	Pipe breakage	N/A

Water supply and reticulation

Scenario 4 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall (direct)	North Shore, central and eastern suburbs (5-50 mm thick, see fig. 1.22 Part 1	Low - moderate risk to reservoirs from ash infiltration	Cover reservoir ventilators, monitor water quality
	South Auckland, Waiheke Island (<5 mm thick)	Low risk to reservoirs from ash infiltration. Contamination of roof/tank supplies.	Cover reservoir ventilators, monitor water quality. Disconnect roof/tank pipes
(indirect)	all ash fall and acid rain areas	High risk to supply capacity due to excessive demand during clean-up operations.	Initiate water management procedures
Ground shaking/ faulting	Out to 1 km from vent (see fig.1.21 Part 1)	Pipe breakage	N/A

Water supply and reticulation

Scenario 5 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall (direct)	South Auckland (5-50 mm thick, see fig. 1.26 Part 1)	Low - moderate risk to reservoirs from ash infiltration	Cover reservoir ventilators, monitor water quality
	West, east and distal south Auckland (< 5 mm thick)	Low risk to reservoirs from ash infiltration Contamination of roof/tank supplies.	Cover reservoir ventilators, monitor water quality. Disconnect roof/tank pipes
(indirect)	all ash fall and acid rain areas	High risk to supply capacity due to excessive demand during clean-up operations.	Initiate water management procedures
Ground shaking/ faulting	Out to 1 km from vent (see fig.1.25 Part 1)	Pipe breakage	N/A

2.5 WASTEWATER RETICULATION AND TREATMENT

Auckland's wastewater system consists of a network of pipes, tunnels, seven major interceptors, 60 pumping stations and a treatment plant (Fig. 2.4). Sewage is collected from local council operated pipe networks, and passes to the bulk wastewater system operated by Watercare Services Ltd. Sewage and stormwater is combined in a part of the system (e.g. Orakei interceptor), which services much of the inner city. Overloads sometimes occur when the volume entering the system exceeds the capacity of the pipes and pumping stations. Overloads are usually a result of high rainfall, prolonged power outage or equipment failure. A sophisticated remote surveillance system monitors the status of pump stations and warns of equipment failure and overflows. The wastewater treatment plant at Mangere uses both primary and secondary treatment methods.

Impacts of the scenario eruptions (see Part 1)

Tephra-falls will cause serious problems to Auckland's sewage and stormwater systems over a wide area. Ash which falls on roads, roofs, and other impervious areas, is easily washed into the stormwater system by rain, or during cleanup operations. [In some overseas eruptions, minor amounts of ash have been cleared from stormwater basins and pipelines by vacuum suction or high pressure water jets]. Ash will enter the sewage system via illegal connections, manholes, gully traps, or where the sewage and stormwater systems are combined (central Auckland). The density of ash is usually too high for a significant amount to remain in suspension at the water velocities normal in the sewer and stormwater pipes, so that ash will readily accumulate to block pipes and channels and lead to surface ponding. Finer ash may remain in suspension and be transported to the sewage treatment plant. Sewage pumps may be abrasion-damaged by ash-laden sewage, or fail due to loss of electricity (see above). Failure will result in the banking up of sewage in urban areas. The removal of ash from sewage and stormwater systems will be a time consuming and costly exercise.

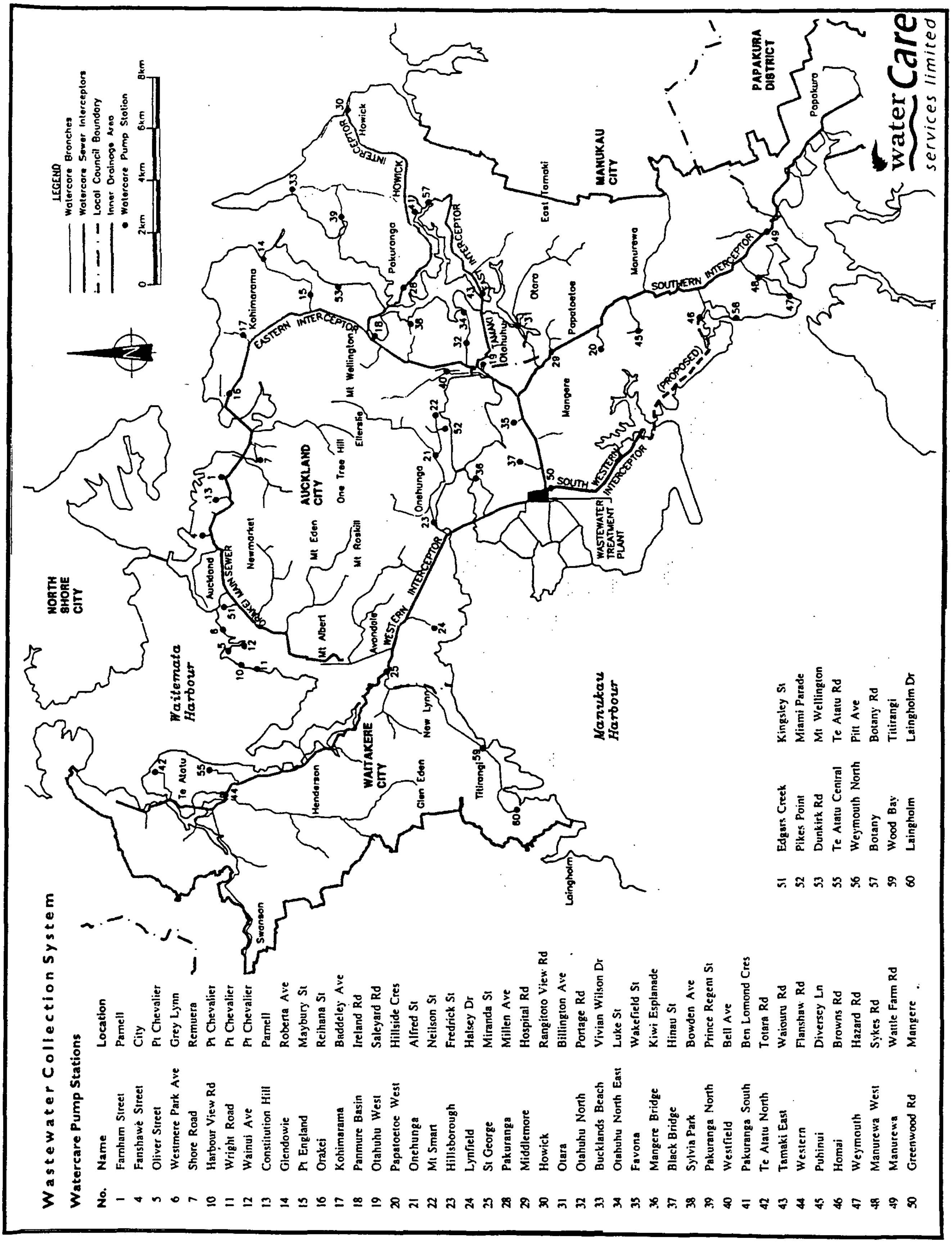

FIGURE 2.4: The wastewater collection system in the Auckland region. (Supplied by Watercare Services Ltd).

Ash-laden sewage which enters the Mangere treatment plant will overload the solid-removal equipment at the pretreatment and primary treatment stages. Milliscreens, mechanical grit/sludge removal mechanisms and other equipment that comes into contact with ash-laden sewage are likely to be rapidly worn and/or damaged. Ash falling directly into sedimentation tanks will add to the volume of solid material that will eventually have to be removed. Ash entering secondary treatment facilities, such as oxidation ponds and biofilters will reduce or halt the oxidation process until such time as the ash settles out or is removed. The ash may affect the acidity or toxicity level of the effluent to an extent that bacteria growth is damaged or lost. Release of untreated sewage will result from failure of the plant and/or its deliberate shutdown to avoid further damage.

Lava flows and thick pyroclastic surge deposits will block existing stormwater reticulation in affected areas, and significantly change local topography, leading to local ponding of surface waters. Heat from lava flows can pressurise water remaining in underlying shallow buried pipes, causing local explosions. (Septic tanks have been exploded in Iceland!) Ground deformation and faulting will break existing sewage and stormwater pipes. All these hazards are restricted to near-vent areas.

Waste water reticulation and treatment

Scenario 1(see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall	North Shore, central and eastern suburbs (5 - 50 mm thick, see fig. 1.7,1.8 Part 1)	High-moderate risk of stormwater/sewerage system blockage, potential risk to treatment plant equipment and processes.	Minimise input of ash to reticulation system, monitor sewage for ash contamination.
	South Auckland (< 5 mm thick)	Low -moderate risk to stormwater/sewerage system, (as above)	(as above)

Scenario 2 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall	Eastern Suburbs, western Waiheke Island (5 - 50 mm thick, see fig.1.13 Part 1)	High-moderate risk to stormwater/sewerage system, potential risk to treatment plant.	Minimise input of ash to reticulation system, monitor sewage for ash contamination
	Central Auckland, eastern Waiheke Island (<5 mm thick)	Low - moderate risk to stormwater/sewerage system, (as above)	Minimise input of ash

Waste water reticulation and treatment

Scenario 3 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall	North Shore, central and eastern suburbs (5 - 50 mm thick, see fig. 1.18 Part 1)	High-moderate risk to stormwater/sewerage system, potential risk to treatment plant.	Minimise input of ash to reticulation systems, monitor sewage for ash contamination
	South Auckland, Waiheke Island (<5 mm thick)	Low - moderate risk to stormwater/sewerage system (as above)	Minimise input of ash
Ground shaking/ faulting	Near-vent and 5 km to SSW (see fig.1.17 Part 1)	Pipe breakage	N/A

Scenario 4 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall	North Shore, central and eastern suburbs (5 - 50 mm thick, see fig 1.22 Part 1)	High - moderate risk to stormwater/sewerage system, potential risk to treatment plant.	Minimise input of ash to reticulation system, monitor sewage for ash contamination
	South Auckland (<5 mm thick)	Low-moderate risk to stormwater/sewerage system (as above)	Minimise input of ash
Ground shaking/ faulting	Out to 1 km from vent (see fig.1.21 Part 1)	Pipe breakage	N/A

Waste water reticulation and treatment

Scenario 5 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Tephra-fall	South Auckland (5 - 50 mm thick, see fig. 1.26 Part 1)	High-moderate risk to stormwater/sewerage system, potential risk to treatment plant.	Minimise input of ash to reticulation system, monitor sewage for ash contamination
	West and east Auckland (<5 mm thick)	Low-moderate risk to stormwater/sewerage system (as above)	Minimise input of ash
Ground shaking/ faulting	Out to 1 km from vent (see fig.1.25 Part 1)	Pipe breakage	N/A

2.6 TELECOMMUNICATIONS

The telecommunication networks provide local and external telephone links in the region. There are a number of telecommunication providers in the Auckland area. For the purposes of this report information has only been sourced from Telecom NZ Ltd. Local lines are connected to local telephone exchanges which are in turn linked to microwave repeater radio stations (nodal points) by underground copper or fibre cables. The microwave radio stations transmit and receive calls to and from neighbouring stations. A number of microwave stations are also the sites of VHF and cellular telephone stations. The telecommunications network in the Auckland is shown in Figure 2.5.

Broadcast radio and television facilities in the Auckland region are provided by state and private organisations, with local stations and nationwide networks originating from studios within and outside the region. Radio and television transmitter sites are located about the city, with some microwave network links to outside areas sharing common facilities. We have not considered impacts on local broadcasting stations which would be affected by the scenario eruptions because emergency management broadcasting can be continued from stations outside the affected areas.

Impacts of the scenario eruptions (see Part 1)

Communications will be severely disrupted during an eruption in Auckland, resulting from interference to radio waves due to disturbed atmospheric electrical conditions, overloading of telecommunication systems due to increased demand, direct damage to communications facilities by eruption products or lightning strikes, indirect impacts resulting from disruption to electricity supplies or transportation of technicians (preventing operations or maintenance). Ash entering telephone exchanges can cause damage to electrical and mechanical systems and general damage to buildings. Exchanges have battery-generator power backup systems to enable continued operation in the event of loss of electricity supply. Generators are housed in the exchange buildings, but rely on external air intakes to air filters. Clogging of these filters by ash would result in failure of the generator, followed by exhaustion of the battery capacity after a few hours demand.

Lava flows, ballistic block impacts, pyroclastic surges and lightning strikes from ash clouds present a high risk of damage to communication installations in the affected areas, but the extent of these hazards (in typical Auckland eruptions) is mostly limited to within a few kilometres of the erupting vent. Severe near-vent ground shaking accompanying volcanic earthquakes (and any associated faulting as in Scenario 3 - Part 1) will also topple poles and rupture underground

services, possibly in areas not greatly damaged by eruption products. There are few or no mitigation options available to counteract any of these near-vent hazards, which apply to all structures. Corrosion of metal surfaces will result from acid rain formed from the release of volcanic gases, notably SO_2 and HCl (see Appendix 1, part A1.5).

Loss of communications will make disaster management extremely difficult before, during and after an eruption.

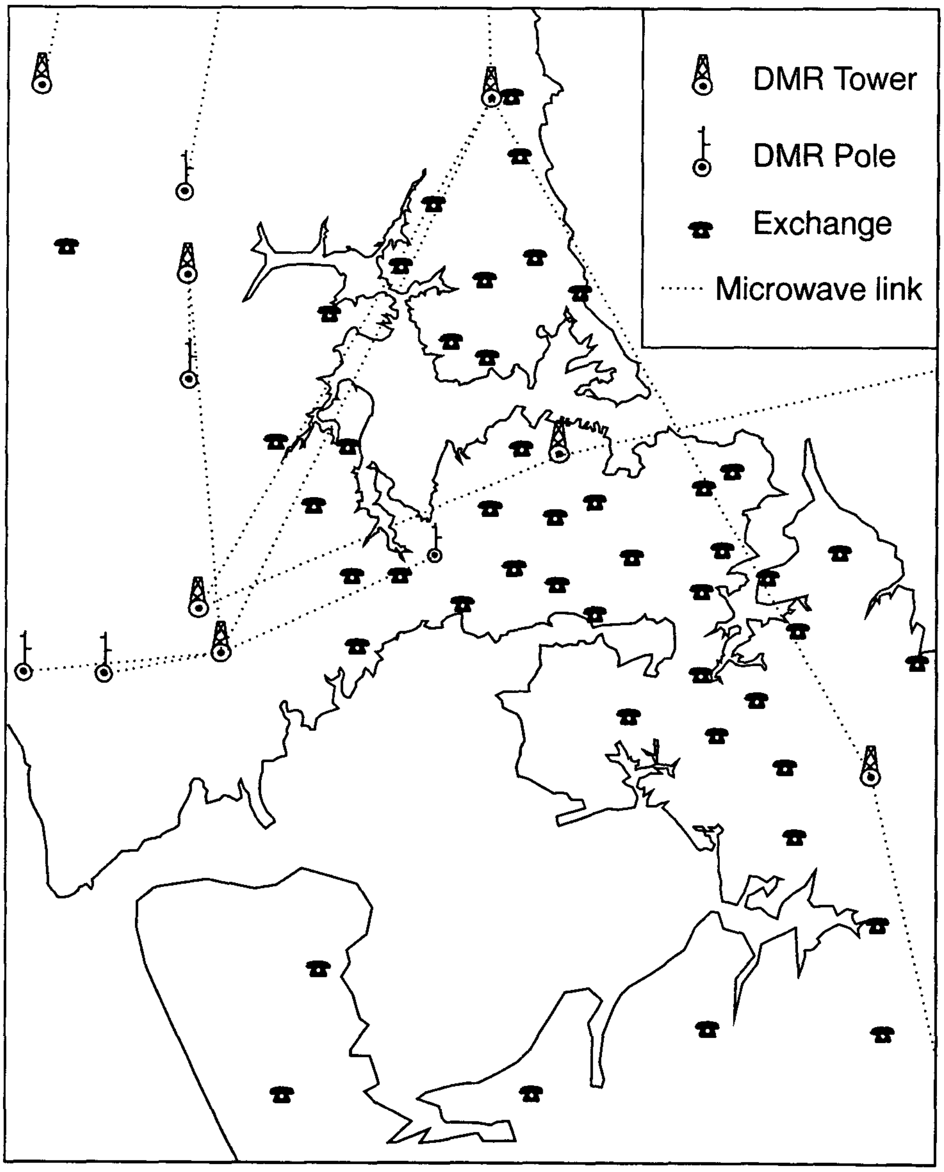

FIGURE 2.5: The telecommunications network in the Auckland region (supplied by Telecom NZ Ltd). (DMR refers to Digital Microwave Repeater)

Telecommunications

Scenario 1 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Exchanges			
Tephra-fall	within 1 mm isopach (see fig.1.7, 1.8 Part 1)	Low to moderate risk of disruption and damage if exchanges are sealed	Seal exchanges, fit internal air-conditioning, remove ash
	outside 1 mm isopach	Low to moderate risk of disruption and low damage if exchanges are sealed.	Seal exchanges, fit internal air-conditioning, remove ash
Acid Rain	up to 10 km downwind from vent (see fig.1.9 Part 1)	Risk of minor to moderate corrosion. Level decreasing away from the vent.	Washing of exterior of buildings.
Lines			
Tephra-fall	within 50 mm isopach (see fig.1.7, 1.8 Part 1)	Moderate risk of line collapse if ash builds up.	Rainfall, hosing or air blasting to remove ash.
Lightning	Out to ?10 km downwind from vent	Pole fires and transformer explosions	N/A
Microwave towers			
Tephra-fall	within 10 mm isopach (see fig.1.7, 1.8 Part 1)	Low to moderate risk of disruption and damage if exchanges are sealed	Remove ash immediately
	outside 10 mm isopach	Low to moderate risk of disruption and low damage if exchanges are sealed.	Remove ash immediately
Lightning	Out to 10 km downwind from vent	Strikes on towers	N/A

Telecommunications

Scenario 2 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Exchanges			
Tephra-fall	within 1 mm isopach (see fig.1.13 Part 1)	Low to moderate risk of disruption and damage if exchanges are sealed	Seal exchanges, fit internal air-conditioning, remove ash immediately.
	outside 1 mm isopach	Low to moderate risk of disruption and low damage if exchanges are sealed.	Seal exchanges, fit internal air-conditioning, remove ash immediately.
Surges	Out to 3 km from vent (see fig.1.12 Part 1)	High risk of disruption and damage exchanges. Risk may be less at the periphery of the surge	N/A
Ballistic clasts	Out to 2 km from vent (see fig.1.12 Part 1)	Possible damage to exchanges if hit	N/A
Acid Rain	up to 10 km downwind from vent	Risk of minor to moderate corrosion, decreasing away from the vent.	Washing of exterior of exchanges.
Lines			
Tephra	within 50 mm isopach (see fig.1.13 Part 1)	Moderate risk of line collapse if ash builds up.	Rainfall,hosing or air blasting to remove ash.
Surges	Out to 3 km from vent (see fig.1.12 Part 1)	High risk of damage to lines and poles.	N/A
Ballistic clasts	Out to 2 km from vent	Some damage to poles and lines	N/A
Lightning	Out to 10 km downwind from vent	Pole fires and transformer explosions	N/A

Telecommunications

Scenario 3 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Exchanges			
Tephra-fall	Within 10 mm isopach (see fig.1.18 Part 1)	Low to moderate risk of disruption and damage if exchanges are sealed	Seal exchanges, fit internal air-conditioning, remove ash
	outside 10 mm isopach	Low to moderate risk of disruption and low damage if exchanges are sealed.	Seal exchanges, fit internal air-conditioning, remove ash
Acid Rain	up to 10 km downwind from vent (see fig.1.16 Part 1)	Risk of minor to moderate corrosion,decreasing away from the vent.	Washing of exterior of buildings.
Lines/cables			
Tephra-fall	within 50 mm isopach (see fig.1.18 Part 1)	Moderate risk of line collapse if ash builds up.	Rainfall, hosing or air blasting to remove ash.
Surges (and lava flows)	Out to 3 km from vent (see fig.1.16 Part 1)	Destruction of poles and lines.	N/A
Ballistic clasts	Out to 2 km from vent	Area also devastated by surges	N/A
Lightning	Out to 10 km downwind from vent	Pole fires and transformer explosions	N/A
Ground shaking/ faulting	Near-vent and 5 km to SSW (see fig.1.17 Part 1)	Cable breakage	N/A
Microwave towers			
Tephra	Within 10 mm isopach (see fig.1.18 Part 1)	Low to moderate risk of disruption and damage if exchanges are sealed	Remove ash immediately.
	Outside 10 mm isopach	Low to moderate risk of disruption and low damage if exchanges are sealed.	Remove ash immediately.
Lightning	Out to 10 km downwind from vent	Strikes on towers	N/A

Telecommunications

Scenario 4 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Exchanges			
Tephra-fall	within 10 mm isopach (see fig.1.22 Part 1)	Low to moderate risk of disruption and damage if exchanges are sealed	Seal exchanges, fit internal air-conditioning, remove ash
	Outside 10 mm isopach	Low to moderate risk of disruption and low damage if exchanges are sealed.	Seal exchanges, fit internal air-conditioning, remove ash
Ballistic clasts	Out to 1 km from the vent (see fig.1.21 Part 1)	High risk of damage from a direct hit.	N/A
Acid Rain	Up to 10 km downwind	Risk of minor to moderate corrosion, decreasing away from the vent.	Washing of exterior of buildings.
Lines/cables			
Tephra	Within 50 mm isopach (see fig.1.22 Part 1)	Moderate risk of line collapse if ash builds up.	Rainfall, hosing or air blasting to remove ash.
Ballistic blocks	Out to 1 km from the vent (see fig.1.21 Part 1)	High risk of damage from a direct hit.	N/A
Lava flows	Downslope from the vent (see fig.1.21 Part 1)	Poles destroyed.	N/A
Ground shaking/ faulting	Out to 1 km from vent (see fig.1.21 Part 1)	Cable breakage	N/A
Microwave towers			
Tephra-fall	Within 10 mm isopach (see fig.1.22 Part 1)	Low to moderate risk of disruption and damage if exchanges are sealed	Remove ash immediately
	Outside 10 mm isopach	Low to moderate risk of disruption and damage.	Remove ash
Ballistics	Out to 2 km from the vent (see fig.1.21 Part 1)	High risk of damage from a direct hit.	N/A
Acid Rain	Up to 10 km downwind	Risk of minor to moderate corrosion. Level decreasing away from the vent.	Washing of exterior of buildings.
Lightning	Out to 10 km downwind from the vent.	Strikes on towers.	N/A

Telecommunications

Scenario 5 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Exchanges			
Tephra-fall	Within 10 mm isopach (see fig.1.26 Part 1)	Low to moderate risk of disruption and damage if exchanges are sealed	Seal exchanges, fit internal air-conditioning, remove ash immediately.
	Outside 10 mm isopach	Low to moderate risk of disruption and low damage if exchanges are sealed.	Seal exchanges, fir internal air-conditioning, remove ash.
Ballistic clasts	Out to 1 km from the vent (see fig.1.25 Part 1)	High risk of damage from a direct hit.	N/A
Acid Rain	Up to 10 km downwind	Risk of minor to moderate corrosion. Level decreasing away from the vent.	Washing of exterior of buildings.
Lines/cables			
Tephra	Within 50 mm isopach (see fig.1.26 Part 1)	Moderate risk of line collapse if ash builds up.	Rainfall, hosing or air blasting to remove ash.
Ballistic clasts	Up to 1 km from the vent (see fig.1.25 Part 1)	High risk of damage from impacts on lines or poles.	N/A
Lava flows	Downslope from the vent (see fig.1.25 Part 1)	Destruction of poles	N/A
Ground shaking/ faulting	Out to 1 km from vent (see fig.1.25 Part 1)	Cable breakage	N/A
Microwave towers			
Tephra	Within 10 mm isopach (see fig.1.26 Part 1)	Low to moderate risk of disruption and damage if exchanges are sealed	Remove ash immediately
	Outside 10 mm isopach	Low to moderate risk of disruption and damage.	Remove ash immediately.
Acid Rain	Up to 10 km downwind	Risk of minor to moderate corrosion, decreasing away from the vent.	Washing of structures
Lightning	Out to 10 km downwind from the vent.	Strikes on towers.	N/A

2.7 CRITICAL FACILITY BUILDINGS (Hospitals, Civil Defence HQ, Fire HQ, Police HQ)

For the purpose of this report, critical facilities are defined as buildings associated with emergency and essential services required during an emergency. A large number of buildings may be included in this category (e.g. hospitals, fire and police stations, civil defence facilities, contractor's yards, ambulance stations etc.). The consequence of disruption to their use will vary depending on their importance to the operation of the emergency management system as a whole. Auckland has a range of critical facilities, of varying importance and only a few are discussed here (i.e. main hospitals, Regional Police, Fire and Ambulance headquarters, City Council Civil Defence headquarters and Regional Civil Defence headquarters).

Impacts of the scenario eruptions (see Part 1)

Critical facility buildings are extremely vulnerable to disruptions of the "lifelines" which provide the services and linkages which allow them to operate. Electricity is required for lighting, ventilation, boiler operations, water heating, freezers/coolers, kitchens, medical services, lifts and security. Water supply is usually required for satisfactory operation of hot and cold water systems, fire hoses and sprinklers, kitchens and laboratories. Communication facilities are critical for the operation of the emergency management organisations (civil defence, police, fire) and require continued electricity supply. Many buildings have back-up systems (e.g. electrical generators, water tanks) to provide limited supplies of these services in the event of loss of main (or primary) services

Tephra can cause direct damage to buildings and building services in several ways; overloading roofs to cause collapse (in excess of 100 mm of wet tephra), soiling interiors, damaging services (electrical and mechanical) and damaging exterior materials.

Lava flows, ballistic clast impacts, pyroclastic surges and lightning strikes from ash clouds present a high risk of damage to critical facilities in the eruption-affected areas, but the extent of these hazards is mostly limited to within a few kilometres of the vent. Severe near-vent ground shaking accompanying volcanic earthquakes (and any associated faulting as in Scenario 3) will also damage buildings, possibly in areas not greatly damaged by eruption products. Apart from the evacuation of people (and removal of plant), there are few or no mitigation options available to counteract any of these near-vent hazards, which apply to all structures (except for example, alternative or duplicate facilities which may be set up outside the affected area in advance). Corrosion of metal surfaces will result from acid rain formed from the release of volcanic gases, notably SO_2 and HCl (see Appendix 1, part A1.5).

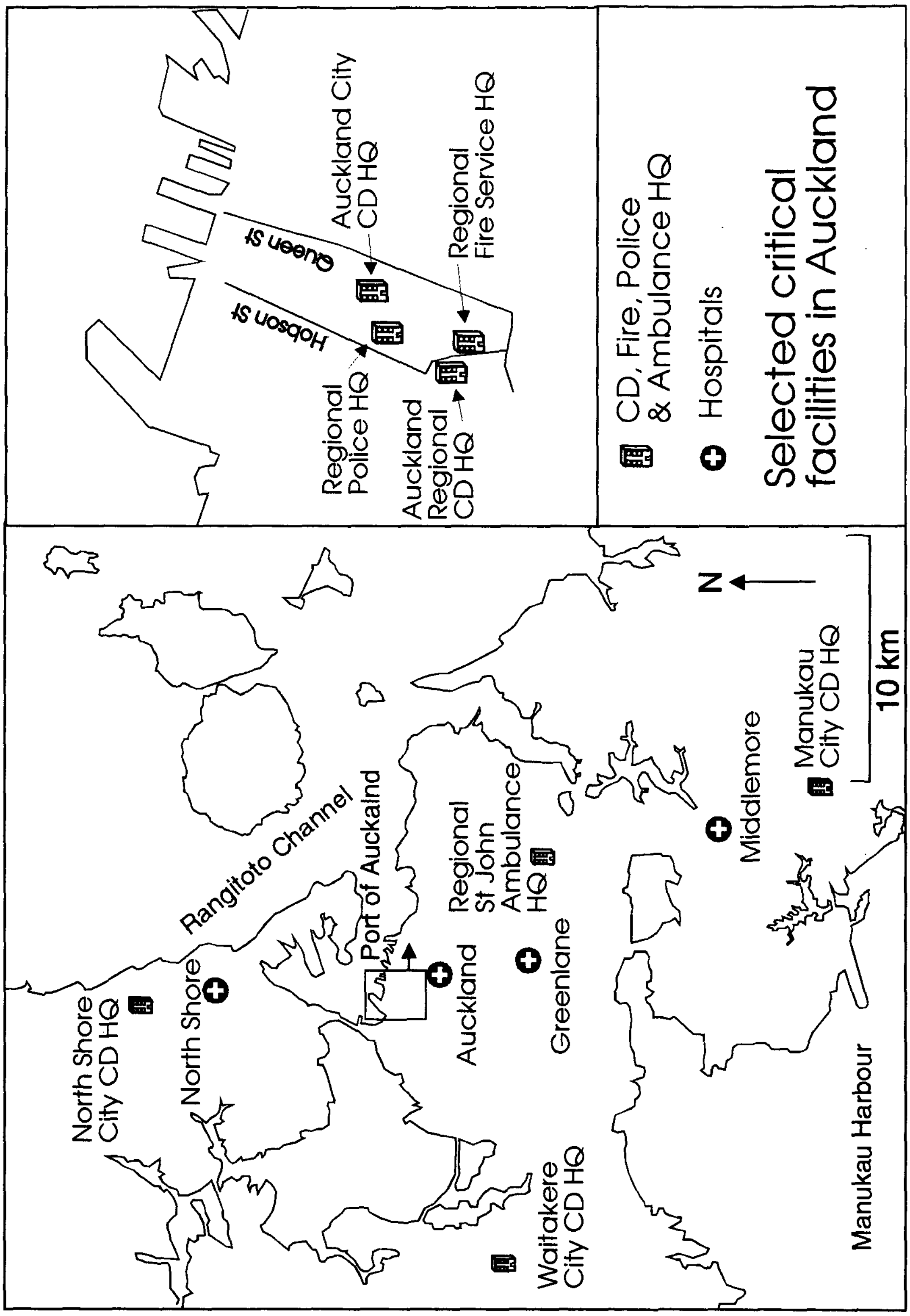

FIGURE 2.6: Locations of critical facility buildings mentioned in the text.

Critical facility buildings

Scenario 1(see Part 1)

Type of facility	Location	Basic risk to service	Mitigation strategies
Hospitals		*Tephra fall*	
	North Shore	10mm	seal against ash, use internal air conditioning, local clean up
	Auckland	30mm	
	Greenlane	10mm	
	Middlemore	4mm	
CD HQs	Auckland City and region	20mm	as above
	North Shore	5mm	
	Manukau	2mm	
Regional Police & Fire HQs		20mm	as above
Regional Ambulance HQ		20mm	as above

Scenario 2 (see Part 1)

Type of facility	Location	Basic risk to service	Mitigation strategies
Hospitals		*Tephra falls*	
	North Shore	trace	Seal against ash, use internal air conditioning, local clean up
	Auckland	trace	
	Greenlane	1mm	
	Middlemore	1 mm	
CD HQs	Auckland City and region	1mm	as above
	North Shore	trace	
Regional Police & Fire HQs		1mm	as above
Regional Ambulance HQ		3mm	as above

Critical facility buildings

Scenario 3(see Part 1)

Type of facility	Location	Basic risk to service	Mitigation strategies
Hospitals		*Tephra falls*	
	North Shore Greenlane Middlemore	10mm 30mm 5mm	<50mm, seal against ash, use internal air conditioning, local clean up
	Auckland	60mm tephra and peripheral to surge zone	evacuate
CD HQs	Auckland City and Region	50mm tephra and peripheral to surge zone	evacuate
	North Shore	10 mm	seal against ash
	Manukau	trace	seal against ash
Regional Police & Fire HQs		50mm tephra and peripheral to surge zone	evacuate
Regional Ambulance HQ		30mm	seal against ash

Scenario 4(see Part 1)

Type of hazard	Location	Basic risk to service	Mitigation strategies
Hospitals		*Tephra fall*	<50mm, seal against ash, use internal air conditioning, local clean up
	North Shore Greenlane Middlemore	40mm 40mm 1mm	
	Auckland	80mm tephra and ballistics	evacuate
CD HQs	Auckland City and region	80mm tephra and ballistics	evacuate
	North Shore	20mm	
	Manukau	trace	
Regional Police HQ Fire HQ		80mm tephra and ballistics	evacuate
Regional Ambulance HQ		30mm	seal against ash

Critical facility buildings

Scenario 5 (see Part 1)

Type of hazard	Location	Basic risk to service	Mitigation strategies
Hospitals		*Tephra falls*	
	Middlemore	30mm	evacuate
	Auckland Greenlane	6mm 50mm	<50mm, seal against ash, use internal air conditioning, local clean up
CD HQs	Auckland City and region Manukau	5mm 10 mm	as above as above
Regional Police & Fire HQ		5mm	as above
Regional Ambulance HQ		40mm	as above

2.8 POPULATION

The Auckland region contains more than one million inhabitants occupying the area surrounding the narrow isthmus between the Hauraki Gulf and Manukau Harbour. The entire population of the region will be affected in some way by an eruption from the Auckland Volcanic Field. Most people will experience tephra fall and some loss of services, but a significant number of people will face evacuation from the potential near-vent area. Evacuation will be deemed necessary by the controlling authorities if a perceived risk to human life reaches unacceptable levels. Within the Auckland Volcanic Field, a 5 km radius around the vent is assumed to be a minimum safe distance to avoid the impacts of surges and ballistic clasts which can be expected to feature in the early, explosive phases, of an impending eruption. The population living within a range of distances from each scenario eruption vent is given in Table 2.2.

TABLE 2.2 Population within a given radius of each scenario vent.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Grid reference	6486000 2673000	6478000 2678000	6482400 2669000	6481200 2667500	6475500 2667100
1 km	0[m]	501[m]	2 688[m]	6 282[m]	6 282[m]
2 km	2 175[m]	15 963[m]	12 102[m]	25 749[m]	29 754[m]
5 km	28 104[m]	103 857[m]	105 096[a]	133 764[a]	146 106[a]
10 km	244 842[a]	245 601[a]	368 004[a]	396 006[a]	385 722[a]

m = S meshblock populations contained with the given radius (1991 census).
a = S area unit populations contained with the given radius (1991 census).

Note: Populations are calculated using the Department of Statistics CD-Rom census database (Supermap 2). A meshblock or area unit is only selected where the arc covers or passes through the centroid of the area. Meshblocks are the smallest geographic units in which data is collected by the Department of Statistics. They vary in size from a city block (or part of) to extensive tracts of rural land. Urban meshblocks generally contain between 150 to 200 people while rural meshblocks have fewer (100 to 150) and some have no population. Meshblocks can only be used in the above calculations when there are less than c. 500 within a given radius. Area units are the next larger statistical unit, made up of an aggregation of meshblocks and are used for population calculations at larger radii. Area units general have a population of between 3 000 to 5 000.

Evacuation

The principal function of evacuation is to ensure that people move from a place of relative danger to a place of relative safety via a route that is itself free from significant danger. The

destination as well as the route must be considered in the plan. There needs to be careful coordination of the timing and conduct of an evacuation and this must be done in association with agencies who are assessing risk and ordering the evacuation, as well as those responsible for receiving evacuees. Evacuation of near-vent areas must be completed prior to the eruption if possible. When precursory seismicity and deformation is severe, some voluntary self-evacuation of the near-vent area is likely to occur (as at Rabaul in 1994), before compulsory evacuation is required.

Post-eruption evacuation may also become necessary in areas where people have survived tephra fall without difficulty, but in which the long term loss of normal services such as water and food supply, electricity, and waste disposal, have made continued habitation untenable.

If the evacuation of a hazardous zone is to proceed in an orderly manner it is essential that people know where to go, and what route to take. Unless the risk to life is immediate and obvious, people will be reluctant to leave their homes. Assurance must be given that the evacuated area will remain off limits to unauthorised people.

New Zealanders' experience of large scale evacuations is minimal, and the logistical and social problems associated with such an action would probably be very substantial. People forced to move are likely to feel demoralized and dysfunctional, and physical and mental health problems may occur at a higher rate than normal. This will depend on the severity of the disaster, and the personal situation of the evacuees.

Evacuations usually involve three types of movement.

1. Self-evacuation where people move out in their own vehicles to stay with friends/relatives. Such self-evacuations may be voluntary, and often precede any compulsory evacuation.

2. Movement of people who do not own or have access to private vehicles;

3. Movement of people with special needs, e.g. hospitals, disabled persons, jails

Public health aspects

Residents outside the compulsory evacuation zone may have to contend with significant thickness of tephra (up to 50 mm). Fresh tephra and aerosols act as an irritant on the upper and lower respiratory tracts and eyes but is non-toxic. Respiratory problems will result from the inhalation of fine ash, but will be more acute in patients with existing respiratory disorders. Eye problems will include foreign material in eyes, corneal abrasion and conjunctivitis. During periods of ashfall the best precaution is to stay indoors. Where it is necessary to move outside, a protective filter mask should be worn. If such a mask if unobtainable, wet cloth over the mouth and nose will prevent inhalation of the ash.

Population

Scenario 1 (see Part 1)

Area	Action/ Mitigation
5 km radius around vent (see fig.1.9 Part 1)	Evacuation (~28 000 people)
North Shore (Devonport, part of Takapuna) Mission Bay Orakei	Take with you: essential medicines, toilet items; important documents; transistor radio and torch; extra clothing. Before leaving: consider your pets and animals, turn off water, electricity, gas and heating oil at the mains; secure premises. When you reach safety: listen to your radio for further instructions, including registration requirements.
Tephra fall	
central and eastern suburbs (5 - 50 mm thick, see fig.1.7, 1.8 Part 1) South Auckland (< 5 mm thick)	Take shelter inside. Listen to the radio for advice and information, stay indoors, close windows and doors, do not run air-conditioning or clothes dryers with outside connection, if outside seek shelter; use a mask or handkerchief for breathing , do not drive unless you have to, but if you must drive, drive slowly as ashfall will reduce visibility, keep pets indoors

Population

Scenario 2 (see Part 1)

Area	Action/Mitigation
5 km radius around vent (see fig.1.12 Part 1)	Evacuation (~104 000 people)
Howick, Pakuranga Panmure, Glen Innes Glendowie	Take with you: essential medicines, toilet items; important documents; transistor radio and torch; extra clothing. Before leaving: consider your pets and animals, turn off water, electricity, gas and heating oil at the mains; secure premises. When you reach safety: listen to your radio for further instructions, including registration requirements.
Tephra falls	
eastern suburbs, western Waiheke Island (5 - 50 mm thick, see fig.1.13 Part 1) Central Auckland, eastern Waiheke Island (< 5 mm thick)	Take shelter. Listen to the radio for advice and information, stay indoors, close windows and doors, do not run air-conditioning or clothes dryers with outside connection, if outside seek shelter; use a mask or handkerchief for breathing , do not drive unless you have to, but if you must drive, drive slowly as ashfall will reduce visibility, keep pets indoors.

Population

Scenario 3 (see Part 1)

Area	Action/Mitigation
5 km radius around vent (see fig.1.16 Part 1)	Evacuation (~105 000 people)
Orakei, Remuera Newmarket, Mount Eden Grey Lynn, Ponsonby Auckland Central Northcote, Devonport	Take with you: essential medicines, toilet items; important documents; transistor radio and torch; extra clothing. Before leaving: consider your pets and animals, turn off water, electricity, gas and heating oil at the mains; secure premises. When you reach safety: listen to your radio for further instructions, including registration requirements.
Tephra fall	
North Shore, central and eastern suburbs (5 - 50 mm thick, see fig.1.18 Part 1) South Auckland, Waiheke Island (<5 mm thick)	Take shelter. Listen to the radio for advice and information, stay indoors, close windows and doors, do not run air-conditioning or clothes dryers with outside connection, if outside seek shelter; use a mask or handkerchief for breathing , do not drive unless you have to, but if you must drive, drive slowly as ashfall will reduce visibility, keep pets indoors.

Scenario 4 (see Part 1)

Area	Action/Mitigation
5 km radius around vent (see fig.1.21 Part 1)	Evacuation (~134 000 people)
Orakei, Remuera Newmarket, Mount Eden Epsom, Grey Lynn, Ponsonby, Mount Albert Auckland Central Northcote, Devonport	Take with you: essential medicines, toilet items; important documents; transistor radio and torch; extra clothing. Before leaving: consider your pets and animals, turn off water, electricity, gas and heating oil at the mains; secure premises. When you reach safety: listen to your radio for further instructions, including registration requirements.
Tephra fall	
North Shore, central and eastern suburbs (5 - 50 mm thick, see fig.1.22 Part 1) South Auckland (< 5 mm thick)	Take shelter. Listen to the radio for advice and information, stay indoors, close windows and doors, do not run air-conditioning or clothes dryers with outside connection, if outside seek shelter; use a mask or handkerchief for breathing , do not drive unless you have to, but if you must drive, drive slowly as ashfall will reduce visibility, keep pets indoors.

Population

Scenario 5 (see Part 1)

Area	Action/Mitigation
5 km radius around vent (see fig.1.25 Part 1)	Evacuation (~146 000 people)
Mount Albert, Sandringham, Mount Roskill, Hillsborough, Mangere Bridge, Onehunga One Tree Hill, Epsom, Mount Eden	Take with you: essential medicines, toilet items; important documents; transistor radio and torch; extra clothing. Before leaving: consider your pets and animals, turn off water, electricity, gas and heating oil at the mains; secure premises. When you reach safety: listen to your radio for further instructions, including registration requirements.
Tephra fall	
South Auckland (5 -50 mm thick, see fig.1.27 Part 1) West and East Auckland (< 5 mm thick)	Take shelter. Listen to the radio for advice and information, stay indoors, close windows and doors, do not run air-conditioning or clothes dryers with outside connection, if outside seek shelter; use a mask or handkerchief for breathing , do not drive unless you have to, but if you must drive, drive slowly as ashfall will reduce visibility, keep pets indoors.

2.9 ROAD AND RAIL TRANSPORTATION FACILITIES

State Highways provide access to the city from north and south (Fig. 2.7). All road transport must pass through the narrow isthmus between the Hauraki Gulf and Manukau Harbour. Within the region much of the state highway system comprises multi-lane motorways. Within the city a number of arterial routes link various suburbs. The North Shore and Auckland City are linked by the eight-lane Auckland Harbour Bridge, as well as an upper harbour bridge and road links to the northwest.

The railway system serving Auckland comprises three lines (Fig. 2.7). The North Island Main Trunk line enters Auckland from the south serving the Port of Auckland. Inter-city passenger and commuter services also utilize this line and commuter services operate on the eastern and western lines.

Impact of scenario eruptions (see Part 1)

Reduced visibility on roads will be experienced over wide areas during and after ash falls (all scenarios). Dry fine ash is readily raised in billowing clouds by passing vehicles and will present an ongoing hazard. Wet fine ash can turn to mud causing vehicle traction problems. Thick (>100 mm) ashfall deposits will absorb a considerable amount of water before being washed away. Thin ash deposits (<2 mm) will generally be moved to the shoulder of roads by traffic, but will remain there. Greater thicknesses of ash will need to be physically removed from road surfaces by scraping, brushing and washing.

Lava flows will block roads over which they flow (in Scenarios 3, 4, 5), and lava removal or road rerouting will present major problems after an eruption has ended. Thick surge deposits will also bury roads in near-vent areas (Scenarios 2 and 3). Severe ground deformation and/or faulting can make roads temporarily impassable (i.e. Scenario 3) by road surface cracking and building collapse onto the roadway. Most such effects will only occur in near-vent areas which will be devastated by other effects of the eruption.

Problems arising as a consequence of closure of roads include lack of access for emergency services, stranding of travellers, disruptions to food supplies, and economic impacts on businesses in the affected areas. Where ash-covered roads remain open, speed restrictions will need to be introduced to ensure traffic safety on roads in reduced visibility, and to reduce dust problems in adjacent communities.

Ash entering vehicle engines and transmissions will cause wear on moving parts, reducing their

life. In most cases severe damage will only result from excessive vehicle use in an ash-affected environment. The most common effect of ashfall on vehicles is blockage of air filters leading to overheating and stopping of motors. The abrasive ash can also damage vehicle brakes, exterior fittings, paintwork and windows.

Acid rain and gas clouds (including "laze") will cause greatly increased corrosion of vehicles.

Rail lines and rail transportation will be affected in a similar manner to road transportation, but rail is usually the ground transport system least affected by tephra fall. Near-vent severe ground deformation and cracking (i.e. Scenario 3) will cut rail lines, which will also be buried beneath thick surge deposits and lava flows (Scenario 2, 3, 4). In distal areas, ashfall less than ~10 mm thick can be quickly cleared from rail tracks, and train running resumed. Problems with ash clouds stirred up by train passage restrict operating speeds, cause operator vision and breathing problems, and can affect diesel locomotive motors and transmissions (as happened during the 1980 Mt St Helens eruptions). Light rain on ashfall has led to extensive short-circuiting of electrically-operated signal equipment in overseas eruptions.

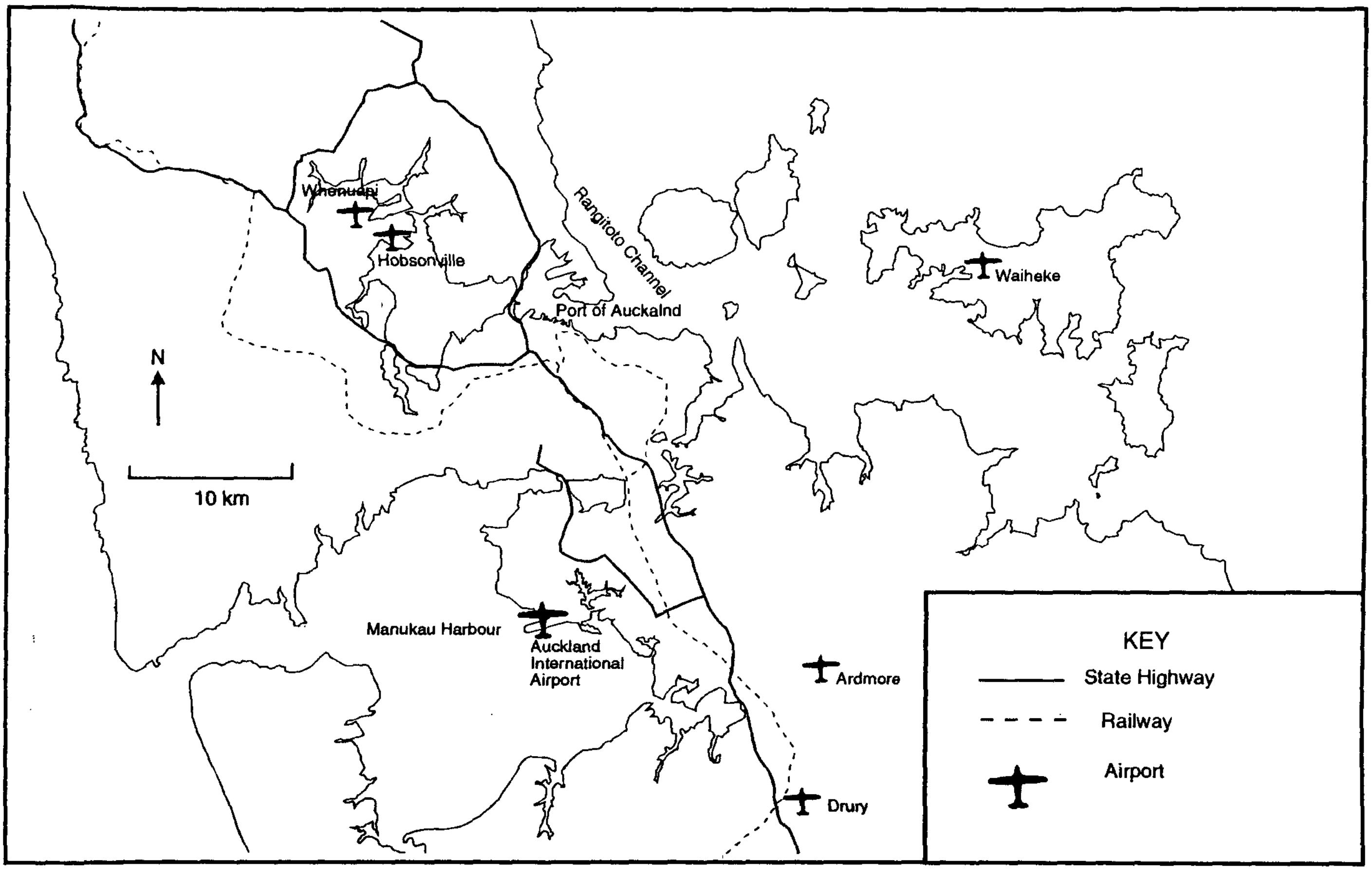

FIGURE 2.7: Main transportation routes and airport locations in the Auckland region.

Road and rail transportation facilities

Scenario 1 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Roads			
Tephra	Within 50 mm isopach (see fig.1.7. 1.8 Part 1)	High risk of closure, reduced visibility and traction problems (if wet).	Remove ash from road surface
	Between 50 and 5 mm isopachs	High-moderate risk of closure, reduced visibility and traction problems (if wet).	Remove ash from road surface
	Outside 5 mm isopach	Temporary risk of closure, reduced visibility and traction problems (if wet).	Remove ash from road surface
Surges and tsunamis	Coastal roads in Takapuna area and Rangitoto Island (see fig.1.9 Part 1)	Roads closed by flooding and erosion	N/A
Vehicles	Within 10 mm isopach (see fig.1.7, 1.8 Part 1)	Moderate-high risk of damage, especially with frequent use.	Avoid non-essential use, change air filters and lubricants often, reduce speed
	Between 10 and 1 mm isopachs	Low -moderate risk of damage, with frequent use.	Avoid non-essential use, change air filters and lubricants often, reduce speed
Railways	Within 5mm isopach	Stirred up ash clouds cause visibility and operator health problems, and can damage rolling stock	Clear ash from lines, reduce speeds,provide face masks, increased locomotive maintenance

Road and rail transportation facilities

Scenario 2 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Roads			
Tephra	Within 50 mm isopach (see fig.1.13 Part 1)	Roads closed until cleared	Clear ash from roads
	Between 50 and 5 mm isopachs	High risk of road closure, reduced visibility and traction problems (if wet).	Clear ash from roads
	Outside 5 mm isopach	Moderate risk of closure, reduced visibility and traction problems (if wet).	Clear ash from roads
Surges and ballistic clasts	Out to 3 km from vent (see fig.1.12 Part 1)	Roads closed by burial and cratering	Excavate roads on margins of surge deposits
Vehicles			
	Within 10 mm isopach (see Fig.1.13 Part 1)	Moderate-high risk of damage, especially with frequent use.	Avoid non-essential use, change air filters and lubricants often, reduce speed
	Between 10 and 1 mm isopachs	Low-moderate risk of damage, especially with frequent use.	Avoid non-essential use, change air filters and lubricants often, reduce speed
Railways			
Tephra	Within 5 mm isopach (see Fig.1.13 Part 1)	Stirred up ash clouds cause visibility and operator health problems, and can damage rolling stock	Clear ash from lines, reduce speeds,provide face masks, increased locomotive maintenance
Surges and ballistic clasts	Out to 3 km from vent (see Fig.1.12 Part 1)	Line closed by burial and cratering	N/A. Excavate line.

Road and rail transportation facilities

Scenario 3 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Roads			
Tephra	Within 50 mm isopach (see fig.1.18 Part 1)	Roads closed until ash cleared.	Remove ash from road surface
	Between 50 and 5 mm isopachs	High risk of closure, reduced visibility and traction problems (if wet).	Remove ash from road surface
	Outside 5 mm isopach	Reduced visibility and traction problems (if wet).	Remove ash from road surface
Surges and lava flows	Out to 2 km from vent (see fig.1.16 Part 1)	Roads buried	N/A
Vehicles	Within 10 mm isopach (see fig.1.18 Part 1)	Moderate - high risk of damage, especially with frequent use.	Avoid non-essential use, change air filters and lubricants often, reduce speed
	Between 10 and 1 mm isopachs	Low - moderate risk of damage, especially with frequent use.	Avoid non-essential use, change air filters and lubricants often, reduce speed
Railways			
Tephra	Within 5 mm isopach (see fig.1.18 Part 1)	Stirred up ash clouds cause visibility and operator health problems, and can damage rolling stock	Clear ash from lines, reduce speeds,provide face masks, increased locomotive maintenance
Surges and lava flows	Out to 2 km from vent (see fig.1.18 Part 1)	Lines buried	N/A.

Road and rail transportation facilities

Scenario 4 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Roads			
Tephra	Within 50 mm isopach (see fig.1.22 Part 1)	Roads closed until ash cleared	Remove ash from road surface
	Between 50 and 5 mm isopach	High-moderate risk of closure, reduced visibility and traction problems (if wet).	Remove ash from road surface
	Outside 5 mm isopach	Temporary risk of closure, reduced visibility and traction problems (if wet).	Remove ash from road surface
Lava flows	To north of vent (see fig. 1.21 Part 1)	Burial of roads	N/A
Ballistic clasts	Out to 1 km from vent (see fig.1.21 Part 1)	Cratering of surface	N/A
Vehicles			
Tephra	Within 10 mm isopach (see fig.1.22 Part 1)	Moderate - high risk of damage, especially with frequent use.	Avoid non-essential use, change air filters and lubricants often, reduce speed
	Between 10 and 1 mm isopachs	Low - moderate risk of damage, especially with frequent use.	Avoid non-essential use, change air filters and lubricants often, reduce speed
Railways			
Tephra	Within 5 mm isopach (see fig.1.22 Part 1)	Stirred up ash clouds cause visibility and operator health problems, and can damage rolling stock	Clear ash from lines, reduce speeds,provide face masks, increased locomotive maintenance

Road and rail transportation facilities

Scenario 5 (see Part 1)

Type of hazard	Area of impact	Basic risk to service	Mitigation strategies
Roads			
Tephra	Within 50 mm isopach (see fig.1.26 Part 1)	Roads closed until ash cleared	Remove ash from road surface
	Between 50 and 5 mm isopachs	High-moderate risk of closure, reduced visibility and traction problems (if wet).	Remove ash from road surface
	Outside 5 mm isopach	Reduced visibility and traction problems (if wet).	Remove ash from road surface
Lava flows and ballistic clasts	To 1.5 km from vent (see fig.1.25 Part 1)	Roads buried and cratered	N/A
Vehicles	Within 10 mm isopach (see fig.1.26 Part 1)	Moderate - high risk of damage, especially with frequent use.	Avoid non-essential use, change air filters and lubricants often, reduce speed
	Between 10 and 1 mm isopachs	Low - moderate risk of damage, especially with frequent use.	Avoid non-essential use, change air filters and lubricants often, reduce speed
Railways			
Tephra	Within 5 mm isopach (see fig.1.26 Part 1)	Stirred up ash clouds cause visibility and operator health problems, and can damage rolling stock	Clear ash from lines, reduce speeds, provide face masks, increased locomotive maintenance

2.10 PORT FACILITIES AND SHIPPING

The port of Auckland is the region's main sea port, loading the largest value of goods per year of any New Zealand port. The main port facilities are located on the southern shore of the Waitemata Harbour, between St Mary's Bay and Judges Bay, with other shipping facilities and wharfs at Devonport and Birkenhead on the north shore of Waitemata Harbour. There are also wharf facilities at Onehunga on the Manukau Harbour.

Impact of scenario eruptions (see Part 1)

Auckland port facilities and shipping are affected by tephra falls, tsunamis, surges and lava flows in the various eruption scenarios. Where relatively thin, (Scenarios 1,2, 5) tephra falls will produce temporary primary and secondary impacts on port operations by affecting staff availability, road and rail access (see above), power supplies and communications, as well as availability of freight (which will probably be largely diverted to other ports). Rafts of scoria will temporarily block sea access in parts of the harbour, although these rafts should rapidly clear after eruption has ceased. Small tsunamis (generated by passage of pyroclastic flows into the sea - Scenario 1) may cause some damage as small vessels (yachts) are thrown against wharf structures by wave action. Larger waves, generated early in the Scenario 3 eruption, would cause considerable damage to ships and wharfs in the Devonport area. All the main port facilities are destroyed by pyroclastic surges and lava flows later in the Scenario 3 eruption, which also causes major topographic modifications to harbour morphology as lava flows block the entrance to the Waitemata Harbour. The Rangitoto Channel main access for Auckland shipping is blocked by growth of a "mini-Rangitoto" island in Scenario 1, and most of the main wharf facilities are destroyed by lava flows in Scenario 4.

Port facilities and shipping

Scenario 1(see Part 1)

Type of hazard	Nature of impact	Basic risk to service	Mitigation strategies
Tephra fall	10-20 mm on main port area (see fig.1.7, 1.8 Part 1)	High risk of temporary disruption, moderate risk of damage	Cease operation, cover vulnerable machinery, remove ships, initiate clean-up operations
Scoria rafts	Temporary blockage of entrance to Waitemata Harbour	Temporary disruption	Await natural clearance
Surges, and lava flows	Blocking of main shipping channel from port (see fig. 1.9 Part 1)	High risk of permanent disruption to port operation	Massive long term dredging operations to open channel?

Scenario 2 (see Part 1)

Type of hazard	Nature of impact	Basic risk to service	Mitigation strategies
Tephra	~1 mm fall on main port area (see fig.1.13 Part 1)	Moderate risk of temporary disruption, low risk of damage to port machinery	Cease operation, cover vulnerable machinery, initiate clean-up operations
Scoria rafts	Impede shipping in Rangitoto Channel area	Moderate risk of temporary disruption to shipping	Await natural clearance

Port facilities and shipping

Scenario 3 (see Part 1)

Type of hazard	Nature of impact	Basic risk to service	Mitigation strategies
Tephra	>50 mm fall on main port area (see fig.1.18 Part 1)	High risk of disruption, but insignificant cf. later destruction	Cease operation, cover vulnerable machinery, remove ships
	~1 mm fall on Onehunga (see fig.1.18 Part 1)	Moderate risk of temporary disruption, low risk of damage to port machinery	Cease operation, cover vulnerable machinery, initiate clean-up operations
Tsunamis	Affect Devonport	Damage to wharf facilities (insignificant cf. later destruction	Prior removal of equipment
Surges and tuff cone growth	Hot wet surges from proximal vent (see fig.1.16 Part 1)	Destruction and burial of main wharf area and Devonport, infilling of shipping channel	Prior removal of equipment
Lava flows	Further burial of wharf areas (see fig.1.17 Part 1)	blockage of Waitemata harbour entrance	N/A

Scenario 4 (see Part 1)

Type of hazard	Nature of impact	Basic risk to service	Mitigation strategies
Tephra	>50 mm fall on main port area (see fig.1.22 Part 1)	High risk of disruption, moderate risk of damage	Cease operation, cover vulnerable machinery, remove ships
	1-2 mm fall on Onehunga (see fig.1.22 Part 1)	Moderate risk of temporary disruption, low risk of damage to port machinery	Cease operation, cover vulnerable machinery, initiate clean-up operations
Lava flows	Flows enter main wharf area (see fig.1.21 Part 1)	Destruction of most of main wharf area, infilling of shipping channels	Remove portable machinery

Scenario 5

Type of hazard	Nature of impact	Basic risk to service	Mitigation strategies
Tephra	1 - 5 mm fall on main port area (see fig.1.26 Part 1)	Moderate risk of temporary disruption, low risk of damage to port machinery	Cease operation, cover vulnerable machinery, initiate clean-up operations
	>50 mm fall on main port area (see fig.1.26 Part 1)	High risk of disruption, moderate risk of damage	Cease operation, cover vulnerable machinery, remove ships

2.11 AIRPORT FACILITIES AND AIR TRANSPORTATION

Auckland International Airport (at Mangere) is the main international airport in New Zealand and is the only airport in the Auckland region to have scheduled passenger services. Scheduled domestic flights account for 65 % of air traffic, international 16 % and the remaining 18 % general aviation (defined as all flights other than regular scheduled flights by domestic and international airlines). Other Auckland region airports affected by the scenario eruptions are located at Ardmore, RNZAF Base Auckland (Whenuapai and Hobsonville) and Dairy Flat, with smaller airfields at Drury and on Waiheke Island. Airport locations are shown in Figure 2.7.

Impact of scenario eruptions (see Part 1)

Air transportation is particularly vulnerable to moderate-large tephra eruptions (as recently demonstrated during the Ruapehu 1995 and 1996 eruptions), with airports being closed by <1 mm thick tephra falls, and large airspace volumes being closed to avoid actual (or suspected) ash clouds which can cause failure of aircraft engines in flight. The Civil Aviation Authority (CAA) will restrict air-space during eruptive episodes because of drifting ash and the sulphur dioxide haze, resulting in cancellation of flights and re-routing of others away from the exclusion zones. The restrictions precluded aircraft flying in cloud or at night within these zones due to the inablity of aircraft radar to detect ash clouds. As the exclusion zones changed constantly regular briefings for pilots are required and the re-routing adds extra distance to flights, increasing fuel costs and flight times.

Acid rain and gas clouds carried downwind during and after eruptions will present a continuing corrosion hazard to exposed aircraft and airport communication/electronic facilities.

There may be possible interference to radio communications and radar affecting traffic control (see Section 2.6).

Airport facilities and air transportation

Scenario 1(see Part 1)

Type of hazard	Airports affected	Basic risk to service	Mitigation strategies
Ash clouds	All Auckland airports	Downwind airspace closed during eruption	Track ash clouds and avoid
Tephra falls (see fig. 1.7,1.8 Part 1)	Ardmore 2 mm Auck. Int. <1 mm Waiheke ~1 mm Drury ~1 mm	Airports closed until ash removed from runways and installations	Clean up after eruption
Acid rain and gas	All Auckland airports, subject to wind direction	Corrosion of aircraft and airport (communication) installations	Avoid aircraft exposure, clean up after acid rain/gas events

Scenario 2 (see Part 1)

Type of hazard	Airports affected	Basic risk to service	Mitigation strategies
Ash clouds	All Auckland airports	Downwind airspace closed during eruption	Track ash clouds and avoid
Tephra falls (see fig.1.13 Part 1)	Waiheke 10 mm	Airport closed until ash removed from runways	Clean up after eruption
Acid rain and gas	Auck. Int. Airport Ardmore, Drury	Minor corrosion of aircraft and airport (communication) installations	Avoid aircraft exposure, clean up after acid rain/gas events

Airport facilities and air transportation

Scenario 3 (see Part 1)

Type of hazard	Airports affected	Basic risk to service	Mitigation strategies
Ash clouds	All Auckland airports	Downwind airspace closed during eruption	Track ash clouds and avoid
Tephra falls (see fig. 1.18 Part 1)	Trace at all major Auckland airports,~2 mm at Waiheke	Airports closed until ash removed from runways and installations	Clean up after eruption
Acid rain and gas	All Auckland airports, subject to wind direction	Corrosion of aircraft and airport (communication) installations	Avoid aircraft exposure, clean up after acid rain/gas events

Scenario 4 (see Part 1)

Type of hazard	Airports affected	Basic risk to service	Mitigation strategies
Ash clouds	All Auckland airports	Downwind airspace closed during eruption	Track ash clouds and avoid
Tephra falls (see fig. 1.22 Part 1)	Whenuapai/Hobsonville and Waiheke ~1mm; Auck. Int. and Ardmore - trace	Airports closed until ash removed from runways and installations	Clean up after eruption
Acid rain and gas	Minor effects at Whenuapai/Hobsonville, subject to wind direction	Corrosion of aircraft and airport (communication) installations	Avoid aircraft exposure, clean up after acid rain/gas events

Airport facilities and air transportation

Scenario 5 (see Part 1)

Type of hazard	Airports affected	Basic risk to service	Mitigation strategies
Ash clouds	All Auckland airports	Downwind airspace closed during eruptions	Track ash clouds and avoid
Tephra falls (see fig. 1.26 Part 1)	Auck. Int. Airport ~20 mm; Ardmore ~1 mm Drury ~ 1 mm	Airports closed until ash removed from runways and installations (3 weeks before Auck. Int. is reopened to essential traffic)	Clean up after eruption
Acid rain and gas	Auckland International subject to wind direction	Corrosion of aircraft and airport (communication) installations	Clean up during tephra removal

2.12 OTHER IMPACTS

A volcanic eruption which occurs within or adjacent to a major city will impact on all aspects of urban life. All the possible impacts in this study have not been considered, in part because of the higher level of detail needed which is beyond the scope of the report (e.g. locations of petrol stations and hazardous chemical stores), but also because there are no closely analogous eruptions which have occurred within a modern city. Some impacts not considered are the effects of pyroclastic surges and lava flows on (a) petroleum storage tank farms, and petrol and LPG and CNG service stations; and (b) hazardous and inflammable chemical stores (destruction of which could produce widespread secondary effects). A review of volcanic impacts on animals and plants is given in Appendix 3. Other factors not considered include the difficulty of reliably identifying the end of an eruption episode (so that rebuilding could commence), and the closely-related downstream economic effects which would follow an eruption (loss of business confidence, loss of market, loss of staff, loss of access to supplies, insurance availability and premium loadings etc). An assessment of economic effects should be considered as part of a comprehensive risk assessment.

2.13 CONCLUSIONS

* Lava flows, ballistic block impacts, pyroclastic surges and lightning strikes from ash clouds present a high risk to life, and destroy near-vent structures in the scenario eruption-affected areas, but the extent of these hazards (in a typical Auckland eruption) is mostly limited to within a few kilometres of the vent. Severe near-vent ground shaking accompanying volcanic earthquakes will also damage buildings, possibly also in areas not greatly damaged by eruption products. Apart from the evacuation of people and removal of transportable assets (<5 km) (if possible) there are few or no mitigation options available to counteract any of these near-vent hazards, which apply to all structures.

* Evacuation, where necessary to save lives in high-risk, near-vent areas (affected by lava flows, ballistic block impacts, pyroclastic surges), should be carried out before an eruption commences, and would have to be completed before the eruption peaks. Elsewhere, later evacuation of people may became necessary in areas where loss of services (electricity, water supply, sewage) makes continuing habitation untenable.

* The various scenario impacts illustrate the vulnerability of urban areas where the deposition of a few mm-cm of ash is sufficient to cause disruption of transportation, electricity, water, sewage and stormwater systems. Most systems, if affected only by

thin tephra fall (<50 mm), can be restored within a few days to weeks.

* Falls of volcanic ash can disrupt electricity supply. Weather conditions will influence how falling ash adheres to insulating surfaces, with power outages occurring if the ash is wet (i.e. conductive). Low voltage systems are more vulnerable than higher voltage systems due to smaller weather sheds on insulators. Most outages are usually of short duration. The abrasive nature of ash can cause damage to mechanically moving parts, such as cooling fans. Immediate ash removal is the best mitigation option to prevent widespread outages.

* Volcanic ash falls can cause severe damage to sewage and stormwater systems. The most effective mitigation measure to lessen the affects of ash falls is to reduce the input of ash into the system. Sewage treatment plants can be severely affected by ash falling directly on the plant or by the receipt of ash-laden sewage. Bypassing and/or shutting down parts of the plant may need to be considered to reduce the likelihood of damage.

* Water supplies are vulnerable to contamination by ash fall into storage lakes preventing their use, and to excessive water demand during post-eruption ash clean-up operations. Water management plans will be required to manage excessive demands and should include procedures to fill service reservoirs (if possible) on receipt of an ash fall warning, when appropriate public information messages outlining water conservation measures should also be broadcast. There is also a need to retain a fire fighting potential.

* Urban areas in the region will be forced to undertake expensive and time-consuming clean-up operations as a consequence of any of the scenario eruptions. In each case there will be a need to develop coordinated community-wide ash-removal plans, which identify appropriate methods of ash removal, collection and disposal. The public will need to be adequately informed on how to deal with volcanic ash.

* Relatively long term effects on people, animal and vegetation health, and on corrosion/deterioration of metallic and other materials may result from volcanic gas clouds (notably SO_2 and HCl) and acid rain carried downwind from vent areas. Release of volcanic gases may continue long after eruptive activity has ceased.

* This eruption scenario/impact exercise has highlighted the value of emergency management planning that will identify likely impacts on community lifelines and strengthen the links between agencies that will have to respond to such events. This needs to be done well in advance of any volcanic activity. Emergency managers need to agree on the early and proactive responses to warnings.

* The social and economic impacts of an eruption in Auckland will be determined not only by direct physical consequences but by the interaction of social, cultural and institutional processes that can amplify and attenuate the public response. Consideration of social and economic impacts must therefore be incorporated in comprehensive hazard management.

* The time required for the community to recover from a volcanic eruption depends on the extent of the impacts and the amount of assistance available. Physical, economic and social recovery planning can reduce this period and minimise ongoing social and economic effects.

APPENDICES

APPENDIX 1 REVIEW OF IMPACTS OF HISTORIC ERUPTIONS ON COMMUNITY "LIFELINES"

A1.1 INTRODUCTION

A number of types of hazards result from volcanic eruptions. The most likely hazards in Auckland include pyroclastic falls (ash falls and projectiles), pyroclastic surges, lava flows, volcanic gases, volcanic earthquakes and atmospheric effects.

A1.2 PYROCLASTIC FALL

Pyroclastic material is produced by three basic processes: (1) degassing of rising magma producing bubble growth and fragmentation, (2) explosive mixing of magma and water, (3) fragmentation of country rock during rapid expansion of steam and/or hot water (Heiken 1994).

A1.2.1 Projectiles

Large fragments (blocks and bombs; > 64mm) follow ballistic trajectories and are termed projectiles. These fragments may land in a near-molten state and are capable of starting fires but rarely land more than 1-2 kilometres from a vent (Blong 1984). The impact of ballistic clasts will cause damage to buildings, with degree of damage dependent on projectile mass and velocity (Blong 1981, 1984). Clasts that are ejected hot have ability to ignite buildings. In the 1973 eruption of Heimay (Iceland) incandescent clasts ranging from 0.1 to 2m across were ejected and caused fires (Self *et al.* 1974).

A1.2.2 Convected air fall

Finer material (ash, <2mm; and lapilli, 2-64 mm) is convected upwards in the eruption column (Self & Walker 1994) before settling out downwind to form pyroclastic fall deposits (tephra). Ash can be deposited to hundreds of kilometres from vent, making volcanic ash the product most likely to affect the largest area and the most people during an eruption.

A community's infrastructure ("lifelines") are vulnerable to disruption and damage from pyroclastic falls, with impact severity largely related to tephra thickness. Pyroclastic falls will not initially result in fatalities unless the fall is extremely heavy, or where victims are hit by projectiles (Baxter 1990). Falling ash is not toxic but will act as an irritant affecting eyes and throats. Deaths and injuries are more likely to result from secondary effects such as roof or veranda collapse, and falling branches or other accidents.

A1.2.3 Impacts of volcanic ash on transportation

Road Volcanic ash falling on roads can be extremely disruptive causing reduced visibility, traction problems and damage to vehicles, resulting in reduced speed limits or even road closures.

Reduction of visibility on roads is commonly reported during and after ash falls (see Table A1.1), and during heavy ash falls total darkness may result (Blong 1982). Dry ash is easily raised in clouds by passing vehicles and presents an ongoing hazard. Wet ash can turn to mud causing further problems to vehicle traction, as seen in and around Rabaul, after the 1994 eruption (Blong & McKee 1995). Ash fall deposits will absorb a considerable amount of water before being washed away. Thin ash (<5 mm) will generally be moved to the shoulder of roads by roadway traffic but will remain there. Greater thicknesses of ash will need to be physically removed.

Warrick et al. (1981) conclude from experience after the 1980 Mount St Helens eruption:

> *"Ash depth had little influence on the initial level of impacts on the transportation systems. On the other hand ash depth had direct influence on the length of recovery time for most transportation systems".*

In most cases vehicles remain operative during ash falls (i.e. Pinatubo 1991, Mt Spurr 1992, Rabaul 1994, Ruapehu 1995-1996). Fine dry ash can result clogging of air-filters, causing vehicles to over-heat. This was a main cause of vehicle strandings, in heavy ash fall areas, after the 18 May 1980 Mt St Helens eruption (Schuster 1981).

Ash entering the engine causes wear on moving parts, reducing their life. In most cases severe damage results from excessive use in an ash-rich environment. A number of ash-affected communities report keeping damage to a minimum by initiating preventive maintenance programmes (i.e. changing oil, oil filters, air-filters etc). The abrasive ash can also damage vehicle brakes, exterior fittings, paintwork and windows.

TABLE A1.1 Examples of ashfall impacts on road transport

Volcano and year	Road closures	Reduced visibility	Vehicle damage	Traction problems	Reference
Hudson					Bitschene 1995
1991		*	*		
Mt St Helens					Blong 1984, Warrick *et al.*
1980	*	*	*		1981 Schuster 1981
Pinatubo					
1991		*	*		Rudolfe 1995
Rabaul					
1937	*		*	*	Johnson & Threlfall 1985
1994	*	*	*	*	Blong & McKee 1995, Finnimore *et al.* 1995
Ruapehu					
1945		*	*		Johnston & Neall 1995
1995	*	*	*	*	Houghton *et al.* 1996
Unzen					
1990-1992		*			Yanagi *et al.* 1992

Secondary problems consequent on road closure will include loss of access for emergency services, stranding of travellers, disruptions to food supplies and economic impacts on businesses. Where roads remain open, speed restrictions may need to be introduced to ensure motorist safety on roads with reduced visibility.

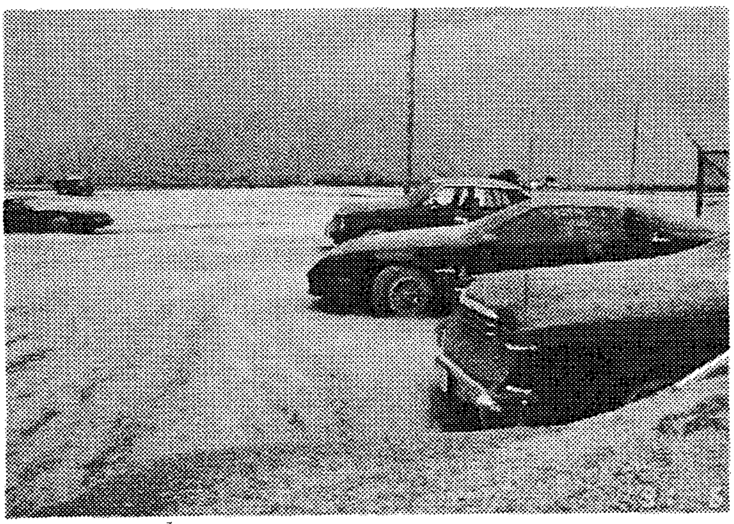

FIGURE: A1.1
Ash from Pinatubo covering vehicles at Clark Air Force Base.

Railways Rail transportation is vulnerable to volcanic ash, with disruptions caused by poor visibility and breathing problems for train crew. Trains will stir up fallen ash, affecting residents close to railway tracks. Light rain on fallen ash may lead to short-circuiting of signal equipment. Fine ash may enter engines causing wear on moving parts.

Blong (1984) describes a number of examples of disruption of rail services. The 18 May 1980 eruption of Mount St Helens severely disrupted rail services in eastern Washington (Warrick *et al.* 1981). In areas receiving ash, train crews reported almost zero visibility and train services were suspended. Operations resumed within 24 hours of the end of ash falls. Speed restrictions were put in place for the following nine days to combat the raising of dust clouds. Rain several days after the eruption caused numerous short-circuits of track signals. Despite the problems, rail was the least disrupted of the transport systems.

Air-transport Air-transportation is extremely vulnerable to volcanic ash (Casadevall 1993, Miller 1994, Ziner 1994). Drifting volcanic ash can affect large volumes of air-space commonly resulting in its closure. Severe impacts can result from aircraft-ash encounters, with seven aircraft losing in-flight jet engine power over the past 15 years world-wide (Casadevall 1993). Luckily, to date, no aircraft have crashed as a consequence of such encounters. Even minor ashfalls on airports will render them inoperative and can damage aircraft and facilities (Labadie 1994). The removal and disposal of ash can be a time-consuming and costly operation.

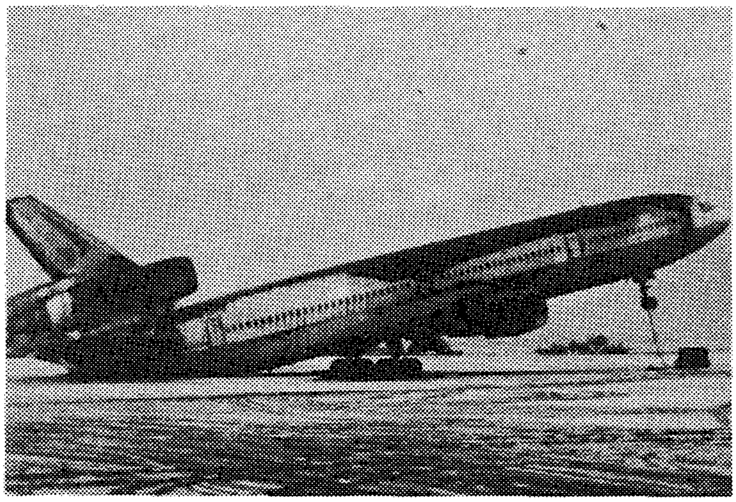

FIGURE: A1.2
World Airways DC-10 aircraft at Subic Bay airport, settled on its tail due to the weight of ash erupted from Pinatubo, 1991 (*photo by R.L. Rieger, U.S. Navy*)

Conclusions Ash falls will cause severe and widespread disruptions to transportation links over wide areas. Air-transport is the most widely affected sector due to closure of air-space and airports. Ash falls reduce visibility on roads and may damage vehicles. Falls of only a few millimetres frequently require time-consuming and expensive ash removal operations before roads and airports can re-open. Rail is commonly the least disrupted transport system.

A1.2.3 Impacts of volcanic ash on water supplies

Contamination can take a number of forms resulting from physical and chemical changes in affected supplies. The most common contamination problem results from the suspension of ash in water (turbidity). Limits for potable water quality for turbidity are easily exceeded by suspended ash; high turbidity can interfere with the disinfecting process at water plants.

Freshly fallen ash readily releases soluble components (leachates), resulting in changes to local water chemistry. Leachates are sourced from surficial coatings of soluble components on individual ash grains and from the release of soluble elements and compounds from within grains (minerals or solid solution glass). The soluble coatings are derived from the interaction of ash particles with aerosols in the eruptive column. Aerosols are principally composed of sulphuric and hydrochloric acid droplets containing absorbed halide salts. The scavenging of aerosols by ash is most active close to the volcano (<50 km). This is indicated by observations that show the amounts of water-soluble material associated with ash falls decrease with increasing distance from source (Smith *et al.* 1983). The amount of available aerosols vary greatly between eruptions of similar volumes (Bernard & Rose 1990).

The flushing of soluble components from surfaces of ash particles is the main initial source of leachates. The most common leachates rinsed from freshly deposited ash are Cl, SO_4, Na, Ca, K, Mg, and F (Smith *et al.* 1982). Other elements reported but in lower concentrations are Mn, Zn, Ba, Se, Br, B, Al, Si, Cd, Pb, As, Cu and Fe. Most of these elements and compounds are naturally present in ground and surface water but become hazardous above certain concentrations. Finer ash deposits have larger surface areas per unit volume allowing them to carry more soluble ions (e.g. F) and moisture than coarser deposits. This is significant because smaller particles travel greater distances from the vent, thus extending the zone of possible contamination. The potential for chemical contamination of water supplies or pollution of rivers and lakes will depend on the ratio between the volume of water contaminated and amount of leachate delivered.

The release of Cl^- and SO_4^{2-} ions from water soluble salts in volcanic ash will lower the pH of water, possibly beyond the acceptable safe limits for potable water supply. Any changes in pH of surface and groundwater will be influenced by the buffering effect of soil. This is affected by the ability of soil to absorb pH changes (Hausenbuiller 1978).

Indirect impacts can result from ash causing physical damage to filters at intake structures and/or treatment plants, greater susceptibility to wear of plant, and interference with electrical equipment. Other indirect problems can occur as a result of increased water demand for clean-

up by residents of communities affected by ash fall.

Historic examples of potable water supply contamination Contamination of water supplies has been reported subsequent to a number of historic eruptions. The most common problems were the result of unacceptable pH and turbidity levels (Blong 1984, Collins 1978, Le Guern *et al.* 1980, Wilmox 1959), but hazardous chemical changes have been reported in a few cases (Blong 1984; Collins 1978; Oskarsson 1980; Thorarinsson 1979). Excess fluorine is recognised as the most hazardous circumstance.

Conclusion Contamination of open water supplies is possible even from relatively small ash falls. Both turbidity and acidity will usually return to normal levels within a few hours to days unless ashfalls are prolonged. Adverse affects on covered water supplies are minimal. Hazardous changes in water chemistry are rare; except close to a volcano where small volumes of water (such as roof-fed water tanks, stock water troughs and shallow surface water bodies) can be contaminated by ash leaching to levels that exceed guidelines for potable water. Levels of contaminants in streams, rivers and lakes may also be elevated for short periods. Observations of historic eruptions show that concentrations of hazardous leachates in ash decrease with distance from the vent, and few examples of serious chemical contamination of potable water supplies exist. Excess fluorine is recognised as the most hazardous circumstance.

A1.2.4 Impacts of volcanic ash on sewage and storm water systems

Sewage and stormwater systems are vulnerable to damage from volcanic ash falls (White *et al.* 1980, Day & Fisher 1981, F.E.M.A. 1984, Schuster 1981, Warrick *et al.* 1981; Blong 1984), which may include; blockage of pipes, damage to pumps and other machinery and interference with sewage treatment processes.

Ash falls can cause serious problems to urban sewage and storm water systems. Ash which falls on impervious surfaces, such as roads, roofs and other paved areas, is easily washed into the stormwater system by rain, or during cleaning up operations. Ash may enter the sewage system via illegal connections, manholes, gully traps or the stormwater system if inter-connected. The mean grain-size and density of ash particles decreases with distance from an erupting volcano with finer ash entering the system more easily. The density of ash is usually too high for most water velocities in the sewer or stormwater system to hold a significant amount of it in suspension, therefore ash deposits will tend to collect easily. Finer ash may remain in suspension and be transported to the sewage treatment plant. Where pipes are blocked local flooding may occur. Sewage pumps may also be damaged by ash-laden sewage or fail due to loss of electricity (due to the affects of ash on the electricity supply system). This may result in the banking up of sewage in urban areas. The removal of ash from sewage and stormwater

systems will be a time consuming and costly exercise.

Sewage Treatment Plants Ash-laden sewage may enter the treatment plant overloading solid removal equipment at the pretreatment and primary treatment stages. Milliscreens, mechanical grit/sludge removal mechanisms, comminutors and other equipment that comes into contact with ash-laden sewage are likely to be damaged. Ash falling directly into sedimentation tanks will add to the volume of material that will eventually have to be removed. Ash entering secondary treatment facilities, such as oxidation ponds or biofilters will reduce or halt the oxidation process until such time as the ash settles out or is removed. The ash may affect the acidity or toxicity level of the effluent to an extent that bacteria growth is damaged or lost. Release of untreated sewage may result from failure of the plant and/or deliberate shutdown. Problems may also be caused by loss of electricity to treatment facilities, due to the effects of ash falls on electricity supply systems.

TABLE A1.2 Examples of ash-affected urban stormwater and sewage systems.

Volcano, year, affected town	Ash thickness (mm)	Impact	Reference
Mt St Helens - 1980			
Moses Lake	25	Stormwater blocked, sewerage rendered inoperative,damage to plant.	Schuster 1981
Yakima	10	Stormwater blocked, sewerage rendered inoperative,damage to plant.	Schuster 1981
Spokane	5	Stormwater filled with ash, sewage plant received ash but remain operative.	Schuster 1981
Ellensbury	3	Stormwater system overloaded in a number of places but city employees kept the system open using high-pressure water jet sewer cleaners.	Warrick *et al.* 1981
Mt Spurr - 1992			
Anchorage	3	Ash settled in stormwater system and caused some local flooding during the spring thaw.	pers. com. City of Anchorage
Ruapehu - 1996			
Rotorua	1	Small amount of ash removed from stormwater but no major problems reported.	pers. com. Rotorua District Council

Conclusion Ash falls can cause severe damage to sewage and stormwater systems. Ash is easily washed from impervious surfaces, such as roads, carparks and buildings and can enter the systems. The most effective mitigation measure is to reduce the input of ash into the systems. Sewage treatment plants can be severely affected by ash falling directly on the plant or by the receipt of ash-laden sewage. Bypassing and/or shutting down parts of the plant may need to be considered to reduce the likelihood of damage.

A1.2.5 Impacts of volcanic ash falls on electrical distribution systems

Volcanic ash can cause a number of problems to electrical distribution systems. Investigations on the effect of ash (Nellis & Hendrix 1980; Stember & Batiste 1981; Sarkinen & Wiitala 1981; Heiken *et al.* 1995) showed that:

* *Dry volcanic ash is not conductive enough to cause insulator flashover problems.*
* *The presence of moisture with ash is the critical factor in initiating insulator flashovers if insulating surfaces are completely coated, since ash contains soluble leachates which makes ash conductive when wet.*
* *Finer ash has a high conductive potential since it has a higher surface area per unit volume therefore can absorb more soluble components and moisture.*
* *Weather conditions at the time of ash fallout influences how ash adheres to and how it affects insulating surfaces. Dry ash sticks generally to horizontal surfaces and causes no immediate electrical problems. Wet ash sticks to all exposed surfaces and causes electrical insulation problems.*
* *Insulation that has 30% or more of its creepage distance either clean or dry has a low probability of initiating insulator flashovers.*
* *Lower voltage insulation has smaller weathersheds and is more prone to becoming completely covered with ash and water.*
* *Because of the shape and orientation of many bushings and insulators, substation insulation is more susceptible than line insulation to flashovers caused by volcanic ash.*
* *Heavy rain was found to wash off about 2/3 of ash from insulators, whereas light rain removed little ash. Wind up to 55 km/hr removed 95% of dry ash.*
* *Ash that falls dry on dry surfaces is easily cleaned by air blast and brushing. Ash that falls wet or is wetted before cleaning is not easily removed without high pressure water or hand cleaning.*
* *Ash contamination on insulators and conductors increases corona activity which in turn causes increase in audible noise and radio interference.*
* *Epoxy insulators are especially vulnerable to tracking and flashovers therefore porcelain insulators are now used widely in the region.*
* *Volcanic ash is a contaminant which abrades and clogs mechanically moving parts. Precautionary measures are needed to service and maintain substation equipment.*
* *Saturated volcanic ash on switch yard gravel has the potential to be hazardous due to its conductivity.*
* *Wet ash-laden tree limbs may fall on distribution lines.*

During the 1980 eruption of Mt St Helens volcanic ash disrupted the electricity supplies of several communities in Washington State, USA (Nellis & Hendrix 1980). The impacts were

largely dependent on the weather prevailing at the time. The main 18 May eruption occurred during dry weather and ash did not cause immediate problems except for a few short-duration outages and ash adhesion to horizontal surfaces. Outages occurred a few days later in areas that received rain. Ash falls from the smaller 25 May eruption occurred accompanying rain fall. Low voltage lines and substations experienced numerous outages from insulator flashovers in areas of >5 mm ash thickness when the ash was wet. A number of wooden electricity poles catching fire were reported. The ash conductivity was found to increase with decreasing grain size and the problem of insulator flashovers increased with distance from the volcano. The 12 June ash fell dry but later rain wetting caused subsequent outages.

Conclusions Falls of volcanic ash can disrupt electricity supply. Weather conditions will influence how falling ash adheres to insulating surfaces, with outages only occurring if the ash is wet (i.e. conductive). The presence of moisture with ash is the critical factor in initiating insulator flashovers if insulating surfaces are completely coated, since ash contains soluble leachates which makes ash conductive when wet. Finer ash has a high conductive potential since it has a higher surface area per unit volume, therefore can absorb more soluble aerosol droplets and/or moisture. Low voltage systems are more vulnerable than higher voltage systems due to smaller weather sheds on insulators. Most outages are usually of short duration. The abrasive nature of ash can cause damage to mechanically moving parts, such as cooling fans. Immediate ash removal is the best mitigation option to prevent wide spread outages. The consequences of loss of electricity are widespread, and a number of public utilities will be inoperative for the duration of the power loss.

A1.2.6 Impacts of volcanic ash on buildings and building services

Volcanic ash can cause damage to buildings and building services in several ways; overloading roof strengths causing collapse, soiling interiors, damaging services (electrical and mechanical) and damaging exterior materials. The effects of ashfalls on structures depends on the thickness of ash, soluble components, ash density, water content, the building's roof form, construction, orientation, and the spacing of other buildings nearby.

Loading of ash Building failure or damage may occur due to ash loading on roofs, and against walls or foundations (Bitschene 1995, Blong 1981 & 1984, Blong & McKee 1995, Johnson & Threlfall 1985).

The loading of a building is given by the equation:

$$L = \frac{dpg}{1000}$$

where L is volcanic ash load (kPa)
d is ash depth (m)
p is ash density (kgm^{-3})
g is gravitation (9.8 ms^{-2})

Observed ash falls commonly show a compaction reduction in thickness of around 50%, even without the effects of rain. Such compaction increases the density of the ash cover but not its weight. The loading caused by ash depends on its thickness, density and whether it is dry or wet. Densities range from about 500 kgm^{-3} for dry uncompacted ash to more than 2000 kgm^{-3} for a compacted very wet ash.

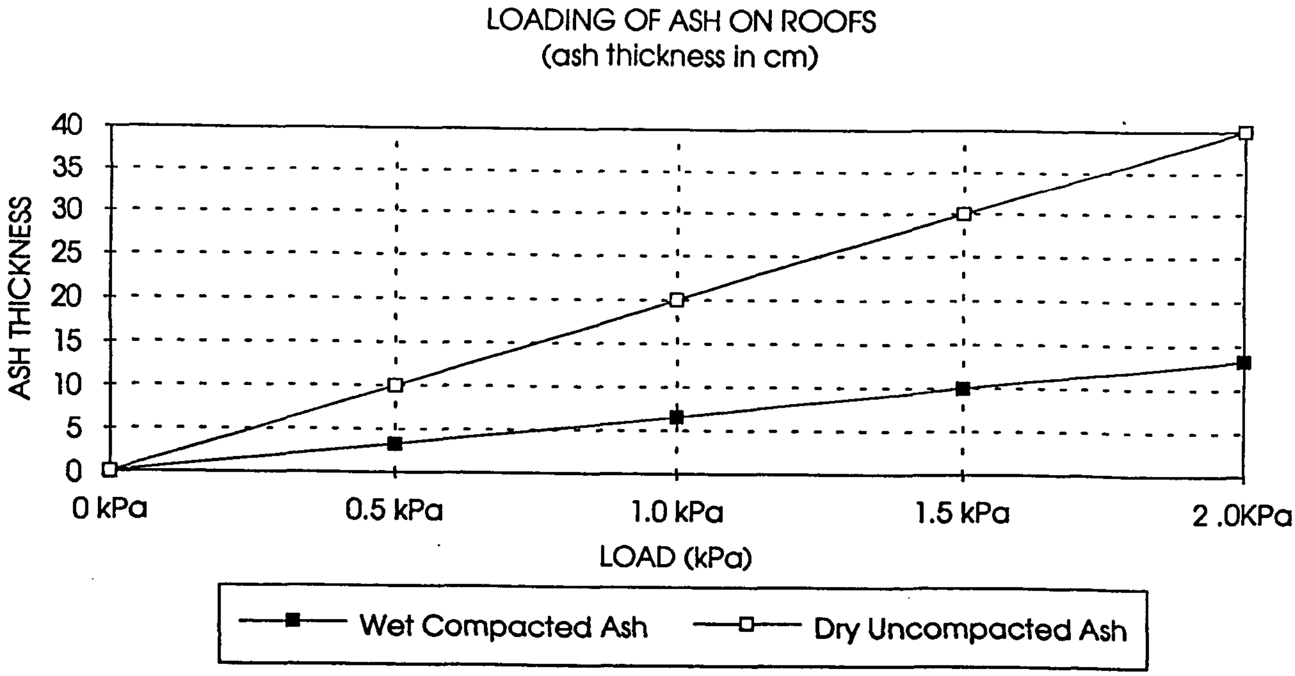

FIGURE A1.3: Loading of tephra on a roof for (a) wet compacted ash, and (b) dry uncompacted ash. The uncompacted ash is assumed to have a density of 500 kgm^{-3}. The wet ash is assumed to have a dry (compacted) density of 1000 kgm^{-3} and a saturation of 50% water by volume and therefore a wet density of 1500 kgm^{-3}.

Blong (1984) gives several examples of roof collapse under ash falls and concludes that 100 mm appears to be a critical threshold. In most cases where ash fell to a thickness <100 mm only a proportion of building suffered roof collapse and/or damage.

Blong & McKee (1995) describe the damage done to building during the 1994 Rabaul eruption. They conclude that:

> *"The damage sustained by roofs under the load of volcanic ash is undoubtedly a function of many key factors including ash thickness, ash bulk density, the moisture content of the ash, extent to which ash drifts (creating unbalanced dynamic loads), roof span and support systems, construction materials, roof slope and age and maintenance of the building."*

They are unclear as to the relative importance of all of these factors. A summary of their Rabaul observations is shown in Table A1.3

TABLE A1.3 The effect of various ash loads on buildings in Rabaul. (from Blong & McKee (1995)

Ash thickness*	Observed damage to roofs
< 100 mm	Roofs and guttering generally remaining intact
< 200 mm	80-90% of roofs remained intact with little apparent damage. Sagging or partial collapse occurred in some buildings
< 300 mm	More than 50 % of roofs did not collapse
500 - 600 mm	More than 50% of roofs collapsed.
>600 mm	It is doubtful that buildings survived without significant damage even though the roof remained relatively intact

*** Ash fell wet**

Ash can slide off steeply pitched roofs, but even moderate pitches can be less susceptible to collapse than flat ones. During the heavy ash falls on the town of Vestmamaeyar, Iceland, in 1973, houses with roofs sloping at angles $> 20\,^{\circ}$ suffered little damage from ash loading.

Obstructions such as parapets, roof tanks or solar panels may cause the accumulation of ash. Roof guttering was one of the most susceptible parts of the house to damage (Blong 1984). After rain, gutters may fill with ash and pull away from houses. Penetration of fine ash into the

ceiling may lead to its collapse.

Damage to exterior materials Acidic ash and associated soluble components can lead to premature ageing and weakening of cladding and other building materials. Most metal roofing used in New Zealand is hot-dipped zinc or zinc/aluminium coated (galvanised) steel, with an additional paint cover. Zinc has a high resistance to atmospheric corrosion due to the development of an insoluble basic carbonate film that protects the surface. However, sulphurous and sulphuric acids are extremely corrosive to almost all metals (Bradford 1992). These acids ionise to H^+ ions and electrode processes occur on the corroding metal surface in contact with the acids. Although rain can release the acidic soluble components from the ash, it will wash off these contaminants and actually reduce corrosion. Unwashed areas such as under eaves, unlined soffits, spouting, overhangs, sheltered walls and the upper part of garage doors may be vulnerable to corrosion if ash infiltration occurs. These areas seldom receive the benefit of rain-washing and as condensation, dew or humidity moistens the ash, a corrosive reaction may take place.

The 1995-1996 Ruapehu eruptions deposited a few millimetres of ash on several North Island towns. In most cases the ash falls were a nuisance but a few insurance claims (~25) for damage were received by the Earthquake Commission. The majority of claims were for damage to roofs resulting from the reaction between ash and galvanised steel and/or paint. Acrylic paint, if it had been applied within the past 3 - 6 months, was found to be susceptible to the acidic nature of volcanic ash.

Metal corrosion resulting from ash falls has been studied by Matsumoto et al (1988) during eruptions of Sakurajima volcano in Japan. Corrosion strongly correlated with volcanic ash and its concentration of soluble components, and concentrations of SO_2 and fluorine compounds in the atmosphere. The degree and rate of metal deterioration decreased in order from, aluminium, steel, galvanised steel, copper, stainless steel.

Soiling interiors Ash can enter a building by a number of routes ranging from open doors and windows to small gaps between roofing iron or tiles and even closed doors and windows (Deguchi 1988). Even small amounts of ash entering buildings can result in considerable amounts of time spent on its removal (Dillman & Roberts 1982). Fine ash can easily penetrate carpets.

A survey of damage from repeated ash falls from Sakurajima volcano on the cities of Kagoshima and Tarumizu found the finer the ash the easier it is to penetrate buildings (Deguchi 1988). Ash that had built up in gaps promotes surface tension thus drawing in water and causing a tile roof to leak. Leaking also occurred as a result of rusty nails caused by corrosion

Ash on outer walls and windows leads to soiling especially when combined with rain.

Damage to Services The highly abrasive and mildly corrosive nature of ash is a threat to mechanical and electrical appliances. Air-conditioning units are vulnerable to ash damage and filter blockage. Penetration of ash into the electrical system can lead to short-circuiting and fires. Computer systems are also vulnerable to ash damage.

Conclusions Volcanic ash loadings can exceed roof strengths causing collapse, soiling of interiors, damaging services (electrical and mechanical) and damaging exterior materials.

A1.2.7 Impacts of volcanic ash falls on communications

Communications can be severely disrupted around an erupting volcano. Disruptions may result from interference to radio waves due to atmospheric conditions, overloading of telephone systems due to increased demand, direct damage to communications facilities, indirect impacts resulting from disruption to electricity supplies or transportation of communication workers (preventing operations or maintenance).

Large quantities of electrically-charged ash can be generated in an eruption column (Anderson *et al.* 1965, Gilbert *et al.* 1991, Gilbert 1994), causing interference to radio waves. Radio communications were inoperative for four days following the 1912 Katmai eruption on Kodiak Island, 160 km from the vent (Erskine 1962). Clicks of radio static were observed from a passing ship during the 1963 Surtsey eruption (Anderson *et al.* 1965). However, there are numerous examples of radio communications continuing to function around an erupting volcano and in areas receiving ash falls (e.g. Mount St. Helens 1980, Pinatubo 1991 and Ruapehu 1995-1996.).

During most natural disasters, telephone and radio communications are susceptible to overloading by public and emergency services use. Telephone systems were overloaded in communities receiving ashfalls during the 1953 Mt Spurr eruption (Wilcox 1959) and the 1980 Mt. St Helens eruption (Dillman *et al.* 1982).

Ash entering telephone exchanges can cause damage to electrical and mechanic systems and general damage to buildings.

Conclusions Communications are a vital part of everyday life and critical in any emergency. Radio, TV and telephone communications are very vulnerable to disruption during a volcanic eruption, and may fail completely in eruption-affected areas. Loss of communications will make disaster management extremely difficult during and following an eruption.

A1.2.8 Ash removal and disposal

Ash removal from roads The removal of ash may be required from urban areas after the fall of only a few millimetres. A number of factors such as the thickness, grain-size and the availability of equipment will influence the removal-method employed, the ease at which ash can be removed and the cost of any clean-up operation. Removal of ash from roads was undertaken by a number of council and works department after the 1980 Mount St. Helens eruption. Few, if any of these organisations had developed plans for ash-removal prior to the eruption and little knowledge of how to undertake this was available (Saarinen & Sell 1984). A range of methods were tried during initial clean-up operations (Hoff 1980, Markesino 1981, Novak & Zais 1981). The best method found was to sprinkle the ash with water, blade it to the side or middle of the road for pick-up using belt or front-end loaders and then use power-broom or more water to remove the remainder (see Appendix 2 for more details). Prior to ash removal, dust retardants have been used to control wind blown ash. "Coherex", an emulsion of petroleum resins, was use as a dust retardant in Oregon (Public Works 1981).

In addition to roads, ash may need to be removed from other paved areas like car parks and airport tarmacs. Similar techniques, described above, have been used. Tyler & Reynerton (1981) describe the clean-up operation at Fairchild Airforce Base, USA after ashfalls from Mount St Helens in 1980. Water was used to wet the ash, graders, snowplows and snow brows worked the ash and loaders picked it up. It was then hauled to a central location, where it was buried using landfill techniques. It was noted that around buildings, the wind blowing ash from roofs tops constantly contaminated previously cleaned areas.

Ash removal from buildings Sweeping dry ash from roofs was found to cause clouds due to the fine particle size of the ash and this slowed the cleanup process (Dillman & Roberts 1982). Wetting down the ash formed a cohesive "glue-like" material, which was not easy to remove and added weight to the deposit. Lightly damping the ash and then sweeping it was found to be the best method for removal ash from roofs. Highest priority should be given to removing ash from roofs for four reasons (F.E.M.A. 1984).

i) *It is a prerequisite to reactivate the ventilating and air-handling system.*
ii) *It is fruitless to clear ground level areas for them to be recovered by windblown ash from roofs above.*
iii) *The rapid removal may prevent the possibility of catastrophic roof collapse.*
iv) *Ash removal from public buildings will enhance morale and confidence of the public if they observe the rapid cleanup and prompt functioning of local buildings.*

See Appendix 2 for more details.

FIGURE A1.4
Belt-loader removing Mount St. Helens ash from a Yakima (USA) street, May 1980. (*photograph: Public Works, City of Yakima*)

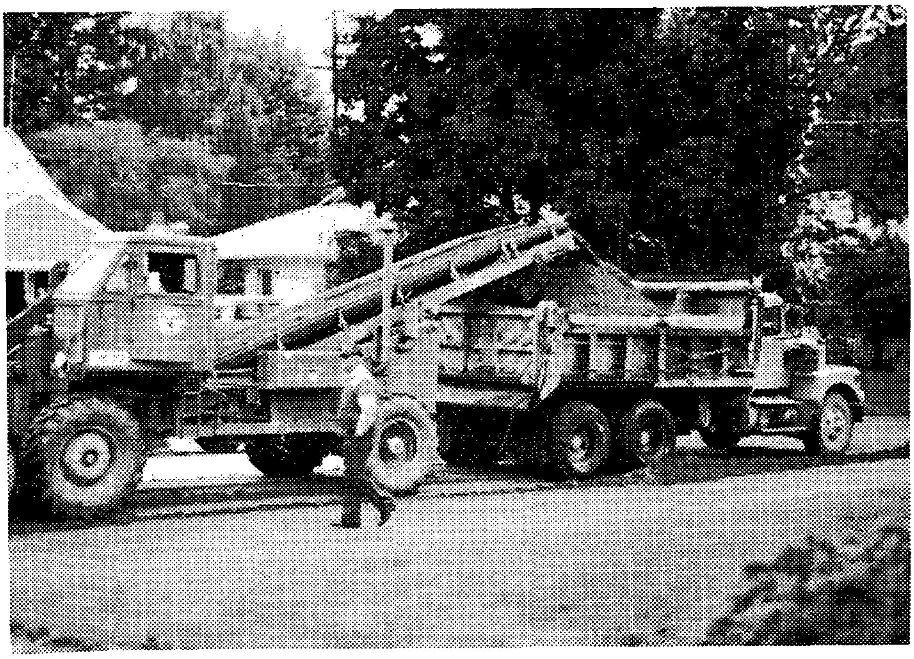

FIGURE A1.5
Mount St. Helens ash from a Yakima (USA) street being loaded into a truck before transportation to a dump site, May 1980. (*photograph: Public Works, City of Yakima*)

Disposal of Ash The fall of a few millimetres of ash on an urban community will result in the need for disposal of large quantities. The disposal of ash should be done in a way that minimises ongoing public health problems and is cost-effective. An ash dump, left uncovered, will result in ash being easily blown from the dump.

Methods of stabilizing the dump will need to be employed such as covering with top soil or hydraulic seeding. Ash is generally a good fill, has a good bearing strength, mixes well with soil and will support vegetation if fertilized (F.E.M.A. 1984).

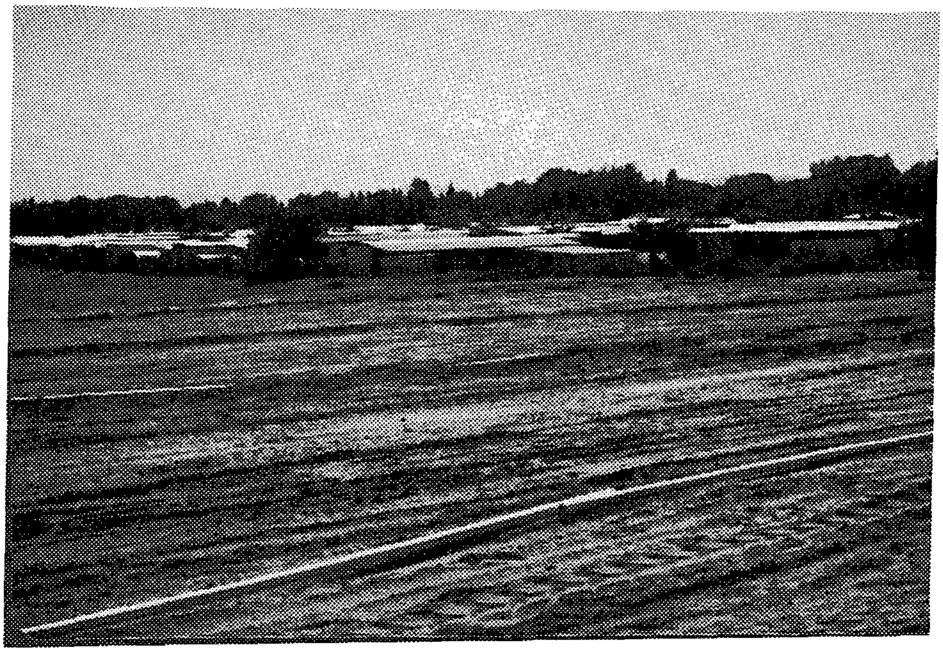

FIGURE A1.6
Ash dump in Yakima (USA) containing 70000 m^3 of Mount St Helens ash, prior to covering by 50 mm of top soil, in 1980. Underground sprinklers were installed to aid compaction. *(photograph: Public Works, City of Yakima).*

A1.3 PYROCLASTIC SURGES

Phreatomagmatic explosions commonly produce rapidly rising, steam-rich vertical eruption columns surrounded by ground-hugging turbulent mixtures of steam and solid ejecta that flow out laterally from the base of the eruption column. People caught in the direct path of pyroclastic surges are most unlikely to survive and any survivors will probably receive severe injuries. Buildings offer some protection on the surge periphery, but will not guarantee survival as the building may be destroyed or severely damaged. The best protection is to evacuate the near-vent area prior to eruption.

Pyroclastic surges travel at high initial velocities and vary from dry mixtures of gas, steam and ash to wet surges with gas, steam, ash and water. Dry surges tend to sandblast objects with a mixture of ash and superheated gas and steam. The ash-laden wind causes varying degrees of

damage to structures depending on its temperature, duration and the amount of solid material it is carrying. Buildings near the vent will be totally obliterated, with the possible ignition of combustible material. Structures near the margins of the surge may be less damaged, as the surge velocity decreases, but damage will still be caused by clast impact. The possibility of ignition exists if the surge is still sufficiently hot.

Surges from phreatomagmatic eruptions are often wet containing both steam and water. They are more dense than dry surges and tend to decelerate more rapidly and deposit sticky wet ash. This wet ash will often cause the collapse of structures it buries due to loading as described in the previous section (pyroclastic fall).

A wet surge deposit will have a density between 1300 - 2000 kg/m^{-3}. In the Tarawera eruption of 1886, surges from Rotomahana overwhelmed the Maori village at Te Ariki, burying it under several metres of ejecta. The surges travelled more than 6km from source. In the 1966 eruption of Taal, (Moore *et al.* 1966, Moore 1967) sandblasting occurred as far as 6km from the vent. The was no evidence of charring or burning. The damage from the surge is shown in Table A1.3.

TABLE A1.3 Surge damage produced by the 1965 eruption of Taal, Philippines

Distance from vent	Impact
0.5 - 1.0 km	All trees and stumps removed
1.0 - 1.25 km	Trees remain but strongly sand blasted. Little or no coating of mud.
1.25 - 6 km	Blast recorded by mud coatings, stripping of bark of trees, breakage of bamboo, deroofing of houses, stripping of palm tree fronds on the blast side and faint scarring of small bushes.

Pyroclastic surges can destroy infrastructural facilities. Any associated structures above ground will mostly likely be destroyed or severely damaged. Pipes which are on the surface may also be vulnerable. Where pyroclastic surges enter reservoirs large amounts of eruptive material can be deposited in the water leading to contamination of the supply. Surges will cut power lines in affected areas. Buried cables and gas pipelines will have a good chance of survival.

A1.4 LAVA FLOWS

Lava flows are streams of molten rock that travel down valleys. The distance they travel depends on the viscosity of the lava, output rates, volume erupted, steepness of the slope, topography and obstructions in the flow path. Basalt flows have low viscosity (flow easily) and have been recorded to travel more than 50 km from a volcano but usually only flow 5-10 km. The Auckland Volcanic Field produces both pahoehoe and a'a lava flows. Both flow types will follow topography but only pahoehoe are sensitive to local perturbations, especially in areas with slopes less than 5^{o} (Trusdell 1995). Shallow slopes may slow the progress of lava flows whereas steeper slopes will accelerate them. Lava flows will seldom threaten human life because of their slow rate of movement. The steep fronts of flows may became unstable and can collapse, causing small pyroclastic flows (Blong 1984, Baxter 1990).

Lava flows may cause extreme damage to buildings and other infrastructure, resulting from burial, ignition and/or excessive forces causing structures to collapse. Blong (1984) describes a number of examples of damage from lava flows. Thick slow-moving a'a flows exert larger stresses on structures than more fluid pahoehoe flows. In numerous cases flows have been diverted by resistant structures. When a flow meets an obstruction its orientation to the structure will influence the flows behaviour. Structures perpendicular to flows have a higher risk of collapse. Inflation of pahoehoe flows may cause flows to overtop structures that initially halted their advance (Hon *et al.* 1994).

The ignition of flammable materials is a common consequence of lava flow inundation.. Some masonry buildings have survived, but most structures are ignited and gutted by fire.

Diversion of lava flows A number of methods have been used in an attempt to divert lava flows (Blong 1984). In Hawaii, authorities used barriers in an attempt to contain advancing flows in 1955 and 1960 and water jets in 1960 and 1983. It was found that using sprays of water could locally check flows for long enough to remove contents from buildings, but eventually flows continued their advance. The US military resorted to bombing in attempt to break levees in 1935, 1942 and 1975-1976. During the eruption of Heimay (1973) in Iceland sea water was pumped onto flows (Williams & Moore 1973). The effectiveness of these methods is debatable. The first unqualified success was in 1992 on Mount Etna where explosives were used to open a lava-tube cutting the supply to the flow front (Barberi *et al.* 1992).

A1.5 VOLCANIC GASES

Volcanic gases consist predominately of steam (H_2O), followed in abundance by carbon dioxide (CO_2) and compounds of chlorine and sulphur. Minor amounts of carbon monoxide, fluorine and other compounds are also released. Concentrations of gases will dilute rapidly away from a volcano and pose little threat to people more than a few kilometres from the active vent. When sulphur dioxide (SO_2) is released it reacts with oxygen, water and sunlight to form aerosols (droplets and tiny particles), sulphuric acid and other sulphur oxide species (Sutton & Elias 1992). This mixture often produces a atmospheric haze known as volcanic smog or "vog". The acid and other compounds in volcanic gases can affect humans and animals eyes and respiration. The same compounds can cause corrosion of metals and other materials (see above). Heavy-than-air gases (i.e carbon dioxide) can collect in depressions and suffocate people and animals. Gases can also be released when lava flows reach the ocean as molten lava boils and vaporises seawater. A series of chemical reactions can produce an aerosol mixture of hydrochloric acid (HCl) and seawater, which is termed lava haze or "laze" (Sutton & Elias 1992). This is potentially harmful to people and is corrosive. Concentrations decrease sharply with distance from the source.

A1.6 VOLCANIC EARTHQUAKES AND GROUND DEFORMATION

Earthquakes have preceded and accompanied most volcanic eruptions and are generated by the movement of magma, the formation of cracks through which the magma moves, gas explosions in the conduit and readjustment of the volcanic edifice to magmatic pressures. Volcanic earthquakes rarely exceed magnitude 5, and are usually much less damaging than the associated eruptions. Damage is usually limited to a relatively small area around the volcano but buildings within this zone may be subject to shaking damage. Many earthquakes occur at or near volcanoes without associated eruptions. Ground deformation may also cause damage to structures near vent, often associated with earthquakes. Commencement of the 1957 eruption of Capelhinos was followed several months later by a seismic crisis and ground deformation that destroyed over 500 houses (Machado *et al.* 1962).

A1.7 ATMOSPHERIC EFFECTS

Volcanic eruptions often produce atmospheric effects such as atmospheric shockwaves and lightning discharges. Atmospheric shockwaves have been recorded from many historic volcanic explosions. The largest observed have produced overpressures sufficient to break windows.

TABLE A1.4 Examples of damage caused by shockwaves (from Blong 1984)

Volcano and year	Damage
Vulcano, 1888-1890	Broken windows 10 km from volcano
Stromboli, 1907	Nearly every window on the island broken
Asama, 1958	Damaged houses within 15 km
Sakurajima, 1977	Broken windows at 3 km from crater

Lightning strikes are commonly generated as a result of electrically charged ash in a convecting eruption column (Anderson *et al.* 1965, Gilbert *et al.* 1991, Gilbert 1994) and can cause injuries to people and damage to facilities. Since telecommunications equipment is commonly situated on high ground it is particularly vulnerable if located near the volcano.

TABLE A1.5 Historical examples of eruption induced lightning strikes.

Volcano and year	Observation	Reference
Tarawera, 1886	Probable forest fires started by lightning.	Keam 1986
Soufrière, 1902	Lightning strikes killed animals and damaged buildings up to 4 km from the vent.	Blong 1984
Kilauea, 1924	Lightning strikes 8 km from the vent destroy 21 consecutive power poles.	Blong 1984
Rabaul, 1937	Lightning strikes hit trees and houses and may have resulted in the loss of several lives.	Johnson & Threlfall 1985
Paricutin, 1943	Three people killed by lightning believed to be caused by the eruption.	Luhr & Simkin 1993
Surtsey, 1963	Spectacular lightning displays within the ash plume.	Thorarinsson 1965
Soufrière, 1979	Strikes 9 km from the volcano.	Shepherd *et al.* 1979
Hudson, 1991	Lightning-strike damage to communication equipment was reported.	Bitschene 1995
Rabaul, 1994	One person killed by lightning.	Blong & McKee 1995

APPENDIX 2 MITIGATION MEASURES FOR VOLCANIC ASH FALLS

2.1 INTRODUCTION

Volcanic ash is highly abrasive, mildly corrosive and potentially conductive (especially when wet). Ash particles are commonly sub-millimetre in size and are easily entrained in the air by wind or by moving vehicles. Particles are very pervasive and can penetrate all but the most tightly-sealed areas. Mitigation actions have two basic purposes: 1) preventing or limiting ash entry, and 2) effective and efficient removal of ash to prevent or reduce damage.

The most effective method to prevent ash-induced damage is to shut down, close off and/or seal off equipment until the ash is removed from the immediate environment. In many cases this is not practical or acceptable. Some mitigation procedures can cause additional problems or may be counter-productive. No single technique provides a solution to all situations and a range of measures will often provide the best results. Constant monitoring and reassessment of ash effects and mitigation procedures is required to achieve the most effective balance between operational requirements and the level of damage limitation.

Pre-planning can reduce the severity of ash impacts. The mitigation planning should undertake the following:

1) Conduct a vulnerability analysis of equipment and facilities to determine which would be the most affected and which are adequately protected.
2) Identify appropriate methods to protect vulnerable equipment and facilities.
3) Develop a priority list of facilities that must be keep operative versus those that can be shut-down during and after ash falls.
4) Identify effective and efficient ash-removal methods for equipment and facilities.
5) Establish plans to implement ash mitigation measures, containing procedures for; the warning and notifying of potential ash falls, reducing or shutting down operations, accelerated maintenance and ash-clean-up operations.
6) Stockpile spare parts for critical equipment, filters and cleaning/disposal equipment.

The following sections list a series of previously published mitigation measures, issued in response to the 1980 Mount St Helens eruption. Some additional suggestions are provided.

2.2 VEHICLES

Damage to vehicles operating in ash-rich environments can be reduced by using a number of suggested mitigation techniques. Accelerated vehicle maintenance will reduce the potential of damage. From the experience gained from the Mount St Helens eruption, Federal Emergency Management Agency (F.E.M.A. 1984) has produced the following recommendations for ash removal and protection of vehicles.

TABLE A2.1 Driving in Ash Fall Areas and Protection of Vehicles (from F.E.M.A. 1984).

1)	*Avoid driving in heavy conditions unless absolutely required. The more dense the dust, more urgent the requirement should be for driving.*
2)	*When required to drive in dense dust, keep speed below 35 mph or lower. Do not follow too close to car ahead. Use headlights on low beam.*
3)	*Change oil often. In very dense dust change at 50 - 100 mile intervals. Light dust conditions change oil at 500 - 1000 mile intervals. Lubricate all chassis components at each oil change.*
4)	*Clean air filters by back-flushing filter paper with compressed air (30 psi). Caution: Blow element from inside (clean side) to outside (dirty side). DO NOT strike filters against anything. Air clean only. If unsure, have a qualified mechanic perform the air filter service. Inspect filters for dents or torn paper. Clean the inside of filters and the filter cover with damp cloth before reinstalling filter. Reinstall filter in housing and tighten on cover very tight, approximately one full turn with pliers after tightening. Do not exceed one full turn with pliers or you may damage the system.*
5)	*DO NOT install hose from carburettor air intake (air clean) to inside of car. Outside dust and ash will be drawn into vehicle.*
6)	*Wrapping air cleaner element with a silk stocking or cheese cloth is of questionable value. It will not improve air cleaner filtration and may actually cause serious if not installed correctly. Rags, or any other intended filtering material, should not be placed over the carburettor inlet inside the air cleaner element, serious damage to the engine and/or loss of vehicle control may result.*
7)	*Cover passenger compartment vent inlet (located at base of wind-shield and usually under hood) with thick, loosely woven felt-type material to filters air into vehicles. With vent filter in place, keep heater blower high. Blower will slightly pressurize inside of vehicle and keep dust from entering through body gaps or holes. If a vent filter is NOT installed, keep air conditioner and heater blowers off.*
8)	*Have service garage clean wheel brakes assemblies every 50-100 miles for very severe road conditions, or every 200-500 miles for heavy dust conditions.*
9)	*Have service garage clean alternators winding with compressed air after heavy accumulation or every 500 to 1000 miles or sever dust exposure.*
10)	*Wash engine compartment with garden hose or steam cleaner. Be sure to seal off air intakes and electrical components before cleaning.*
11)	*Commercial truck filters can be installed to increase the filtering capacity of the cleaner. However this is expensive and should only be attempted by trained garage mechanics or experienced personnel. This would be beneficial for vehicles operating continuously in extreme dust conditions.*
12)	*Air filter restriction gauges can be installed by qualified mechanics. The gauge will tell you when your air filter requires servicing in order to avoid over-servicing.*

TABLE A2.2 Ash removal methods for roads (from F.E.M.A. 1984).

* *Notify bordering property owners to move ash from roofs and the rest of their property to the street, away from the gutters, to prevent the need for more than one ash removal project and to avoid storm sewer blockages.*
* *Encourage and monitor block efforts and volunteer work.*
* *Before beginning cleanup activities, build small dike (using sandbags or other methods) around catch basin inlets to screen ash.*
* *To keep ash out of storm drains, hand sweep the dry ash outwards from the gutters about two feet or so. (Volunteer teams can provide important assistance in this area.)*
* *Moisten the ash using a sprinkling system. Avoid moistening it too much, for it will become unmanageable. Due to its fineness, ash powder when saturated can retain large amounts of water and weigh up to 80 pounds per cubic foot. (Wet sawdust or wood-chips have been used to help reduce the dust, but these methods are not as effective as only wetting ash.).*
* *Use motor patrol graders to blade the ash. Collect, load and transfer the ash to trucks to be hauled to dumps sites.*
* *For a thorough cleaning of paved roads with storm sewers, use power brooms on the dampened residue.*
* *To remove the remaining ash on paved roads without storm sewers, flush the roads with water.*
* *As soon after the street cleanup as possible, remove ash deposits from catch basin inlets with vacuum trucks or machines with jet rodding and vacuum systems. Delaying the cleanup allows time for the ash to crust and cake, making it harder to remove. Further, the ash density impairs the self-cleaning function of the sewer's grade, creating the potential for plugging the sewer.*

Paved or Oiled Roads That Have No Curbs or Sewers

* *Sprinkle ash with water and blade it onto the shoulders or into the ditches. Then load and remove the ash. Remove the residue by sweeping or flushing it, if necessary. Where gravel shoulders exist, replace lost gravel so as not to lose the integrity of the road way.*

Gravel Roads

* *Blade the ash into ditches, being careful to avoid unnecessary loss of surface materials.*
* *If the existing right - of - way is wide enough, spread the ash along the back slopes outside the ditch. (Note that much of the ash may become integrated into roadside vegetation and that the ash in these areas will blow for some time during windstorms.)*
* *Remove ash blocking the drainage in ditches and culverts, and transport it to a disposal site. A considerable amount of ash will remain on the roadbed surfacing, creating a serious visibility problem for traffic. Nothing can be reasonably done to eliminate it totally, but it will decrease with time.*
* *On the roadbed, place a thin lift of rock consisting of graded material 5/8 inch to 0 in size and crushed to standard specification. This layer can be added and processed into the existing surface to achieve the binding effect that will stabilize the surface under traffic. (While this expensive method will not provide total dust control, it is, nevertheless, the most suitable method available for achieving visibility levels so that traffic operations can be restored.)*

A2.3 WATER SUPPLIES

The main problems facing surface water bodies are ash-induced changes in turbidity and acidity. Intake of water should be cut before these levels become excessive and regular monitoring will indicate when the supply can be resumed. High turbidity levels are manageable if water-treatment filters are cleaned or replaced frequently but filters may be blocked if ash loadings become excessive. Where turbidity is high, precautionary warnings to "boil water" should be issued. This is because the suspended ash may have decreased the affectiveness of any disinfection or flocculation processes. As fine ash can remain in suspension for long periods, a coagulation-flocculating agent may need to be added. Alum has been found to be the best agent. To reduce physical damage to the plant, equipment and pumps should be covered when there is an impending eruption, and the ash removed before continuing operations.

A2.4 SEWAGE AND STORMWATER SYSTEMS

The blockage of sewer and stormwater pipes is a major problem created by ash falls therefore it is of prime importance to limit the amount of ash in the initial sections of the systems. F.E.M.A. (1984) recommend a number of measures to reduce the amount of ash entering the system.

TABLE A2.3 Protection of sewage and stormwater systems from volcanic ash (from F.E.M.A. 1984)

1)	*Have local ordinances in effect banning connections of downpipes and roof drains to the sewer.*
2)	*Warn citizens against disposing ash down manholes of both sewer and stormwater systems.*
3)	*When hosing streets, place sand bags around or over manholes covers or avoid covers entirely, since the vent holes and the areas between the cover and the rings allow passage of ash.*
4)	*When washing streets, parking areas, roofs, use a weir (sandbags) in each manhole and stormwater intake to trap the ash.*
5)	*Instruct the public how to protect storm water systems*
6)	*When possible, disconnect downpipes from the stormwater system until roof clearing is complete.*
7)	*Instruct citizens where to deposit ash cleared from property.*
8)	*Closely monitor the cleanup activities of privately owned parking areas.*
9)	*Use dry methods, like hand sweeping, prior to flush cleaning when clearing streets and parking areas served by a free discharging or dry well stormwater system.*
10)	*Sweep the ash outwards from the gutters about two feet or so.*

Note: Shallow deposits of ash in the stormwater or sewerage system will not reduce the hydraulic capacity of the pipes by a significant amount, thus expenditure of time and money to clean lines may not be warranted.

Sewage Treatment Plants

Ash entering sewage treatment plants can cause considerate damage. F.E.M.A. (1984) and White *et al.* (1980) recommend the following precautions to be taken:

TABLE A2.4 Protection of sewage treatment plants from volcanic ash.

1)	*Temporarily cover all equipment (e.g. mechanical, biofilters), including ventilation intakes, that might be directly exposed to the ash fall before or during the onslaught.*
2)	*Shut down all equipment not absolutely necessary.*
3)	*Where possible, place sandbags or other devices at the entrance channel to the plant to trap ash. This procedure will require frequent attention due to normal settleable solids present in sanitary sewage.*
4)	*Consider removing or bypassing the comminutor during the initial heavy flows of ash into the plant.*
5)	*Frequently check the primary clarifiers to prevent (a) damage to the sludge collection mechanism and/or the digesters sludge pumps and (b) the transference of ash to the digester. Depending on the type of mixing employed in the digester, further damage may occur in the sludge transfer pumps.*
6)	*To clear ash from individual sections of the treatment facility, bypass individual units, or extreme instances, make a complete plant bypass to a holding pond or lagoon.*

A2.5 ELECTRICITY SUPPLY

The presence of moisture with ash is the critical factor in initiating insulator flashovers if insulating surfaces are completely coated, since ash contains soluble leachates which makes ash conductive when wet. The abrasive nature of ash can cause damage to mechanically moving parts, such as cooling fans. Immediate ash removal is the best mitigation option to prevent wide spread outages. Mitigation recommendations are presented by F.E.M.A. (1984).

TABLE A2.5 Protection of Electricity Supply (from F.E.M.A. 1984)

*	*Immediately after the ash fall, dispatch personnel to the substations to dust, sweep, and blow ash from electrical equipment. Prompt adequate maintenance of the mechanical and electrical systems is essential.*
*	*Shut down all electrical systems before any attempt is made to clean or service them. Throw the main circuit breakers, not just the nearest switches.*
*	*Remove dry ash immediately from the most sensitive systems by blowing it off using air pressure of 30 psi or less, so as to avoid a sandblast effect. Avoid rubbing or brushing equipment, as that will damage many surface. Be careful not to blow the dust other places that should be kept clean. Vacuum ash when possible and change filter bags often.*
*	*Clean electric components such as small motors and light bulbs, as they will generate excess heat when blanketed with dust. The excess heat can cause fires and short term operating life. The ash should be vacuumed or blown off as described above.*
*	*Avoid saturating electrical components when hosing dust off. Many of these systems can handle rain and moisture, but not the effect of water jets from hoses.*
*	*Check for trees heavily loaded with ash near power lines because the added weight can cause limbs to fall on power lines.*
*	*Check and keep insulators clean. A moderate wind, while the ash is still dry, will clean most insulators on outdoor distribution lines and equipment. Light rain, which does not wash the ash away, is harmful and can cause flashovers and short circuits. Ash that has hardened may require special cleaning methods such as hand cleaning or water jetting.*
*	*Protect backup and auxiliary units to avoid starting problems when they are activated.*
*	*Maintain protection and cleaning programs continuously until the treat of windblown ash is over.*

A2.6 TELECOMMUNICATIONS

From the experience gained from the Mount St Helens eruption Labadie (1983) has produced the following observations and recommendations for mitigating the effects of volcanic ash on communication systems. The most serious problems result from the conductive and abrasive properties of ash.

TABLE A2.6 Communications systems: observations and mitigation techniques (from Labadie 1983).

Mitigation techniques
- *Teflon insulators on communications antennas were covered with dust and shorted out. Very difficult to clean as residue would adhere. Replacement with ceramic insulators required.*
- *Plastic switches and push-buttons (especially those with self-cleaning contacts) abrade quickly. Necessary to replace.*
- *Seal up repeater stations and other installations; shut air intakes; internal air circulation and leakage should be sufficient for cooling.*
- *Blow out or vacuum out radio equipment; brush off.*
- *Seal equipment that is not already watertight. Smaller units have low-power consumption and do not generate much heat.*
- *Magnetic particles that stick to relay cores should be blown off.*
- *Keep moisture out of equipment.*
- *Clean equipment daily; increase use of filter paper.*
- *Clean out microwave dishes, feed horns, wave guides. Install covers; plastic tarp will do in an emergency.*

A2.7 BUILDINGS AND BUILDING SERVICES

Volcanic ash can cause damage to buildings and building services in several ways; overloading roof strengths causing collapse, soiling interiors, damaging services (electrical and mechanical) and damaging exterior materials. The following table is a list of general guidelines proposed by Labadie (1983) for removing and controlling volcanic ash in buildings, heating/cooling systems and computer services.

TABLE A2.7 The management of volcanic ash in buildings (from Labadie 1983).

Mitigation techniques:

- *Establish a written procedure; train personnel.*
- *Stockpile disposal containers, mops, brooms, shovels, pails, industrial vacuum cleaners, plastic bags, and sheets.*
- *Stock filters and filter materials.*
- *Remove dust from roofs and entry ways prior to re-activating machinery.*
- *Keep roof drains, storm drains, gutters, etc, clear of dust clogging. It is best to sweep dust from roofs and not flush with water; roof drains clog very easily.*
- *Make a written record of all steps taken to secure the building, so these steps can be retraced for start-up procedures, or if problems arise.*
- *Use a damp mop to clean hard floors.*
- *Use a water-type industrial vacuum cleaner, if possible, for cleaning rugs and cloth furniture.*
- *Use damp, disposable cloths to dust furniture, window sills.*
- *Restrict building access to the most protected entrance. Admit only authorised personnel.*
- *Close and seal all unnecessary outside openings, including air intakes and vents.*
- *Shut down all unnecessary building operations and equipment.*
- *Establish decontamination rooms for personnel entering the building. Require personnel to brush down clothing and shoes prior to entering the building and to vacuum off clothing immediately upon entering the building, or to bring a change of clothing and shoes for use while in the building.*
- *If outside air intake is required, monitor air intake filters at regular intervals, and change as required. Remove dust from area of outside-air intakes.*
- *Maintain a relatively clean environment throughout the entire building. Damp-mop floors, wipe off machinery and furniture at least once a day.*

TABLE A2.8 Heating/cooling systems: observations and mitigation techniques (from Labadie 1983).

- *Close external air intakes; use internal circulation only; this will create positive pressure inside building.* - *Control access, seal doors.* - *Establish decontamination rooms for entering personnel; provide vacuum cleaners, shoe covers, disposable caps.* - *Stockpile cleaning supplies, duct tape, disposal containers.* - *use extra (and heavier) filters for external air intakes.* - *Clean dust away from external intakes; restrict vehicle and foot traffic near intakes.* - *Install intake hoods that extend farther above ground.* - *Install pre-filters.* - *Add sand filters to cooling towers.* - *Cover cooling towers.* - *Clean coils, radiators, etc, with compressed air and/or water.* - *Add cooling coils to un-interruptible power supply to reduce temperature of incoming air by 10° (increases cooling capacity).* - *Add back-flushed filters to cooler sumps.* - *Install alarm circuit to warn of excessive pressure differential across filters; filters that get too clogged can break open.* - *Change from open, drip-proof type motors to totally enclosed, fan-type motors.* - *Reduce staff to minimum required.* - *Close and seal unused rooms; turn off unused equipment.* - *Shutdown air handling system to prevent damage to chillers, fans, pumps, etc.*

TABLE A2.9 Computer services: observations and mitigation techniques (from Labadie 1983).

-	*Best tactic for ash mitigation is prevention. Clean and condition surrounding air to keep ash out of equipment.*
-	*Cotton mat filters (used in clean rooms) were found to be best for filtering particles, but they reduce the air flow. A solution is to use larger fans to maintain required air flow. Rack-mounted equipment can be modified to add a larger fan; smaller instruments or components with a built-in fan would require design change to increase fan capacity.*
-	*Use fluted filters as a compromise; increases surface area but reduces air flow by only about 20%.*
-	*Digital integrated circuits can vary 5-10% in performance (depending on type of circuit) and still be acceptable. It is difficult to generalize about other equipment (e.g. high-voltage power supplies).*
-	*Humidifying ambient air (e.g. wet down carpets) will help to control ash re-entrainment.*
-	*Ash on equipment can be blown out with compressed air. If the air is too dry, static discharge could damage sensitive components (e.g. MOS integrated circuits). If the air is too damp, the ash will stick. Relative humidity of 25-30% is best for compressed air.*
-	*Cleaning with a pressurized water-detergent mix and a hot water rinse is quite effective. However, this process requires at least partial disassembly.*
-	*Ash on digital circuits won't cause much of a problem because of the low voltages involved. High voltage or high-impedance circuits are very vulnerable to leakage caused by semi-conductive ash. Ash that is acidic is conductive as well as corrosive.*
-	*Ash should be blown or brushed away from power supplies and CRTs (especially high-voltage leads, capacitors).*
-	*Ash may have high static charge and be hard to dislodge; requires brushing to dislodge.*
-	*Accelerate filter change; use pre-filters.*
-	*Change to absolute filters; will keep out particles down to 1 micron.*
-	*Keep computer power on to operate filtration, but don't run (especially disk drives).*
-	*Maintain "room-within-a-room" configuration; restrict access; re-circulate air; accelerate cleaning of area.*

From the experience gained from the Mount St Helens eruption F.E.M.A. (1984) has produced the following recommendations for ash removal.

TABLE A2.10 Ash removal methods for buildings (from F.E.M.A. 1984).

- *Promptly notify building owners to remove ash from roofs in a timely manner to prevent streets from being repetitively cleaned.*
- *Inform public of effective methods for (1) removing ash from roofs and property and preparing it for pick-up by emergency crews and (2) organizing neighbourhood cleanup activities.*
- *Caution residents against flushing ash into sewers.*
- *Remove ash dry and before the first rain. Dampen ash with a light spray of water to reduce billowing. (Do not use large amounts of water which will cause the ash to cake).*
- *Make sure that the ash cleanup is supervised by knowledgeable building maintenance personnel to prevent unnecessary damage to roof material and surfaces.*
- *Use protective measures when removing ash from roofs. Walking on roofs and using tools and small equipment can cause breaks and punctures is the roof is dry and brittle. The full force of water from fire hoses will break lap shingles or tear lap roofing.*
- *Do not flush ash into drains and down-spout, for it can clog the small-sized pipes. Ash flushed into dry wells can seal them, rendering them inoperative.*
- *Thoroughly remove all traces of ash near intakes of ventilation systems.*
- *To protect sewer lines, disconnect down drains at ground level until cleanup is complete.*
- *To prevent or reduce the accelerated deterioration of roof coatings by mildly acidic property of ash, clean and/or protect the roof surfaces accordingly. Metallic roofs surfaces, particularly older galvanized roofs which are pitted, and lower gage galvanized roofs are most susceptible to increased deterioration from the properties of ash.*
- *On flat roofs, hand sweep ash into windrows and transport it by wheelbarrow to an edge dump. Use proper protection such as planking, mats, plywood sheets, and pliable footwear to prevent unnecessary damage from impact and abrasion. Hoppers with a funnel pip suspended above a loading truck can be used to collect the ash. To remove final dry residue or thin layer of ash, use air pressures with regulation. Note the small vacuum equipment is not practical because of the abrasiveness of the ash.*
- *On steep shingle roofs, place dams in the troughs to prevent the ash from reaching the down drains. Then hose down the ash and clear it from the eave troughs. This operation must be preformed with care to avoid deforming the gutters and tearing them loose.*
- *On low slope bitumastic mopped roofs, where there is only a thin ash layer or small residue, flush the ash with water. Again too much pressure from high pressure hoses can damage roof materials.*
- *To avoid clogging the inlets to roof drains, encircle the roof inlet with a fabricated ring made from heavy sheet metal about four inches wide and two feet in diameter. This serves as a dam allowing water to spill over the top, while the ash settles in the surrounding roof depression. Later, when dry, the ash can be removed manually*

TABLE A2.10(contin.) Ash removal methods for buildings (from F.E.M.A. 1984).

Building Exteriors

- *Sills, ledges, parapets, and wall surfaces - usually these building features will not warrant extra cleanup efforts or expenditure if the primary functioning of the building is not impaired.*
- *Air-handling and air conditioning mechanisms.*
  - Shut down systems prior to or during the initial onslaught of the ash fall. Simultaneously, check all public buildings to make sure windows are closed, air conditioners are off, and that all unnecessary outside openings, including air intakes, are closed and sealed. These initial activities will help prevent or reduce the introduction of ash to building interiors and air-handling system's ingestion of ash.
- *To restart air-handing systems:*
  - Clean the roof-mounted intakes and the roof area adjacent to intakes.
  - Clean or replace filters.
  - Inspect, clean or lubricate moving portions of the mechanism, following prescribed routine maintenance.

Building Interiors

- *Restrict building access to the most protected entrance.*
- *Instruct building managers to educate occupants in preventing ash entrainment into the building.*
- *Have building managers establish an entry room or zone where personnel are required to brush or vacuum clothing and shoes or make clothing changes, if appropriate.*
- *Establish any necessary, extra cleaning procedures to protect the interior environment.*
- *To substantially reduce the need for extensive maintenance of equipment, place coverings over office machines as standard procedures.*
- *Carefully monitor vacuum cleaners to assure that filters and ash bags are changed when necessary.*

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House hold surfaces should be vacuumed to remove ash much ash as possible.

- *After vacuuming carpets and upholstery may wish to be cleaned with a detergent shampoo. Avoid excess rubbing action because the sharp ash particles may cut textile fibres.*
- *Glass, porcelain enamel and acrylic surfaces may be scratched if wiped too vigorously. Use a detergent soaked cloth or sponge and dab rather than wipe.*
- *High-shine wood finishes will be dulled by the fine grit. Vacuum surfaces and then blot with a cloth treated to pick up ash. A tack cloth used by furniture refinishers should work well*
- *Ash-coated fabrics should be rinsed under running water and then washed carefully.*

Remember: Soiled clothing will require extra detergent. Wash small loads of clothing, using plenty of water so the cloths will have room to move freely in the water. Do not mix heavily soiled clothes with garments that are lightly soiled. Be sure clothes are free of ash before putting them in an automatic dryer Ash may scratch the inner surface of the dryer.
During the next few months, filters must be replaced often. Air conditioner and furnace filters need careful attention. Clean refrigerator air intakes. Clean any surface that may blow air and recirculate the ash. Stove fans and vents should be cleaned thoroughly.

APPENDIX 3 REVIEW OF VOLCANIC IMPACTS ON ECOLOGY

A3.1 IMPACTS ON ANIMALS

A3.1.1 Mammals

Pyroclastic surges, toxic gases and lava flows Pyroclastic surges will usually kill all animals caught in their paths. Close to the vent the build up of toxic gases may also have detrimental effects on the health of any animals who enter this zone. Lava flows will rarely pose a hazard to animals because of the slow rates of advance.

Tephra fall is unlikely to immediately kill animals except when deposition rates are exceptionally high and thickness is great. Tephra cover on pastures will result in lack of feed for animals. During the 1945 Ruapehu eruption pastures covered by ash were often described as being unpalatable to stock but no significant pasture damage to occurred (Johnston & Neall 1995). No stock losses due to lack of feed were reported (Cunningham 1946). Following ash falls from Ruapehu in 1995 and 1996 farmers noted that animals were readily put off their feed by ash deposits of around 2-5 mm thickness. Ash from the 1980 Mount St Helens eruption had little impact on livestock as long as they had access to sufficient feed (Blong 1984). Trials on cows being fed ash at a rate of 1.5 kg per day showed no obvious effects on milk production.

Some tephra falls have been poisonous to stock, i.e. in Iceland and New Zealand. Fluorine aerosols attached to fine tephra pose the most significant threat to animal well being (Gregory & Neall 1996). Poisoning occurs where the fluorine content of dried grass exceeds 250 ppm. Before death the poisoning causes lesions in the nose and mouth, and hair to fall out around the mouth. Fluorine poisoning of livestock has occurred a number of times in Iceland (Thorarinsson 1979). The eruption of Lakuggar in 1783 killed 50 % of the island's horses and cattle and 79 % of the sheep. In the 1947 eruption of Hekla, only sheep were affected with other animals (cattle, horses, cats, dogs and poultry) unaffected. In 1970 fluorine poisoning occurred in areas which only received 1 mm of ash.

As a result of £ 5 mm ash fall on the Rangitaiki Plain (Taupo) during the 1995 Ruapehu eruption, approximately 2000 ewes and lambs (2.5% of the area's sheep population) were killed as a result of eating ash-affected pastures. Autopsies of the dead animals suggest fluorine poisoning or pregnancy toxaemia was the cause of death (Gregory & Neall 1996). Three Ayrshire dairy cows died at Atiamuri in June 1996 (*pers. comm.* MAF). It was reported that they stopped eating, showed signs of lethargy before dying after swallowing quantities of ash. Toxic levels of fluorine were found in the dead animals blood. The Department of Conservation also reported the death of a number of wild deer in Kaimanawa Ranges, downwind from

Ruapehu, following the two largest October 1995 eruptions (possibly up to 5% of the sika deer population).

A3.1.2 Aquatic plants and animals

Aquatic life is very susceptible to changes in water conditions such as increases in acidity, turbidity, temperature and concentrations of soluble elements.

Pyroclastic surges and thick **tephra falls** will have a dramatic impact on water conditions in affected areas. Rivers draining such areas will produce sustained high sediment yields due to the availability of readily erodible material as the river flows through the new deposits. Rivers flowing through barren areas that were previously vegetated will suffer from lack of shade, raising water temperatures beyond previous levels. After the 1980 Mt St Helens eruption, water temperatures soared beyond levels for growth and survival of salmon where the Toutle River flowed through the area devastated by the debris avalanche (Lucas 1986). Another problem for such rivers is the lack of leaf litter that is an important food source for aquatic invertebrates. Further away from the mountain little impact was noted on streams in areas with ash thicknesses of 2 cm (Gamblin *et al.* 1986).

In normal circumstances little sediment is added to rivers by tephra in areas away from stream or river channels, unless the stream channel lies directly below steep slopes. Only during severe rainstorms is tephra readily eroded from the land surface and deposited in streams or rivers. Such events are little different to the behaviour of soils on non-vegetated land during similar severe rainstorms. Keam (1988) notes Dr Hectors observation of the tephra deposits from the 1886 Tarawera eruption. "*While rain had certainly washed a great deal of mud off steep slopes, it was showing no tendency to slide .... the mud was there to stay, unless it was removed by normal erosional processes.*"

The primary factors causing fish to die in the rivers around Ruapehu after the 1969, 1975 and 1995 lahars were suspended sediments, acidity and concentrations of fluoride. Minor fish kills were also reported in ash-affected rivers after the 1995 eruption but insignificant in terms of the total population (Maxwell 1996). Minor disturbance to the 1995 trout spawning migration was observed but the Tongariro River fishery has generally remained in good condition.

Aquatic floral and faunal invertebrate populations are susceptible to ash suspended in rivers and lakes. Reductions in primary production of planktonic and rooted plants will reduce secondary grazers important as fish food.

A3.1.3 Birdlife

Tephra may cause several problems for birds, with falls of fine ash preventing flight. Widespread ashfall may result in lack of food. Gases from the vent area can kill overflying birds. In the 1886 Tarawera eruption, pigeons, ducks and sparrows were killed in large numbers (Keam 1988). Surviving sparrows were blinded at least temporarily, with eyelids gummed together by the falling mud.

A3.1.4 Other living things

Ash particles are especially destructive to insects largely due to abrasion of the epicuticular wax layer which causes rapid desiccation and death (Cook *et al.* 1981). One advantage noted in agricultural areas which received small amounts of Mount St Helens ash was the destruction of insect pests.

A3.2 IMPACTS ON PLANTS

Pyroclastic surges can cause complete destruction of vegetation, often removing forest cover completely by uprooting, and stripping foliage, branches and bark from standing trees. Heat damages the hydrated tissues of plants.

Lava flows will also cause complete destruction of vegetation, often igniting trees and shrubs.

Tephra Damage to small vegetation and the soils on which they depend will vary with tephra thickness and composition of the ash. The effects in Table A3.1 are based on observations from past eruptions described by Folsom (1986) and Blong (1984).

TABLE A3.1 Impacts on plants and soil from increasing tephra thickness.

Thin burial (< 5 mm tephra)
- No plant burial or breakage - Ash is mechanically incorporated into the soil within one year - Vegetation canopies recover within weeks
Moderate burial (5 - 25 mm tephra)
- Buried microphytes may survive and recover - Larger grasses are damaged but not killed - Tephra layer remains somewhat intact on the soil surface after one year - Soil underneath remains viable and is not so deprived of oxygen or water that it ceases to act as a topsoil - Vegetation canopies recover within next growing season
Thick burial (25 - 150 mm tephra)
- Completely buries and eliminates the microphytes - Small mosses and annual plants will only be present again in the local ecosystem after recolonization - Generalized breakage and burial of grasses and other non-woody plants - some macrophytes of plant cover do not recover from trauma - Large proportion of plant cover eliminated for more than one year - Buried soil is revitalized when plants extend roots and decaying organic matter from the surface of the tephra layer down to the top of the buried topsoil and affect an integration of the tephra and buried A horizon. Generally accomplished in 4 - 5 years - Vegetation canopy recovery takes several decades
Very thick burial (> 150 mm tephra)
- All non-woody plants are buried - Burial will sterilize soil profile by isolation from oxygen - Soil burial is complete and there is no communication from the buried soil to the new tephra surface - Soil formation must begin from this new "time zero" - Several hundred (to a few thousand years) may pass before new equilibrium soil is established

Eruption impacts on trees are described by Rees (1970) below (Table A3.2).

TABLE A3.2 Impacts on trees of tephra.

Tephra Thickness	**Impact on Trees**
150 - 500 mm	Slight damage and partial survival of shrubs
500 - 1500 mm	Tree damage, large branches were broken, heavy kill of shrubs
1500 mm	Total kill zone

Eggler (1948) noted pines surviving in tephra depths of 1240 mm and 1780 mm. Pine seedlings and small trees were killed as a result of excessive bending and burial while large mature trees suffered from branch breakage under the load of ash. Pines with basal diameters of 100 - 300 mm survived best because their stems were strong enough to resist excessive bending yet sufficiently flexible to dump part of the load and avoid breakage.

Crop damage will result from burial which can kill or damage plants depending of the thickness of the tephra. During the 1995 Ruapehu eruption major losses (~$250 000) to cauliflower crops were reported in Gisborne, 250 km downwind but market gardens were fortunate that many crops were not in the ground at the time of the ash falls. The following table (A3.3) was prepared by the Ministry of Agriculture in 1995 following the Ruapehu eruption.

TABLE A3.3 Periods of high crop risk from tephra (from M.A.F. 1995)

Periods when crops are most at risk
Pea: from emergence until end of flowering.
Squash: during the initial stages of growth and flowering.
Tomatoes: during seed emergence and flowering stages.
Sweetcorn: during the early stages of growth.
Pipfruit has three danger periods: - Blossom where severely acidic ash (pH less than 3) could burn plant tissue and result in poor pollination; - 6 to 8 weeks after blossoming, when the skin of fruit is particularly sensitive; and - later stages of development when fruit is prone to cosmetic blemishing.
Stonefruit is also susceptible at the same times as pipfruit, except that the early fruit development period is 4-6 weeks after blossoming, when sensitive fruit skins could be damaged, and show russet or deformation in severe cases.
Kiwifruit is also at risk at, and 6-8 weeks after, blossom. There would also be a problem at harvest time. As kiwi fruit cannot be washed prior to packing, the hairy nature of the fruit would make ash removal very difficult.
Grapes have three main periods when damage could occur: - Flowering, when acidic ash could burn plant tissues, reduce pollination and reduce bunch fill; - Fruit development, where ash deposits would block sunlight and reduce quality; and - Harvest, where ash deposits would be a contaminant. with the extra acidity of the ash possibly having a significant impact on wine quality. Ash would have to be removed prior to harvesting by washing and allowing bunches to dry.

Damage to soils may result from the tephra fall affecting the productive potential of the area. Small amounts may improve soils. A positive impact of the 1995 - 1996 Ruapehu ash falls has been to temporarily reduce the sulphur fertilizer requirement for all sheep, beef and dairy farmers within the ash fall area (Cronin *et al.* 1996). Contamination of water supplies may cause damage to plants and limit production.

Acid rain (and acidic ash) has been reported as causing a number of effects on plants. Blossom drop, poor fruit set, small almost seedless fruit have also been reported in horticultural areas. In most areas where ash fall has occurred, crop damage has only been sporadic. Minor acid burns were reported on some plants on Ruapehu and the Kaimanawa Ranges following the 1995 Ruapehu eruption but most had recovered by late 1996 (Keys 1996).

Plant recovery Most detailed studies of plant growth after tephra fall result from the 1980 Mount St Helens eruption. Algal covers became established on most tephra surfaces within a few weeks, providing a protective surface skin against erosion, although the mat is easily disturbed.

Folsom (1986) showed that the recovery of plants from the trauma of tephra deposition will follow a sequence:-

1. Recovery of surviving not completely buried plants
2. Emergence of surviving buried plants
3. Germination of local seed reserves
4. Colonization from outside seed sources

with individual plant recovery dependent on :-

1. Thickness of ash
2. Degree of continuing disturbance
3. Amount and reliability of rainfall

Chaplin *et al.* (1986) noted that certain species of plant do not suffer from mineral deficiencies when growing in the nutrient-poor volcanic soils. Such plants will obviously be better suited to recolonization in areas where tephra or surge deposit thicknesses are great or on lava flows. The re-establishment of plants on barren areas influences the colonization of subsequent plants by trapping seeds and changing the microclimate (Dale 1986). After five years specie richness had stabilized in areas where recolonization had occurred (del Moral and Wood 1986). Sites far removed from seed sources were unlikely to be recolonized rapidly.

The recovery of the area devastated around Mount Tarawera in 1886 is well documented (Clarkson and Clarkson 1991). The devastated area remained barren for over 10 years. Where bush had only been partly buried it resprouted quickly. On the lower slopes of the mountain toetoe and tutu shrubs re-established within 20 years and a mat of daisies colonized the middle slopes. After 27 years post-eruption shrubs had established on the middle slopes and daisies and grasses were present high up the mountain. The summit area was still barren. By 42 years after the eruption a young forest was present at the base of the mountain. Higher up the slopes a tutu association was common. After 75 years the forest was dominated by tawa at low altitudes and kamahi at higher altitudes. Near the top of the mountain, shrubs were common and the crater and summit area had widespread grasses, mosses and daisies. In the past 20 years an influx of tutu and scattered introduced conifers has occurred on large areas of the upper part of the mountain.

CONCLUSION

Pyroclastic surges will usually kill all animals caught in their paths. Close to the vent the build up of toxic gases may also have detrimental effects on the health of any surviving animals. Lava flows will rarely pose a hazard to animals because of the slow rates of advance. Tephra fall is unlikely to immediately kill animals except when deposition rates are exceptionally high and thickness is great. Tephra cover on pastures will result in lack of feed for animals. Some tephra falls have been poisonous to stock. Fluorine aerosols attached to fine tephra pose the most significant threat to animal well being. Aquatic life is very susceptible to changes in water conditions such as increases in acidity, turbidity, temperature and concentrations of soluble elements.

Surges and lava flows will destroy vegetation in their paths. Volcanic gases may result in acid rain damaging plants close to the volcano. The effects of tephra fall depend on ash thickness and the size and types of plants. Where tephra fall results in a total kill of plant life the area will remain barren until recolonization.

APPENDIX 4 SCIENTIFIC ALERT LEVELS

Volcano surveillance in the Auckland Volcanic Field is carried out by the ARC in conjunction with the Institute of Geological & Nuclear Sciences (GNS) and University of Auckland. Monitoring enables the background or normal state of the volcano to be determined. Departures from the normal state indicate the onset of an eruptive episode.

As detailed in the National Civil Defence Plan the volcanic field is assigned a Scientific Alert Level by GNS, denoting its **current status.** The scientific alert system is based on a 6-stage classification (Table 4.1) where the lowest level is 0 (dormancy) and the highest level is 5 (large scale hazardous eruption in progress). The New Zealand system has two parallel tables one for **frequently active cone volcanoes** and the other for **reawakening volcanoes**. The Auckland Volcanic Field is classified as a reawakening volcano for the purposes of setting scientific alert levels. GNS will adjust the alert level based on observations from the surveillance programme and notify the Regional Council, Ministry of Civil Defence, and the media (as per the National Civil Defence Plan).

A move from Alert Level 0 to Alert Level 1 does not necessarily signal imminent volcanic activity. Alert Level 1, simply means that indications of unrest have been detected by the scientific community and is being evaluated. Level 2 is confirmation that the apparent unrest is volcanic in origin and indicates that an eruption may occur in the future. Level 3 indicates the commence of minor steam eruptions and high increasing trends of unrest indicators suggesting a real possibility of a hazardous eruption. Level 4 signals the eruption of new magma and a hazardous local eruption is in progress, with a large scale eruption possible. Level 5 indicates a large hazardous eruption in progress with a significant risk over a wide area.

Once it is recognised that a 'volcanic crisis' exists, GNS will issue Science Alert Bulletins which give information on the status of the volcano and set the Scientific Alert Level. The following bulletins have been written for Scenario 5 to illustrated their format and content.

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

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SCIENCE ALERT AS/1

Day 9
1000 hours NZDT (UT +13)

AUCKLAND VOLCANIC FIELD

Situation Summary

As of 1000 h the situational status is:

* Three days ago (Day 6) two high-frequency earthquakes were recorded by the Auckland volcano-seismic network, with near-simultaneous arrival times on Waiatarua (WTAz) and Motutapu (MTAz) seismographs. Both events were regarded as aftershocks of the M_L5 event which had occurred five days earlier.

* Yesterday, four high-frequency earthquakes were recorded with near-simultaneous arrival times on WTAz and MTAz seismographs. A portable seismometer has been installed at an additional site. Three high-frequency earthquakes have been recorded on Auckland network seismographs up to 1000 h today.

* The Institute of Geological & Nuclear Sciences (GNS) was contacted at 1800h yesterday by the Auckland Regional Council. GNS staff are travelling to Auckland this morning. They will install additional portable seismometers, and carry out other investigations.

Conclusion and Alert status

* A total of 9 high-frequency earthquakes have been recorded beneath Auckland City over the last 4 days. The previous average occurrence of high-frequency earthquakes is in the order of one per three months. Based on this anomalous seismicity, a **Scientific Alert Level 1*** is declared for the Auckland Volcanic Field.

Programme Leader, Volcanology

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* See attached Science Alert classification

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SCIENCE ALERT AS/2

Day 19
2200 hours NZDT (UT +13)

AUCKLAND VOLCANIC ACTIVITY

Situation Summary

As of 2200 h the situational status is:

* Seven high-frequency earthquakes were recorded on the Auckland volcano-seismic network between Day 10 and Day 16.

* Today, 25 high-frequency earthquakes were recorded by the volcano-seismic network. These events appear to be originating at shallower depths than the previous earthquakes recently recorded in the Three Kings area. Two apparent long period earthquakes were also recorded. Long-period events are often recorded at active volcanoes.

* Two further portable seismographs have been installed in Auckland City, and a volcanic tremor analysis system attached to the Auckland volcano-seismic network. These instruments will increase our capability to monitor the ongoing seismicity.

Conclusion and Alert status

Due to the rapid increase in earthquakes recorded beneath Auckland City, with apparent shallowing and appearance of long-period events, a **Scientific Alert Level 2*** is declared.

Programme Leader, Volcanology

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*See attached Science Alert classification

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SCIENCE ALERT AS/3

Day 22
2200 hours NZDT (UT +13)

AUCKLAND VOLCANIC ACTIVITY

Situation Summary

As of 2200 h the situational status is:

* Over the past two days, 18 high-frequency earthquakes were recorded on the Auckland volcano-seismic network. The epicentres of all located earthquakes appear to lie within the Three Kings area.

* Today, 150 high-frequency earthquakes were recorded on the volcano-seismic network with the two largest events felt in the Three Kings area, where minor shaking damage has occurred. Some of these events have been located at 5-10 km depths.

* Volcanic tremor was recorded on seismographs close to the epicentral area, over a two hour duration from 1600h.

* We have installed tilt-levelling sites in the epicentral area to determine if ground deformation is accompanying the increased seismicity.

Conclusion and Alert status

The **Scientific Alert Level** remains at **2***. The further shallowing of epicentres and the occurrence of volcanic tremor is recognised as indicating an increased probability of an eruption actually occurring.

Programme Leader, Volcanology

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* See attached Science Alert classification

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SCIENCE ALERT AS/4

Day 23
2200 hours NZDT (UT +13)

AUCKLAND VOLCANIC ACTIVITY

Situation Summary

As of 2200h the situational status is:

* 45 high-frequency earthquakes were recorded today on the volcano-seismic network 25 of these events were felt, some accompanied by ground noises - indicating shallow depths of origin. 60 long-period earthquakes were recorded, as was the increased duration and intensity of volcanic tremor.

* Initial relevelling of the ground deformation sites installed yesterday appears to have detected minor inflation centred on the Mt Albert/Mt Eden Road intersection. Confirmation of this result depends on remeasurements to be made during the next few days.

Conclusion and Alert status

The **Scientific Alert** remains at **Level 2***, although occurrence of an impending volcanic eruption is becoming more likely.

Programme Leader, Volcanology

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SCIENCE ALERT AS/5

Day 24
2200 hours NZDT (UT +13)

AUCKLAND VOLCANIC ACTIVITY

Situation Summary

As of 2200h the situational status is:

* 30 high-frequency earthquakes have been recorded on the volcano-seismic network; 4 of these events were felt. All appear to have been located beneath the Three Kings area.

* Seismicity levels, including volcanic tremor duration and intensity, have decreased since yesterday. Relevelling of the ground deformation sites has detected no further inflationary trends.

Conclusion and Alert status

The **Scientific Alert** remains at **Level 2***.

Programme Leader, Volcanology

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*See attached Science Alert classification

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SCIENCE ALERT AS/6

Day 25
1000 hours NZDT (UT +13)

AUCKLAND VOLCANIC ACTIVITY

Situation Summary

As of 1000h the situational status is:

* More than 1100 high-frequency earthquakes have been recorded beneath the Three Kings area since 0800h yesterday. At least 200 of these events have been felt. Many have been accompanied by ground noises. Minor shaking damage to buildings is common in the epicentral area around the intersection of Mt Albert and Mt Eden Roads.

* Near-continuous volcanic tremor started at 0300h. The WTAz, MTAz and AUC seismographs have been saturated by this tremor.

* Relevelling of the ground deformation sites has found significant and continuing inflation centred on the Mt Albert and Mt Eden Road intersection.

Conclusion and Alert status

A **Scientific Alert Level 3*** has been declared. An eruption appears likely to occur in the vicinity of Mt Eden/Mt Albert Roads intersection within the next few days.

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SCIENCE ALERT AS/7

Day 26
0900 hours NZDT (UT +13)

AUCKLAND VOLCANIC ACTIVITY

Situation Summary

As of 0900h the situational status is:

* Ground cracking commenced around the Mt Albert/Mt Eden Roads intersection early this morning, where continuous ground shaking was felt with increasing intensity. Severe damage was caused to adjacent buildings.

* Steam and volcanic gases (including SO_2) were emitted from vents along the fissures from about 0600 h.

* Eruption of incandescent scoria and ash began at about 0800 h, with fire fountaining initially occurring along a 200 m fissure. Buildings within a few hundred metres of the vents have been partially buried, burnt, and impact-damaged by incandescent ejecta. Gas clouds (including SO_2) are being carried NE across Greenlane, and are noticeable in Remuera. Strongly felt earthquakes are accompanying the eruption.

Conclusion and Alert status

A **Scientific Alert Level 4*** has been declared, due to commencement of the anticipated eruption.

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SCIENCE ALERT AS/8

Day 26
2200 hours NZDT (UT +13)

AUCKLAND VOLCANIC ACTIVITY

Situation Summary

As of 2200h the situational status is:

* Fire fountaining has continued throughout today, with the progressive growth of a scoria cone around the vent. Ash and scoria was initially deposited to the northeast, between fallout margins at Newmarket and Ellerslie. A wind change at 1800 h has carried scoria, ash, gas and smoke further to the south, over the Penrose and Mt Wellington areas.

* A lava flow is moving down Mt Albert Road, where it has buried and/or ignited structures in its path. The lava has flowed into some buildings and many fires are burning. The ultimate size of this lava flow is unknown.

Conclusion and Alert status

A **Scientific Alert** for Auckland City remains at **Level 4*** due to the eruption.

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SCIENCE ALERT AS/9

Day 27
0900 hours NZDT (UT +13)

AUCKLAND VOLCANIC ACTIVITY

Situation Summary

As of 0900h the situational status is:

* At 1800h yesterday the wind changed to the west, carrying gas clouds and fine ash over the Royal Oak, Penrose and Mt Wellington areas.

* The lava flow advancing down Mt Albert Road is now 800 m long, about 8 m high, and 100 m wide. It has entered and ignited some adjacent buildings.

* Growth of the scoria cone and apron to NE and E of the vent has largely or partially buried the remains of adjacent buildings, in which all inflammable contents have been burnt.

* By 0800h today the eruption rate had decreased to one explosion per minute, feeding an eruption column of decreasing height. The wind has shifted back to a light southwesterly, with gas and ash dispersal into the same areas as yesterday. Lava continues to issue from the base of the cone.

Conclusion and Alert status

The **Scientific Alert** for Auckland City remains at **Level 4*** due to the eruption.

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SCIENCE ALERT AS/10

Day 28
0900 hours NZDT (UT +13)

AUCKLAND VOLCANIC ACTIVITY

Situation Summary

As of 0900 h the situational status is:

* Lava production appears to have ceased from the vent area, although the flow may continue to move.

* The scoria cone is now 100 m in height and 500 m across. Intermittent explosions continue from the vent which remains dangerous to approach. Large scoria clasts are being thrown several hundreds of metres from the crater.

* Strong gas emission continues, with fume clouds being carried across Penrose at low elevation.

Conclusion and Alert status

The **Scientific Alert** for Auckland City remains at **Level 4*** due to the eruption.
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*See attached Science Alert classification

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GLOSSARY

Accretionary lapilli	More or less spherical masses of weakly-cemented ash.
Aerosols	Solid particles or liquid droplets which are dispersed in gas (ie air).
Ash	Fine pyroclastic material under 2 mm in diameter.
Ashfall	Rain of airborne volcanic ash from an eruption cloud.
AVSN	Auckland Volcano-Seismic Network
Ballistic clast	A block or bomb explosively ejected from the vent and which (**block or bomb)** travels on a ballistic trajectory
Basalt	Dark-coloured, fine-grained volcanic rock of mafic composition (>53% SiO_2).
Base surge	Volcanic density current that moves laterally outwards as a dilute, turbulent mixture of hot gas (steam), water and solid ejecta.
Block	Pyroclast larger than 64 mm that was solid when ejected.
Bomb	Pyroclast larger than 64 mm that was partly or wholly fluid when ejected.
CBD	Central Business District
Clast	An individual constituent, grain or fragment of rock (see pyroclast).
Conduit	A passage that magma moves through.
Convected airfall	Airfall particles that were initially carried upwards by the convecting eruption column.
Crater	A basin-like, rimmed structure from which volcanic material is ejected.
D.R.E.	Dense-rock equivalent. The volume of rock erupted after all pore space caused by vesiculation and fracturing has been subtracted. This calculation is used to determine the volume of magma that reached the surface during an eruption.
Earthquake	Sudden motion of trembling in the earth caused by the abrupt release of accumulated strain.
Ejecta	Material thrown out by a volcano.
Eruption column	Column of volcanic gases and solid particles rising into the atmosphere, initially driven by gas pressure and later thermal convection.
Eruption cloud	Cloud of volcanic gas and other pyroclastic fragments.

Fault	Fracture or zone of fractures along which displacement takes place or has taken place in the past.
Felt intensity	A measure of earthquake ground shaking based on the effects on structures and people at specific locations. There is an outwardly decreasing range of intensities for a single earthquake.
Fissure	Long, narrow crack or vent along which an eruption takes place.
Flysch	A marine sedimentary facies characterised by bedded sandstones and mudstone.
Hawaiian eruption	An eruption characterised by the continuous and voluminous discharge of highly fluid lavas, often with gas-driven "fire-fountaining" of scoria to hundreds of metres above the vent.
H_2O	Water.
Hz	Hertz (measure of wave frequency; 1 Hz is 1 cycle per second)
Isopach	Line on a map drawn through points of equal thickness of a designated rock unit.
Lapilli	Pyroclasts between 2 and 64 mm in size.
Lava	Molten extrusive rock on the earth's surface; also the rock that solidified from it.
Lithic	Fragment of previously formed rock, not magmatic at time of eruption.
Maar	A low-relief, vertical-walled volcanic crater that has been cut (largely by collapse) into pre-eruption country-rock and surrounded by a low ejecta rim.
Magma	Molten rock within the earth.
Magmatic	Pertaining to or derived from magma.
Monogenetic	Resulting from one process of formation; developing at one place and time.
Phreatomagmatic	A volcanic explosion that ejects both magmatic material and steam formed by the contact of magma with groundwater or shallow surface water.
Pyroclast	Individual particle ejected during an eruption.
Radiometric dating	Calculating an age in years for geological materials by measuring the presence of radioactive elements (i.e. carbon-14, potassium 40/argon 40).
Scoria	Vesicular, coarse-grained pyroclasts, usually of basaltic or andesitic composition.

Seismicity	The rate and location of earthquakes in an area.
Seismograph	A device for recording seismic waves (produced by earthquakes).
Seismometer	The sensor part of a seismograph.
SO_2	Sulphur dioxide (gas)
Spatter	Accumulation of fluid pyroclasts around a vent.
Strombolian	Type of eruption characterized by discrete explosions ejecting basaltic magma.
Surge	Volcanic density current pulse that moves laterally outwards as a dilute, turbulent mixture of hot gas (steam), water and solid ejecta.
Surtseyan	Type of eruption which occurs when basaltic magma is erupted in shallow-moderate water depths, producing violent steam explosions ejecting highly fragmented clasts.
Tephra	Collective term used for volcanic material, regardless of size, explosively ejected from a vent through the air.
Tuff cone	A cone with smaller crater and higher rim than a tuff ring, with steeply dipping beds produced by the deposition of ejecta close to the vent..
Tuff ring	A constructional crater that lies mostly on or above the pre-eruption surface. The crater rim usually dips at a low angle both outwards and inwards
Turbidity	The state, condition or quality of opaqueness or reduced clarity of a fluid (water), due to the presence of suspended matter.
Viscosity	The property of a substance to offer internal resistance to flow.