# Rotorua District Council Hazard Studies, Part 1 Volcano and Geothermal Hazards

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**DISCLAIMER**



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# CONTENTS



# FIGURES



# TABLES

# EXECUTIVE SUMMARY

The Rotorua District Council (RDC) has commissioned GNS Science to undertake a series of hazard studies to underpin recommendations for best practice in areas of natural hazard management and planning. This report is focused on volcano and geothermal hazards. The information in this report can be used for future managing of land use to minimise the impacts of volcanic or geothermal activity.

Although four caldera volcanoes exist in the Rotorua District, only the Okataina Volcanic Centre (OVC) has erupted historically or within the last 22,000 years and is assessed as the only realistic source to consider for scenarios to establish effective crisis or District management planning of local volcanic hazards.

Volcanic hazards related to eruptions from OVC can be roughly divided into two categories: (i) near-vent destructive hazards producing areas that are completely devastated in a typical eruption; and (ii) distal damaging and/or disruptive hazards in areas where considerable damage occurs during a typical eruption. The boundary between these zones is gradational.

Active caldera volcanoes like Okataina have a tendency to experience periods of volcanic unrest that do not necessarily lead to an actual eruption, but have the potential to cause severe management and economic problems. Caldera unrest needs to be acknowledged in the District Plan and longer term plans (e.g. 10 year planning) as such unrest events/episodes cannot be ignored. This is the most likely impact that may occur during the life of the Plan.

The ash fall hazard from distal volcanic centres is likely in the life of the Plan. The disruptive rather than destructive nature of this should be acknowledged and there should be awareness that this will primarily affect utility services. These can be restored within days to weeks after ash fall has stopped.

The revised District Plan should acknowledge the new information available about the volcanism in the Rotorua District and the likely impacts from volcanic eruptions and volcanic unrest. The District Plan should recognise the District Emergency Management plans and contribute support to the manner in which these function.

The areas affected by geothermal and hydrothermal hazards are limited to relatively localised rural parts of the Rotorua District, except for parts of Rotorua city where substantial residential and commercial activities or recreation activities occur. Within Rotorua city there is thus significant potential for damage to people and property as a result of geothermal activity. The geothermal activity which poses a hazard also provides a significant resource being utilised in various ways.

Surface geothermal features provide both a hazard and features to be protected because of the intrinsic value they create. Fortunately this can be achieved by simple set backs, where no activity is allowed. This provides public safety in one instance and preservation of the feature and its micro climate-ecology on the other. Several of the building issues encountered in Rotorua city have been related to the covering of surface features, this would be avoided by setting a set back (3-5 m) from all known features. While in the rural area it also protects the environment about the features.

Hydrothermal eruptions are most likely to occur in places where the geothermal heat flow is very high, where there are existing boiling springs or high flows of steam. They can also be

triggered by nearby volcanic activity or large earthquakes. Most geothermal areas have experienced some form of eruption, but the sizes are very variable. The site and timing of these events is not available in near real-time, however the area affected is defined very early in the event. Hydrothermal explosions are usually short lived and diminish over a few hours.

Evacuation and restriction of access once an event has started are the most effective means of management.

The most common of the building issues encountered in Rotorua city have been related to the covering of surface features or boreholes and the feature or borehole reactivating. This could be avoided by setting a set back (3-5 m) from all known features and boreholes. When activity occurs this can be accommodated by evacuation and restriction of access. Usually the flow can be quenched by coldwater.

The other common problem is the development of migrating hot ground or gas flow. This is often related to a borehole or building practices and can be attributed to or contributed to by the ground cover about the building. As with heat flow, gas flux can be inhibited by the use of low porosity materials for car parks and access lanes between buildings. The use of more porous media will help maintain the natural gas flux and heat flow from the ground and lessen gas or heat being forced into buildings in many situations.

The District Plan should recognise the District Emergency Management plans and contribute support to the manner in which these function to deal with hydrothermal activity. The District Plan can contribute to this in the first instance by identifying areas of surface geothermal features and boreholes to enable latter planning and land use considerations for areas at greatest risk.

One the most important aspects of the mitigation of the volcanic hazard is detailed monitoring of the status of the volcano systems. This is conducted via the GeoNet project in New Zealand, funded by EQC. This should be acknowledged and supported in the plan for the significant contribution it makes. Additionally, enhanced knowledge of the behaviour of geothermal and volcanic hazards will help reduce the risks due to these hazards. The role of applied research should also be acknowledged and supported in the plan.

# VOLCANO

## INTRODUCTION

The Rotorua District Council (RDC) has commissioned GNS Science to undertake a series of hazard studies to underpin recommendations for best practice in areas of natural hazard management, this report is focused on volcano and geothermal hazards. The information in this report can be used for future managing of land use to minimise the impacts of volcanic or geothermal activity.

The Rotorua District is highly vulnerable to immediate and long-term effects of volcanic activity, due to its location within the Taupo Volcanic Zone (TVZ), the focus of intense volcanic activity that extends from White Island in the north to Tongariro National Park in the south. The Rotorua District also hosts many geothermal systems which are expressed at the surface as areas of warm-hot ground, hot springs and steam vents. Geothermal systems in this area are typically the by-product of volcanism and are long lived geological features with economic and intrinsic values.

Volcanic activity within the TVZ is characterised by an enormous range of eruption magnitudes, as indicated by the volumes of erupted material. The larger events have ejected 200-700 $km^3$ of pyroclastic material, whilst the smallest produced less than 0.001 $km^3$. The duration of eruptive episodes is also highly variable, ranging from a few hours to months, through to sustained intermittent activity for several centuries. The magma type and vent location have determined the variety of eruption styles, ranging from relatively gentle extrusions of lava to violent explosive discharges.

Two dominant types of volcano are present in the TVZ: cones like Ruapehu, White Island and Ngauruhoe, which erupt small volumes with minor impacts on a geologically regular basis (5-20 years), to the major caldera volcanoes which erupt significantly less frequently (1000-5000 years). The eruptions of either could produce regionally damaging affects.

The Rotorua District contains four major caldera volcanoes, those of Okataina, Rotorua, Reporoa and Kapenga (Figure 1). Eruptions from these have been characterised by large scale explosive events with regional to North Island scale impact and smaller eruptions with mainly local scale impacts. The Rotorua District is subject to a minor ash fall threat from the Tongariro National Park volcanoes and Mt Taranaki and would be impacted by virtually any activity at Taupo caldera. Eruptions of Mayor Island or White Island could have a small impact on the District if northerly winds carry ash ashore.

Geothermal systems in the District present a range of hazards in their existing state, which may be enhanced or have new hazards created by renewed volcanic activity or major earthquakes near by.

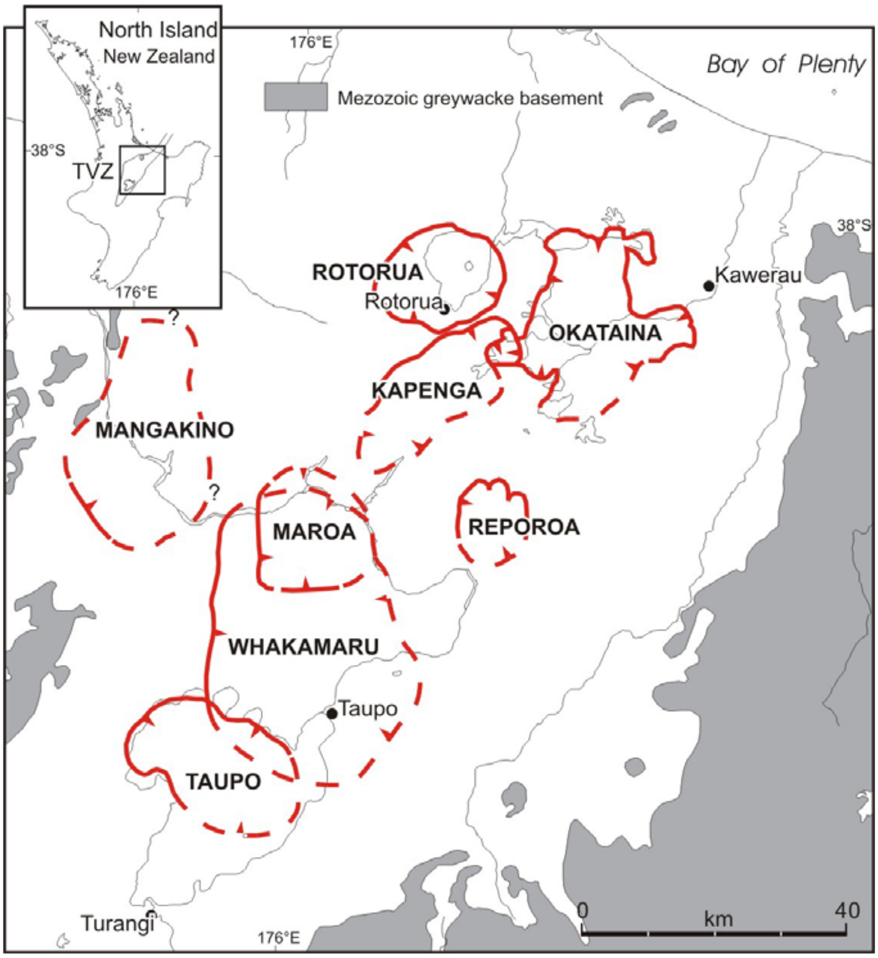


**Figure 1:** Sketch map showing the locations of the major caldera systems active in the Taupo Volcanic Zone, during the last 1 million years. The insert shows the location of the Taupo Volcanic Zone. After Nairn (2002).

In common with many other natural hazards such as floods and earthquakes there is an inverse relationship between the frequency of events and their magnitude (i.e. the less frequent the eruption, the larger the event and vice versa).

## VOLCANIC HAZARDS IN THE ROTORUA DISTRICT

The Rotorua District is exposed to a wide variety of volcanic hazards. These vary in severity and many occur simultaneously with the eruption itself, while others develop later in response to the impact of the erupted material on the landscape. The District contains four major caldera volcanoes, those of Okataina, Rotorua, Reporoa and Kapenga, while the active caldera of Taupo lies to the south (Figure 1). The cone volcanoes of the Tongariro National Park (Ruapehu, Ngauruhoe, and Tongariro) to the south (Figure 2), the offshore volcanoes of White Island and Mayor Island to the north and Taranaki in the distal south west could all produce volcanic ash fall in the Rotorua District.

The most serious hazards include tephra falls (ash falls), pyroclastic density currents (pyroclastic flows and surges), lava extrusion (flows and domes), gravitational instability of the volcanic edifice (debris avalanches and sector collapse), lahars (volcanic mudflows and floods), and hazards associated with steam and gas emissions (acid rain and poisonous gases).

## Near Source Volcanoes

Although four caldera volcanoes exist in the Rotorua District, only the Okataina Volcanic Centre (OVC) has erupted within the last 22,000 years. In our assessment, Okataina eruptions are the only realistic scenarios to consider for effective crisis or District management planning.

Volcanic hazards from OVC can be roughly divided into two categories: (i) near-vent destructive hazards producing areas that are completely devastated in a typical eruption; and (ii) distal damaging and/or disruptive hazards in areas where considerable damage occurs during a typical eruption (Figure 3). The boundary between these zones is gradational.

The eruptive history of OVC (Nairn 2002) suggests that future eruption sites are most likely to be located on the Haroharo and Tarawera vent zones; however the positions of any new vents within these zones cannot be predicted until volcanic unrest signals are detected. On the Haroharo zone, vents could be located anywhere between Lake Tikitapu and Lake Rotoma. On the Tarawera zone, vents could be located between Waimangu and the Puhipuhi hills (Figure 3).

Following a scenario based on moderate to large scale prehistoric eruptions, a future eruptive episode is likely to begin days to months in advance, with seismic activity, increased gas, fluid and heat flow and ground deformation. Initial vent-clearing steam driven explosions with significant local effects from blast and fall, would be followed by the development of kilometre-scale eruption columns that would create heavy ash fall, pyroclastic surges and flows. It is possible that eruptive activity will occur from multiple vents in simultaneous or sequential outbreaks, spread over 8-10 km along the active vent zone. Airfall volcanic ash will be showered over a downwind dispersal area, probably covering 1000 to 10000 $km^2$ to depths exceeding 30 cm over most of Rotorua District (Figure 3). Pyroclastic surges and flows are likely to travel 5 to 10 km from the eruptive vents, causing complete devastation in the near-vent region (Figure 3) and minor to moderate damage elsewhere, including destruction by forest fires spreading beyond the immediate damage zone. The most vigorous activity is likely to occur early in the eruptive sequence.

In a typical eruption of rhyolite magma, extrusion of lava flows from the explosion vents follows the pyroclastic eruptions. Due to the high viscosity of the typical OVC lavas, these flows will advance a short distance and only slowly, and should not threaten human life, although they will overwhelm any structures in their paths and start forest fires. The lava flows are very likely to be confined within the Okataina Volcanic Centre. Note that the area affected by lava flows will have been virtually destroyed by the earlier pyroclastic eruptions.

Hydrothermal eruptions are likely to recur in any of the larger high-temperature geothermal fields associated with the OVC (see Geothermal section). These may be triggered by a nearby volcanic eruption or by a major earthquake. Although locally devastating, the effects of hydrothermal/phreatic eruptions are unlikely to extend more than a kilometre from the source vents. The 1886 eruption at Rotomahana is an exception to this. The combination of a large hydrothermal system, lakes, and the intrusion of magma directly into the geothermal system lead to an unusually large phreato-magmatic event.

## Distal Volcanic Sources

Tephra studies elsewhere in the North Island indicate that eruptive activity from the Tongariro National Park (TNP) volcanoes (Figure 2), Mayor Island and Taranaki could produce ash fall up to a few centimetres thick in the Rotorua District, in episodes lasting days to months. White Island was in eruption from 1975 until 2000 and only once produced minor ash fall in Rotorua city. Activity at Taupo caldera could have a significant impact on the Rotorua District, but arguably the hazard from Taupo is less than from TNP or Taranaki volcanoes because while the latter eruptions have been small, they have been far more frequent than those from Taupo.

**Figure 2:** Small scale ash explosion at Ruapehu, June 1996. (Photo: T Hughes).

The major distal hazard is volcanic ash fall, which is likely to be disruptive rather than destructive, affecting such services as water supply, sewerage reticulation and treatment, electricity supply, and transportation (Johnston 1997). However, most systems, if affected only by thin ash fall (<50 mm) for a short duration, can be restored within a few days to weeks after ash fall has stopped. A range of impacts that could be expected are summarised in Table 1. The thickness and median grain-size of ash deposits generally decrease exponentially with distance from a volcano. The dispersal of ash will depend on several factors including the initial grain-size of the ejecta (reflecting degree of fragmentation during the eruption), dynamics of the eruption column and plume and its interaction with wind. Based on the fining and thinning relationships, the expected grain size of ash falls from the distant cone volcanoes is sub-millimetre (and comprising mostly volcanic glass), whereas eruptions from Taupo and Okataina will produce coarser tephra (pumice, rock fragments and crystals) up to centimetre size.

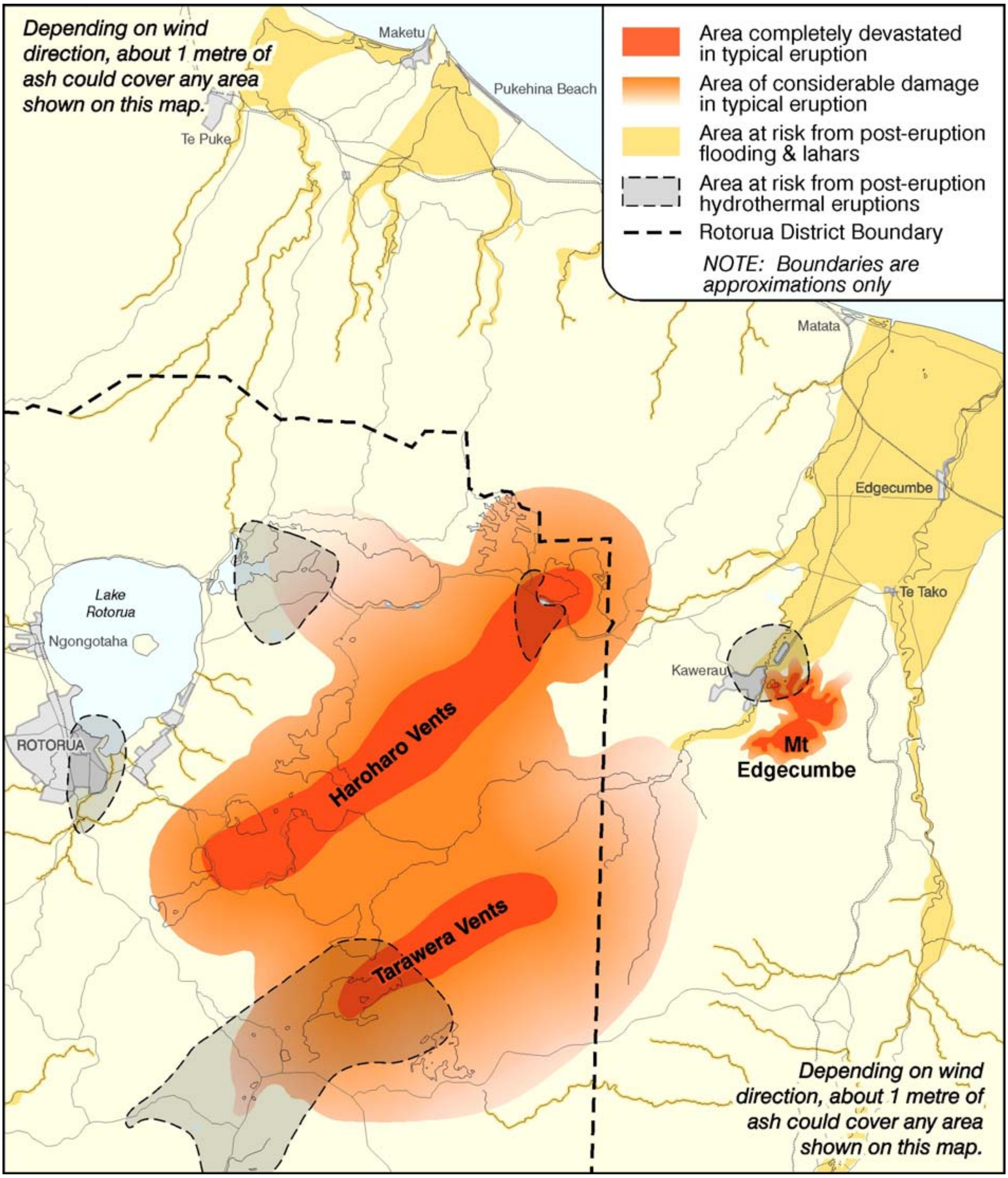


**Figure 3:** Simplified volcanic hazard map showing the areas likely to be totally destroyed by an eruption from the Okataina Volcanic Centre. After Scott and Nairn (1998), Nairn (2002). The dark orange area indicates total destruction, while the gradational orange to white area will vary from total to partial destruction.

**Table 1:** Summary of impacts of ash falls classed by thickness.

**Less than 1 mm ash thickness**

* Will act as an irritant to lungs and eyes.
* Airports will close due to the potential damage to aircraft.
* Possible minor damage to vehicles, houses and equipment caused by fine abrasive ash.
* Possible contamination of water supplies, particularly roof-fed tank supplies.
* Dust (or mud) affects road visibility and traction for an extended period.

**1-5 mm ash thickness**

Effects that occur with < 1 mm of ash will be amplified, plus:

* Possible crop damage.
* Some livestock may be affected but most will not be unduly stressed but may suffer from lack of feed, wear on teeth, and possible contamination of water supplies.
* Minor damage to houses will occur if fine ash enters buildings, soiling interiors, blocking air-conditioning filters etc.
* Electricity may be cut; ash shorting occurs at substations if the ash is wet and therefore conductive. Low voltage systems more vulnerable than high.
* Water supplies may be cut or limited due to failure of electricity to pumps.
* Contamination of water supplies by turbidity levels and chemical leachates may occur.
* High water-usage will result from ash clean-up operations.
* Roads may need to be clear to reduce the dust nuisance and prevent storm-water systems may become blocked.
* Sewage systems may be blocked by ash, or disrupted by loss of electrical supplies.
* Damage to electrical equipment and machinery may occur.

**5-100 mm ash thickness**

Effects that occur with < 5 mm of ash will be amplified, plus:

* Burial of pasture and low plants. Foliage may be stripped off some trees but most trees will survive.
* Most pastures will be killed by over 50 mm of ash.
* Major ash removal operations in urban areas.
* Most buildings will support the ash load but weaker roof structures may collapse at 100 mm ash thickness, particularly if the ash is wet.
* Road transport may be halted due to the build up of ash on roads. Cars still working may soon stop due to clogging of air-filters.
* Rail transport may be forced to stop due to signal failure bought on by short circuiting if ash becomes wet.

**100-300 mm ash thickness**

Effects that occur with < 100 mm of ash will be amplified, plus:

* Buildings that are not cleared of ash will run the risk of roof collapse, especially large flat roofed structures and if ash becomes wet.
* Severe damage to trees, stripping of foliage and breaking of branches.
* Loss of electrical reticulation due to falling tree branches and shorting of power lines.

**> 300 mm ash thickness**

Effects that occur with < 300 mm will be amplified, plus:

* Heavy kill of vegetation.
* Complete burial of soil horizon.
* Livestock and other animals killed or heavily distressed.
* Kill of aquatic life in lakes and rivers.
* Major collapse of roofs due to ash loading.
* Loading and possible breakage of power and telephone lines.
* Roads unusable until cleared.

## VOLCANIC HAZARDS ISSUES

### Discussion of Existing Policy

Currently natural hazards are covered in Part 13 of the Rotorua District Plan. Only the volcano based portion is reviewed here. The background text acknowledges the presence of larger volcanoes in the district, but not all of them. An association of volcanoes with geothermal systems is also noted. There is a focus on supporting research to further understand the issues. Since the Plan was published, considerable knowledge has been published on the volcanic history (Nairn 2002; Smith et al. 2005; Cole et al. 2010), volcanic hazards (Scott and Nairn 1998), caldera unrest (Johnston et al. 2002), volcano monitoring (Scott and Travers 2009), volcanic impacts (Johnston and Nairn 1993) and land use planning for volcanic hazards (Robertson 2007, Becker et al. 2008, 2010).

Hazard mapping (Scott and Nairn, 1998; Nairn 2002) is now able to identify at a district scale (1:100,000) the likely areas of total destruction within and about the OVC (Figure 3), but it would be very difficult to achieve this at a scale useful for smaller scale planning or policy (e.g. 1:10,000). However this should not preclude this style of information being noted on planning maps. This issue is further discussed by Becker et al. (2010). In the case of the destructive hazards that exist close to an erupting volcano, apart from the evacuation of people and removal of transportable assets (if possible), there are few or no mitigation options available to counteract the destructive hazards. This does not preclude the inclusion of this area in the District Plan and the development of policy for this area.

Similarly the areas that are more distal to OVC, where considerable damage is likely to occur during a typical eruption (Figures 3 and 4) can be identified at a District scale in the Plan and need to be noted on maps. Policy and rules could then be developed to acknowledge this. These may include policy on subdivision, land use and development, along with development of an understanding that there are hazards and landowners are aware of the level of risk and consequence. Rules could be developed that apply greater scrutiny to development in these areas. For example, further development in existing subdivisions could be prohibited or restricted (see the example in Nelson of the Tahunanui landslide area where certain types of further development are prohibited) or low-density development only allowed in Greenfield developments. However the primary mitigation issue is the development of contingency plans and preparing for the implementation of them.

A significant issue more likely to be dealt with than an eruption will be volcanic unrest, this may occur without an identified volcanic threat.

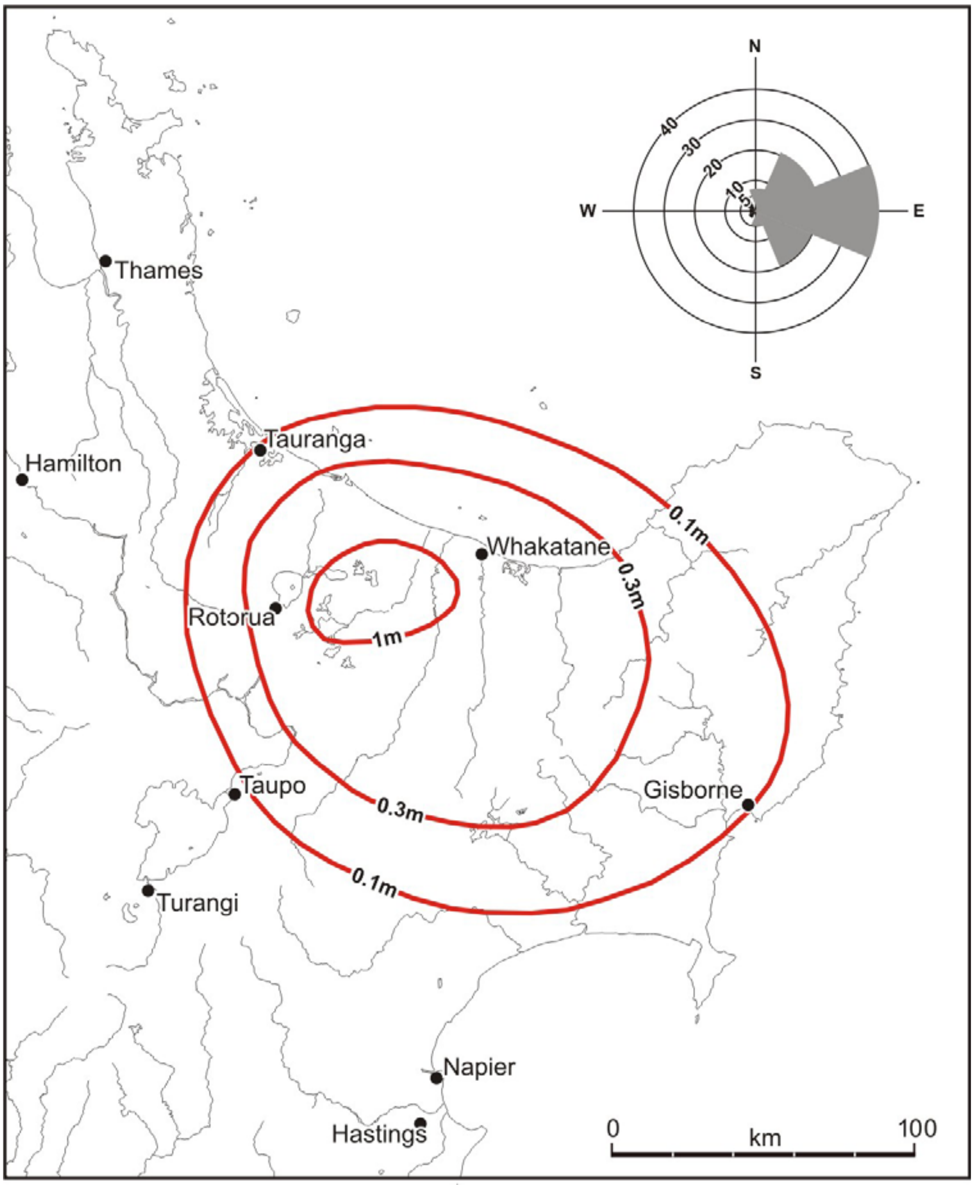


**Figure 4:** Sketch map showing possible thickness and distribution of ash fall deposits from a typical moderate to large scale explosive eruption at OVC (after Nairn 2002). The rose diagram shows typical wind directions and speed.

The District Plan does not embed Emergency Management plans, but could identify the need to do so and contribute supporting functionality for such plans. The District Plan can contribute to this by identifying planning and land use considerations that will assist in this function. For example some of the satellite population in the district lives in areas that are only accessed by one road, in particular the lakes Okareka and Tarawera areas. The plan could identify the development of additional escape routes and other emergency planning issues. As mentioned above an issue more likely to be dealt with than an eruption will be volcanic unrest, this may be more significant in the short term than the identified volcanic threat and needs to be acknowledged in District planning in both the short term and longer planning cycles (e.g. 10-20 year plans).

The major distal hazard is volcanic ash fall (Figure 2), which is likely to be more disruptive rather than destructive, primarily affecting utility services. However, most systems, if affected only by thin ash fall (<50 mm), can be restored within days to weeks after ash fall has stopped. A range of impacts that could be expected are summarised in Table 1. The thickness and median grain-size of ash deposits generally decrease exponentially with distance from a volcano.

The expected grain size of ash falls from the distant cone volcanoes is millimetre to sub-millimetre whereas eruptions from an Okataina source will produce coarser falls up to centimetre size. The distribution of ash will depend on the prevailing winds and grain-size of the ejecta.

The hazards that are likely to impact on the Rotorua District and community have been identified and from these, a number of scenarios could be developed to show the likely impacts. Then the hazards could be assessed in terms of their seriousness in relation to human, economic, social, infrastructural and geographical impacts. The manageability of readiness, response, recovery, and reduction can also be developed for each of the hazards. The assessment can then be used to moderate or lower risk and uncertainty from the hazards by raising awareness, identifying hazard based research, assessing management activities to provide more efficient operational arrangements when low likelihood events occur.

Lahars can be generated during even small eruptions, and can constitute a major hazard along any watercourse that has received pyroclastic material (ash fall or flow) during a local eruption. The hazard will exist for many kilometres downstream. The most severe, long-term, and wide-reaching impacts associated with volcanic activity involve the remobilisation of the large volumes of pyroclastic material produced during the eruption in the months to years afterwards (Figure 5). In addition to increasing flood frequency and severity within the area of primary ash fall, streams and rivers draining the affected area will also be prone to aggradation and flooding. This can be recognised at a District scale, and accommodated for in planning by introducing a policy that creates wider buffer zones along water ways when applying subdivision, use and development policy.

**Figure 5:** An example of remobilised ash and sediment in the Town of Plymouth, Montserrat, July 2005. (BJ Scott, GNS Science).

Having a buffer is one option, but another option might include ensuring low density development in areas subject to known flood or lahar risk. This might mean not allowing infill housing in already developed areas, or keeping to low density development in Greenfield areas. This can then be coupled with good subdivision design (i.e. ensuring evacuation routes are available) and warnings/emergency response planning. Obviously such planning for lahars will only work for smaller, more contained, eruptions. Widespread lahar activity after a large eruptive event is more problematic, although is a much lower probability event. Requirements for elevated floor levels in flood areas, is a sensible option for flooding, but it will have little mitigation effect for lahars where aggradation can raise flooding levels by meters (Figure 5).

The Rotorua District contains many major lake bodies which have been frequently impacted by past eruptions. For example, Lake Rotomahana significantly increased in area following the 1886 Tarawera eruption. In November 1904, a rock and sediment debris dam at the outlet area of Lake Tarawera failed, resulting in major floods downstream and a 3 metre lowering of the lake level. The geological record also indicates some of the larger hydrothermal eruptions happened when large lake level changes occurred. These often accompany volcanic eruptions in the Rotorua District. It is not possible to predict the changes ahead of eruptive activity, however the potential could be acknowledged in the District Plan. Note, Lakes Okareka and Tarawera are located in the Lakes A zone.

## Caldera Unrest

Active caldera volcanoes like Okataina and Taupo can experience periods of volcanic unrest (Johnston et al. 2001, 2002) which do not necessarily lead to an actual eruption, but have the potential to cause severe management and economic problems (e.g. Rabaul, Papua New Guinea 1972-1994; Long Valley caldera, USA 1982-present). The acknowledgement of the potential for large and highly destructive eruptions in District Plan means that unrest events/episodes cannot be ignored. This is the most likely event that may occur during the life of the Plan.

Caldera unrest is defined as a series of changes in the various background indicators of the state of the system. These may include earthquake swarms (clusters of minor, often unfelt seismic events which may last weeks to months), geodetic changes (earth movements such as uplift, subsidence, or extension), and changes in the geothermal systems like variations in hot-water spring discharges, temperatures, and water and gas chemistry. Signals of this type may or may not be significant in indicating the onset of eruptive activity, but such periods of unrest themselves present a range of hazards and social impacts and therefore require organisational acknowledgement in District, 10 year and Emergency Management plans.

As the Okataina Volcanic Centre is globally one of the most active caldera systems, caldera unrest should be regarded as a significant potential problem for the Rotorua District. However, in most cases unrest at Okataina merely reflects the broad-scale tectonic processes associated with rifting in the TVZ and central North Island. Active faulting, volcanism and geothermal activity are linked processes associated with the tectonics of the TVZ region.

## GeoHazards Monitoring

Although the OVC has been the site of the only major volcanic eruption in New Zealand during historic times, monitoring of this centre has only begun relatively recently (Scott and Travers 2009). Today an extensive modern geological hazard monitoring system has been implemented in New Zealand, including all the active volcanoes.

This monitoring is achieved via the GeoNet project, through which a network of geophysical instruments has been installed; automated software applications and skilled staff enable the detection, analysis and response to earthquakes, volcanic activity, large landslides, tsunami and the slow deformation that precedes large earthquakes. Not since the 1930s and early 1940s - a period in which large shallow earthquakes struck repeatedly - has New Zealand suffered major social disruption or serious economic setback due to geological hazards. However, historical evidence and scientific research convincingly show that risk to the population and economy from geological hazards is significantly greater than the experience of recent years. The 4 September 2010 Darfield earthquake is a reminder of this.

GNS Science monitors and assesses New Zealand’s volcanoes regularly and issues volcanic alerts as part of the GeoNet project and the National Civil Defence Plan. Volcanic Alert Levels give an indication of how active a volcano is, on a scale of 0-5. Normal background levels are ‘0’, while ‘5’ indicates a large hazardous volcanic eruption is in progress. The Volcanic Alert Levels in New Zealand guide responses that are set out in Emergency Management plans. The GeoNet website (http://www.geonet.org.nz) provides responding agencies and the public access to hazards information, including earthquake reports and Volcanic Alert Bulletins. It also allows the retrieval of fundamental data sets, such as GPS data, earthquake hypocentres and instrument waveform data. These data are made freely available to the research community and public.

Continued surveillance is required at the OVC to monitor the local volcanic induced changes and regional tectonic signatures. The integration and acknowledgement of GeoNet in the District Plan and emergency management planning is essential as the consequence of geological hazards in the Rotorua District can include the loss of life, with disruption to lifelines and services (power, water and telecommunications etc), loss of transport services (air, road), loss of medical facilities and over extension of emergency services. Thus resulting in loss of assets, disrupted economies and delays in service/product provision, an inability to access food supplies, public health issues with disruption of society (employment, education, housing). The impact of any or a combination of the above on the social and economic well being of the Rotorua communities will be significant.

### RiskScape

RiskScape is a Java based software program being developed by GNS Science and NIWA that can evaluate 'risk' from natural hazards. RiskScape combines natural hazard models and the derived spatial outputs (hazard maps) with inventory databases and inventory vulnerability estimates (fragility functions) to estimate exposure and risk. Although RiskScape is under development, a prototype volcano model is available and has been tested on the Rotorua District (Kaye 2007). The model tested was based on two of the most recent large scale eruptions from OVC (0.7ka Kaharoa or 5ka Whakatane eruptions, Nairn 2002) and demonstrates the likely impacts on population, agriculture and infrastructure.

Kaye (2007) showed that the tephra fall poses the greatest hazard, but is very dependent on the wind direction at the time of the eruption. It indicates up to 13,000 people could be exposed to harm or death, while other volcanic hazards like pyroclastic flows put another 320 at risk. RiskScape can be used to model the impacts of various scenarios.

## OPTONS TO UPDATE VOLCANIC HAZARD INFORMATION

The revised District Plan should acknowledge the new information available about the volcanism in the Rotorua District and the likely impacts from volcanic eruptions and volcanic unrest.

Hazard mapping is now available at a District scale for the Okataina Volcanic Centre. This should be introduced to the Plan, along with development of an understanding that there are hazards. Landowners should be made aware of the level of risk and potential consequences. Consideration should be given to incorporating volcanic hazards onto planning maps within settlement areas (Lakes zone A) and using district scale maps to draw attention to rural areas.

The District Plan should recognise the District Emergency Management plans and contribute support to the manner in which these function. The District Plan can contribute to this in the first instance by identifying planning and land use considerations for areas at greatest risk. For example additional escape routes could be identified and developed with other emergency planning issues.

Active caldera volcanoes like Okataina have a tendency to experience periods of volcanic unrest that do not necessarily lead to an actual eruption, but have the potential to cause severe management and economic problems. Caldera unrest needs to be acknowledged in the District Plan and longer term plans (e.g. 10 year planning) as such unrest events/episodes can not be ignored. This is the most likely impact that may occur during the life of the Plan.

The ash fall hazard from distal volcanic centres is likely in the life of the Plan. The disruptive rather than destructive nature of this should be acknowledged and draw awareness that this will primarily affect utility services. These can be restored within days to weeks after ash fall has stopped.

One the most important aspects of the mitigation of the volcanic hazard is detailed monitoring of the status of the volcano systems. This is conducted via the GeoNet project in New Zealand, funded by EQC. This should be acknowledged and supported in the plan for the significant contribution it makes.

Other options for consideration:

- Ash fall design standards for new buildings of importance, e.g. key lifelines buildings such as sporting venues, schools, supermarkets or hospitals. Even if it is considered too difficult to implement urban design for all buildings in the district, key buildings could have specific design standards applied to them.
- Likewise considering situating new key buildings out of the high hazard areas (pyroclastic flows, lahar hazards).
- New residential or industrial buildings in rural areas, that rely on their own water or sewerage supplies, could have design standards applied whereby they are able to stop ash fall entering the system (e.g. have the option of disconnecting guttering that transfers water and ash from the roof to a water supply tank).
- Preventing high density development in volcanic hazard areas (i.e. restrictions on infill housing, preferences for low density development).

Traditionally when dealing with hazards a District Plan will focus on the hazards and risk (including timeframes for these), but possibly the plan should also include the option to look at consequences as well. Recent work (Saunders 2010) has highlighted a need to consider planning timeframes for different hazards/risks and define options like acceptable levels of risk and potential resource consent categories for land use activities.

New research on these and other volcanic hazard issues will continue to inform new methods of assessing and mitigating volcanic hazards. The District Plan should acknowledge and support applied research for natural hazard risk reduction.

# GEOTHERMAL

## INTRODUCTION

In the Rotorua District many geothermal systems are expressed at the surface as areas of warm-hot ground, hot springs and steam vents. Geothermal systems in this area are typically the by-product of volcanism and are long lived geological features with economic and intrinsic values (Figure 6). They range from larger scale fields like Rotorua, Waiotapu and Waimangu, to small ones like Golden Springs or Soda spring at Rotoma.

Within a geothermal system, a variety of features can be present, ranging from hot crater lakes to boiling springs and geysers, small springs, hot and warm pools, steam vents (fumaroles) and mud pots and streams. Gas can also be discharged from the geothermal system. Unique plants, animals and micro-organisms also live in conjunction with them.

**Figure 6:** Pohutu (right) and Prince of Wales (left) geysers in eruption. New Zealand's only remaining large geysers. (B J Scott, GNS Science).

As a general rule, geothermal fields do not present a large natural hazard. There is a risk of accidental burns to people who live and work in thermal areas, or are attracted to visit them, and the emission of toxic gases can present a danger in certain circumstances. However, the greatest hazard to life and property is the infrequent occurrence of hydrothermal eruptions and collapse of unstable hot ground. A more regular problem within Rotorua is changes in heat flow induced by the failure of drillholes, both actively in use and abandoned ones.

The location of geothermal systems and features is usually stable over long periods of time, hence they are easy to manage via suitable set backs (3-5 m) and land use practises nearby. The hazards from explosive activity in steam heated features or boiling springs, larger overflows, ground collapse and ground heating are almost always contained to within the boundaries of the geothermal system, so can be managed by adopting suitable practises within these areas.

Underground services through geothermal areas will be subjected to higher than normal temperatures and acidic conditions and require special materials, design and installation, and additional maintenance.

## THE GEOTHERMAL RESOURCE

The geothermal resource in the Rotorua District is composed of the thermal energy stored in the hot rock at depth, and carried by local ground water. This is expressed at the surface as hot lakes or pools, streams carrying mineralised fluids, deposits from the mineralised waters like sinter terraces, steaming ground and fumaroles, mud pots and the unique plants, animals and micro-organisms that live in conjunction with them.

The broad spectrum represented by a geothermal resource produces a combination of values and hazards. The hazards can be physical from the features and threats to the values they create. The values include perspectives of the biological, ecological, historic, heritage, scientific, and recreational aspects. These can have local through regional or national significance and support many activities like tourism and energy or mineral exploitation.

The geothermal resource in the Rotorua District supports unique plants and organisms which evolve to add diversity to the environment and genetic pool. The environment provided by geothermal areas provides microclimates and microcosms in which these unique plants and fauna evolve.

From a historic and heritage perspective, the geothermal resource has been used by Te Arawa for more than 500 years. The potential therapeutic values of the waters were well known to the Maori before the first Europeans arrived and have since been developed in the district. Visitors both local and international have been visiting the area to witness the ‘thermal wonders’ or 'take the waters' for at least a century now. Aspects of these like the Government Gardens, Polynesian Spa, the bathhouse and the living villages of Whakarewarewa and Ohinemutu now form part of the NZ Heritage.

Rotorua is one of the key tourist attraction areas in New Zealand. Tourism has been one of the major economic bases in Rotorua since the mid-1800’s.

## GEOTHERMAL SYSTEMS

There are 20 geothermal systems recognised in the Rotorua District (Figure 7). The size of the surface and sub-surface expression is variable as is the style of activity and features and degree of exploitation or preservation. Note that the definition of the geothermal resource and its extent are the subject of a separate report (Milicich 2010). Briefly they are:

### Rotorua

A large and exploited system that underlies part of Rotorua city, running from Whakarewarewa in the south, to Ohinemutu-Kuirau-Ngapuna in the north. The system hosts the remaining large geysers in New Zealand and is subject to a regional management plan. The surface expression is variable and problems arise due to the juxtaposition of the city and geothermal system. Note that Mokoia Island is included in this area.

### Atiamuri

Small scale system, with high temperature overflowing pools in a rural area. Essentially undisturbed.

### Horohoro

A small scale system about 15 km SW of Rotorua, small springs in a rural area.

### Hot Water Beach, Lake Tarawera

Area of hot springs and warm seeps on the lake shore, and fumaroles in the bush above. Used extensively by recreational boaters and some tour operators. There maybe a connection with Lake Rotomahana.

### Humphreys Bay (Lake Tarawera)

A series of warm seeps into the lake. Maybe hydrologically connected to Lake Okataina seeps.

### Lake Okataina Springs

Small warm seepages on the lake shore. Maybe hydrologically connected to Humphreys Bay.

### Lake Rotoiti (Centre Basin)

An area of high heatflow recognised on the floor on the lake towards the eastern end.

### Lake Rotokawa

An area of small warm springs, supporting a local bath and several shallow boreholes.

### Ngakuru

An area only know as a prospect due to a small geophysical anomaly. No surface features.

### Ohaaki-Broadlands

An extensive geothermal system, exploited for electricity production.

### Orakeikorako

An extensive area of hot springs and sinter terraces, used for tourism. A significant part (70%) of this area was submerged under Lake Ohakuri when it was formed.

### Reporoa

An area of high temperature springs, located in a rural area. Also included here are the minor warm springs at Golden Springs and Butchers Pool used for local bathing.

**Rotoma-Soda Springs (Tikorangi)**

Area of warm-hot ground and springs, with lake side seeps. Supports a local bath.

**Taheke**

Moderate size area of hot ground, fumaroles and warm to hot springs. Maybe connected to Tikitere.

**Te Kopia**

Extensive area of hot ground, fumaroles, mud pools and springs on the Paeroa range about 20 km south of Rotorua. Small hydrothermal eruptions have occurred here.

**Tikitere (Hells Gate)**

Extensive area of hot ground, fumaroles, mud pools and springs about 16 km south of Rotorua. Small hydrothermal eruptions have occurred here. Supports a large tourism business and sulphur mining. Some shallow local drill holes have been drilled. Maybe connected to Taheke.

**Waikite Valley**

Area of hot and boiling springs, warm lakelets and warm ground. Exploited to support a public pool complex. Also the site of an experiment to re-establish the local springs and ground water levels.

**Waimangu-Rotomahana**

The site of extensive large scale eruptions in 1886 as the magmatic material intruded in Mt Tarawera reached the geothermal system. Today the location of large hot crater lakes, hot springs and ground. Has been the site of many moderate sized hydrothermal eruptions. Supports a large tourism business.

**Waiotapu**

An extensive area of geothermal features, including numerous explosions craters, hot springs, steam vents and warm ground. Supports a large tourism business.

**Whangairorohea**

Area of warm-hot springs near the Waikato River, in a rural area.

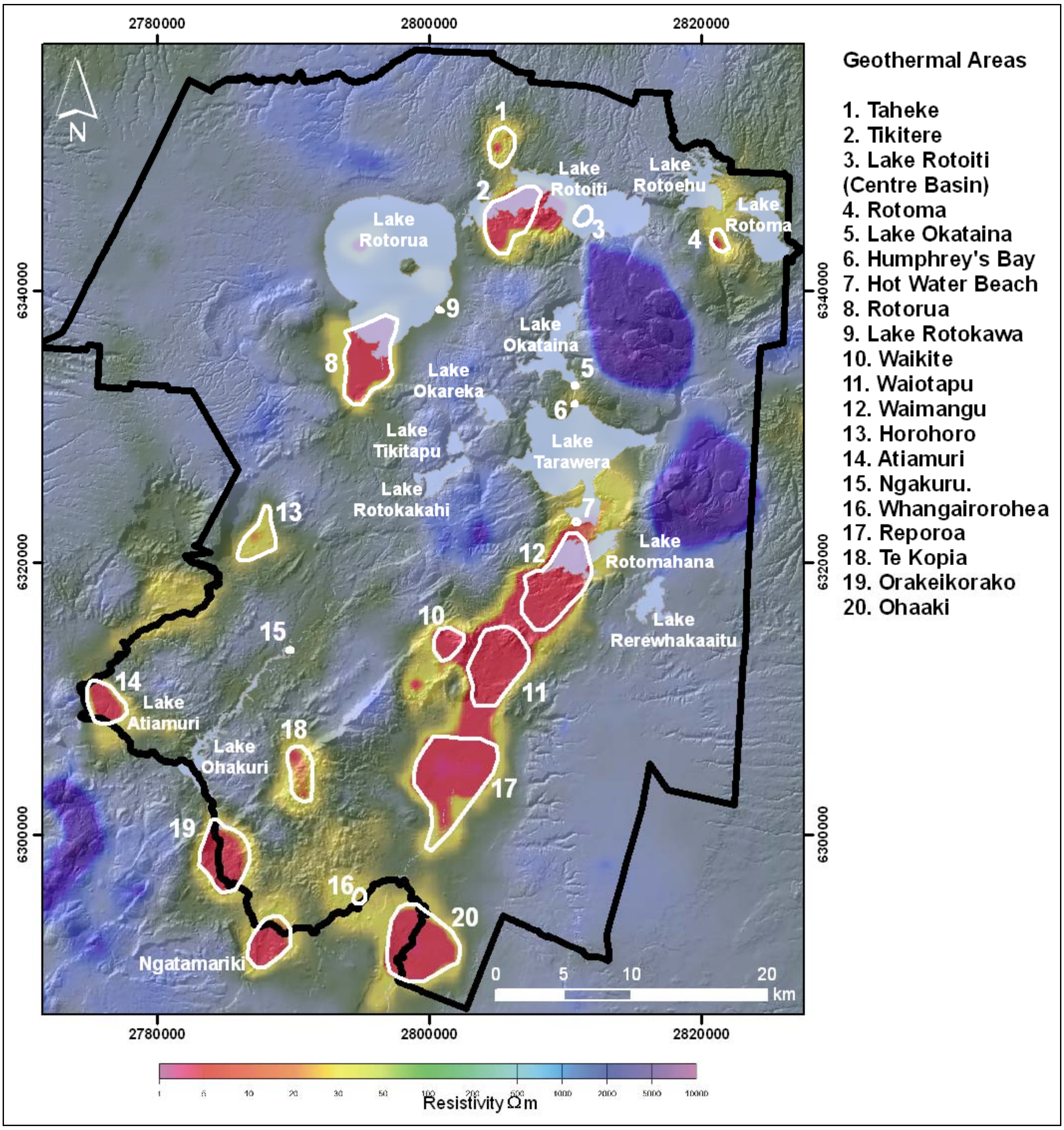


**Figure 7:** Rotorua district Schlumberger apparent resistivity (AB/2 = 500 m Schlumberger array), with geothermal areas indicated (after Stagpoole and Bibby, 1998). The areas enclosed by white lines are based on the boundary of the respective geothermal fields as defined by Environment Waikato. The black line indicates the boundary of the Rotorua District.

## SURFACE THERMAL ACTIVITY

Geothermal systems produce a variety of surface activity forms according to the nature of the processes which occur at any particular site. Activity can be grouped according to the geothermal processes that are occurring and the nature of the resulting landforms and deposits. There are two distinctive end member geothermal features. One is pools and vents fed by deep primary geothermal fluids which basically ascend directly to the surface, the other is acid-sulphate pools fed from condensed steam and gas that result from boiling at depth (10-100 m). With a continuum between these two end members, many intermediate forms of surface features and effects can result.

The availability of groundwater has a significant impact – altering the form and appearance of surface features due to addition of water and dissolved oxygen. Air entrainment allows oxidation of sulphides within exsolved gases and geothermal fluids, which in turn produce strong acid attack on most rock forming minerals.

Where geothermal fluids reach the surface without groundwater mixing, hot-clear (70-100$^{o}$C) and neutral to alkaline (pH 6.5-8) chloride hot springs occur. These fluids can be saturated in dissolved silica and silica deposition from the cooling waters as they outflow is common. These springs typically contain clear water, with pale grey-cream hard silica formations around them. Above 70$^{o}$C sulphur does not form but sulphates occur, so the fluids tend to remain clear. Below about 70$^{o}$C, photosynthetic algae can grow in fluids that contain sulphides, and of alkaline-neutral-weakly acid pH. These spring or pool waters will appear opaque or cloudy due to colloidal sulphur produced from sulphide oxidation-metabolism by bacteria.

Where geothermal fluids mix with ground waters, acid and turbid springs or pools occur, associated with low overflows. Due to longer residence times in contact with air, oxidation of sulphide to form sulphates is common in the pools. This produces acid fluids that lower the pH and the acid waters attack and dissolve adjoining ground to digest many minerals in the rock. This process and style of such a geothermal feature is common about all the geothermal areas in the Rotorua District.

In the absence of any groundwater mixing, areas heated by underground boiling permeate steam and gas to the surface through permeable materials forming barren ground. Geothermal (alum) salts will form in these areas. In addition, geothermal gas upflows attack the soils and rock to form viscous mud pools, or in dry conditions can build mud cones.

All these processes are occurring in the geothermal areas in the Rotorua District.

### Geothermal Collapse Holes

Often a conspicuous feature of the warm ground areas are the geothermal collapse holes. These appear similar to hydrothermal explosion craters, but lack explosion deposits about their margin. They are topographically closed basins or depressions that have developed by internal subterranean erosion, dissolution and subsequent collapse to form deep, steep-sided features.

These are formed by either physical or chemical erosion processes, or more commonly by a combination of both. Active processes include:

- downward percolation of acid groundwater,
- rising steam and gas condensing in groundwater to form acid fluids and
- long residence times of warm acid fluids.

These processes lead to the gradual removal of underlying rock and ash materials until collapse or subsidence occurs.  These features are common all through the geothermal areas.

## GEOTHERMAL HAZARD ISSUES

There are a variety of hazard issues associated with geothermal systems, some are generic to all systems, while others are specific to individual systems.

The surface features in a geothermal system tend to be long lived and behave in a known fashion depending on the type of feature present. For people working near or visiting there is a risk of accidental burns, and the emission of toxic gases can present a danger in certain circumstances. Certain activities have the potential to increase the potential hazards associated with geothermal activity. For example, excavation and filling of geothermal surface features may interfere with the geothermal systems, and mask the surface activity until it re-establishes itself. This may not always be passive. Weakening of the ground can occur by steam and/or acid condensate, resulting in the collapse of cavity formed by the activity. Disused geothermal production bores and soak holes are another hazard. The location of many of the earlier bores and soak holes was never accurately recorded in Rotorua city. In many cases, when abandoned they are not always totally made safe. These disused bores often manifest themselves years later as ground collapse and uncontrolled emissions of hot water, steam and gases. Carbon dioxide and hydrogen sulphide gas can be emitted from the ground, and even with low levels of emission, gas can build up to lethal levels in depressions and poorly ventilated spaces.

The intrinsic values of the geothermal areas can also be threatened by activity, in particular farming and urban development. Often mud pots are used for rubbish disposal or as offal pits. Cattle and sheep grazing or forestry can threaten the unique plants. In some case surface features are infilled in attempts to create useable ground.

Hydrothermal eruptions are likely to recur in any of the high-temperature geothermal fields in the Rotorua District. Major explosions may be triggered by magmatic eruptions (most likely in or about the OVC) or may occur in isolation related to large level changes of the lakes or may be triggered by local major earthquakes. Isolated hydrothermal explosions will be difficult to predict.

Damage from hydrothermal eruptions related to magmatic activity, large scale lake level changes and large local earthquakes could extend more than a kilometre from the eruption vents.  The geological record suggests that large hydrothermal eruptions are very infrequent, occurring only a few times in the lifetime of a geothermal field, with thousands of years separating major events. The related volcanic event is likely to have a higher impact.

Hydrothermal eruptions vary greatly in size. Minor events originate at depths of a metre or so below ground and discharge mostly water, mud and blocks to few tens of metres from the vent. The 27 January 2001 event in Kuirau Park (Rotorua) is an example of a small scale eruption (Figure 8). Major eruptions originate as deep as 300-450 m, and eject thick deposits of mixed mud and rock. The central crater of a large hydrothermal eruption can be as wide as 500 m. Major eruptions have occurred in most large geothermal areas. The best known examples are at Waiotapu and Waimangu within Rotorua District. Despite the impressive dimensions of some pre-historic deposits, they rarely extend beyond the geothermal field boundaries, and in this respect they differ from volcanic eruption deposits which can create hazards far beyond the volcano itself.

**Figure 8:** Aerial view of the area impacted by the 27 January 2001 hydrothermal eruption of Spring 721. (Photo: Rotorua Daily Post).

Exploitation at Rotorua through until 1987 was destructive to hot spring and geyser activity, but fortunately did not draw the hydrothermal system down deep enough to create dangerous, shallow production of steam. Many of the small hydrothermal events that have been documented in the Rotorua City area are directly attributable to damaged geothermal boreholes. Within Rotorua City, geothermal water levels have been rising following the 1987 bore closures and reinjection of waste fluids. In places this has resulted in reactivation of surface activity (Scott and Cody 2000; Scott et al. 2005). Whatever the cause, the eruptions do not usually eject material to more than a few tens of metres from source and are not a significant hazard to life or property, unless it has encroached on the area when geothermal activity has been at lower levels.

Frequently boiling or near-boiling springs can or do produce short lived geysering activity and/or overflows (Figure 9). Often these events will discharge debris from the vent area but do not disrupt the vent structure. Often this style of activity will be classed as hydrothermal eruptions, but are not true hydrothermal eruptions. This style of activity will rarely extend more than a few metres from the vent. These are the most common event in the Rotorua District.

Landsliding and subsidence are the two main types of land instability found in geothermal fields. Hot water, steam and gases readily alter the volcanic rocks and ashes found in Rotorua District, producing weak, clay-rich deposits, which are prone to collapse. Fortunately, most of the geothermal fields are in areas of subdued relief with gentle slopes, where gravitational collapse has a reduced likelihood. The Paeroa escarpment between Waikite and Te Kopia is the most hazardous geothermal area (with respect to land stability) in the district, particularly because it is located on an active fault. Other areas of steep, hydrothermally altered terrain occur at Rainbow Mountain and on the south side of Whakarewarewa.


**Figure 9:** Small scale violent boiling from an existing hangi (cooking pool) at Whakarewarewa Village, 11 December 2008. (BJ Scott, GNS Science).

The areas affected by geothermal and hydrothermal hazards are limited to relatively localised rural parts of the Rotorua District, except for parts of Rotorua city where substantial residential and commercial activities or recreation activities occur. Within Rotorua there is thus significant potential for damage to people and property as a result of geothermal activity. The geothermal activity which poses a hazard also provides a significant resource being utilised in various ways.

In order to effectively plan to reduce the risks from geothermal activity, it is important to establish those areas that are vulnerable from it as well as the vulnerability it also faces. Those vulnerable areas can be zoned for and have conditions applied. Surface geothermal features are unique as well as hazardous, hence setting 'set back distances' around 3-5 metres would provides protection to the features as well as reducing the risk from the hazard.

## Discussion and Land Use Criteria

Surface geothermal features provide both a hazard and features to be protected because of the intrinsic value. Fortunately this can be achieved by simple set backs, where no activity is allowed. This provides public safety in one instance and preservation of the feature and its micro climate-ecology on the other. Several of the building issues encountered in Rotorua city have been related to the covering of surface features; this would be avoided by setting a set back (3-5 m) from all known features. While in the rural area it also protects the environment about the features.

Similar applies to existing and used boreholes. These provide one of the most common issues in the Rotorua city area, it's less apparent in the other areas. Building consents should not allow for siting a building over the known site of any bore hole (as per S 71-74 of the Building Act – as it states consent should not be given in a known and unmitigated hazard area), whether it is a production or soak bore. Again this can be accommodated by setting a suitable set back distance (3-5 m), so providing enough space for a drill rig to be brought in if required for remediation.

Hot ground is a more difficult issue to address, as this is gradational across an area, and in places may only affect a small portion of an area used. There is also a lot of traditional use that has set past precedence. It has not being regulated for in the Rotorua District, but is in Taupo. Some guidance can be taken from there, where use is permitted, controlled or a restricted discretionary activity depending on the temperature and percentage of the property above set ambient temperatures (see 4e.12 Hot Ground Hazard Area in the Taupo District Plan). The guidance is:

- Permitted activity if the 'Performance Standards' for the utility or structure can accommodate the environment and ambient ground temperatures at 1 m depth does not exceed 10°C above the ambient.
- Activity is controlled if the 'Performance Standards' for the utility or structure can accommodate the environment and ambient ground temperatures at 1 m depth lies between 10 and 40°C above the ambient. Up to 75% of the area can be utilized.
- A restricted discretion is applied once the ground temperature lies in the range 40 to 60°C above the ambient. Up to 60% of the area can be utilized if the maximum temperature does not exceed 45°C, while only 40% in the range 45 to 50°C and 25% in the range 50 to 55°C.

Also the Taupo District Council uses the exercise of its discretion on the design and construction of the building and location of the building within the site; coverage of the site with buildings and sealed surfaces; the alteration or disturbance of the ground including any below ground excavation and site stability; the proposed method of venting any gas or steam; health and safety of occupants and users of the site and the general public.

The process of urbanisation and land utilisation has had an influence on the natural processes in the Rotorua geothermal area and to much lesser extent in the others in the District. These are primarily the redirection of heat flow (steam and gas) due to asphalting of road surfaces and building over warm ground and the redirection of runoff into geothermal features or collapse holes. The covering or sealing of warm ground will redirect heat flow, cause longer residence times and indirectly focus heat flow (steam and gas) into specific areas. The higher volumes of runoff will have a greater ability to flush hydrothermally altered material out of the country, therefore accelerating cavity growth, and eventual collapse of altered ground. Consideration should be given to stop the use of geothermal areas as sites for storm water disposal. More importantly consideration should be given to reducing the total area of warm ground covered by semi impermeable material (e.g. asphalt and concrete) so artificially high ground temperatures are not focused into specific areas. The use of more permeable materials should be encouraged (e.g. cobbles). This also applies to areas of gas flux discussed below.

Geothermal water always contains dissolved gases which are evolved as the water boils or cools and depressurises as it rises to the surface. The main toxic geothermal gases are carbon dioxide ($CO_2$) and hydrogen sulphide ($H_2S$). Both are denser than air, and flow into depressions. $H_2S$ has caused a minor number of deaths in Rotorua urban area over the years, always in situations where the victims have been in a confined space such as a road work trench, small room or enclosed thermal bathing pool. Many have had contributing circumstances.

Under normal circumstances, $H_2S$ concentration in air around open thermal areas is unlikely to build up to the very dangerous level of >430 mg/m$^3$. $H_2S$ is a hazard in all areas where geothermal water or steam is used, and regulation is in place to administer this. Use of the appropriate safety procedures should always be encouraged and endorsed. Especially when working in enclosed spaces or below ground level.

There is also an issue with gas entering buildings and accumulating. In some cases this can be attributed to or contributed to by the ground cover about the building. As with heat flow, gas flux can be inhibited by the use of low porosity materials for car parks and access lanes between buildings. The use of more porous media will help maintain the natural gas flux from the ground and lessen gas being forced into buildings in many situations. Unlike ground temperatures it is more difficult to ascertain and quantify the gas flux. The $CO_2$ flux in Rotorua city has been mapped in some detail (Werner 2005) and this provides a good guide to areas where gas flux maybe an issue. $H_2S$ flux has not been mapped in the same detail but the technology is now available to do this.

The quantification of gas flux and sub surface temperatures during site investigations should be uniformly instigated or maintained so Council can establish if activity should be permitted or restricted during development.

Ground collapse is the most frequent cause of accidents to people visiting thermal areas.

Sinter sheets and hardened bare ground surfaces often conceal holes filled with steam or scalding water, and are liable to give way under the weight of a person. Popular thermal areas usually have adequate warning signs, board walks and fences in dangerous areas to avoid this. This problem is restricted to areas of hot springs and warm ground.

## Response Criteria

Hydrothermal eruptions are most likely to occur in places where the geothermal heat flow is very high, where there are existing boiling springs or high flows of steam. They can also be triggered by nearby volcanic activity or large earthquakes. Most geothermal areas have experienced some form of eruption, but the sizes are very variable. The site and timing of these events is not available in near real-time, however the area affected is defined very early in the event. Hydrothermal explosions are usually short lived and diminish over a few hours.

Evacuation and restriction of access once an event has started are the most effective means of management.

Frequently boiling or near-boiling springs will produce short lived geysering activity and/or overflows that will discharge debris from the vent area but do not disrupt the vent structure. Although this style of activity is not classed as hydrothermal eruption, the mitigation remains the same, evacuation and restriction of access once an event has started. If the active vent is small it may be possible to reduce the activity by quenching with cold water. This needs to be assessed on a case by case basis.

The most common of the building issues encountered in Rotorua city have been related to the covering of surface features or boreholes and the feature reactivating. As discussed above this could be avoided by setting a set back (3-5 m) from all known features and boreholes. When activity occurs this can be accommodated by evacuation and restriction of access. Usually the flow can be quenched by cold water.

The other common problem is the development of migrating hot ground. Almost always this relates to a borehole and is remedied by locating the borehole and repairing it.

The District Plan should recognise the District Emergency Management plans and contribute support to the manner in which these function to deal with hydrothermal activity. The District Plan can contribute to this in the first instance by identifying areas of surface geothermal features and boreholes to enable latter planning and land use considerations for areas at greatest risk.

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