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Modelling Geophysical Precursors to the Prehistoric c. AD1305 Kaharoa Rhyolite Eruption of Tarawera Volcano, New Zealand

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Abstract. The ∼AD1305 Kaharoa rhyolite eruptive episode is the largest volcanic event (≥4 km^3 magma) to have occurred in New Zealand during the last 1000 years. Proximal areas were devastated by pyroclastic flows, and tephra fell over much of the northern North Island. No eyewitness observations are recorded, but ejecta analyses show that the rhyolite eruptions were primed and triggered by basalt intrusions. This key finding, combined with observations of similar modern eruptions, has allowed construction of a conceptual scenario of the seismic and other activity that likely preceded the Kaharoa episode.

The precursory scenario begins at −5 years (before the first eruption). Rising basalt magma intrusions generate deep long-period earthquakes in the lower crust, before intersecting and heating a rhyolite magma body at ∼6 km depth beneath Tarawera. By −1 year, increased heat flux from the rhyolite magma body had raised temperatures and pressures in the overlying hydrothermal system; generating shallow long-period earthquakes and increased heat flow at the surface. At −2 months, shallow volcano-tectonic earthquake activity intensified, driven by inflation of the rhyolite magma body, with magmatic gas appearing in fumarole discharges. Rapidly accelerating seismicity, ground deformation and surface heat flow occurred in the last few weeks and days, before the initial vent-opening explosions intensified into major plinian eruptions.

Effectiveness of the present volcano monitoring system at Tarawera can be evaluated against this scenario. The precursory seismic activity, including the critical deep long-period earthquakes, would be recorded but not accurately located. Similarly, the existing ground deformation monitoring systems would detect early magma chamber inflation, but discrimination from the background tectonic tilting signal would be difficult. Continuous telemetering of geodetic data from existing and additional instruments would be required for any useful monitoring of rapid ground deformation in the final precursory phases.

Key words: prehistoric, eruption, rhyolite, basalt-triggered, precursory, seismicity, ground deformation, monitoring.

1. Introduction

The ∼AD1305 (Hogg *et al.*, 2000) Kaharoa eruptive episode occurred at Tarawera volcano within Haroharo caldera, Okataina Volcanic Centre, Taupo Volcanic Zone

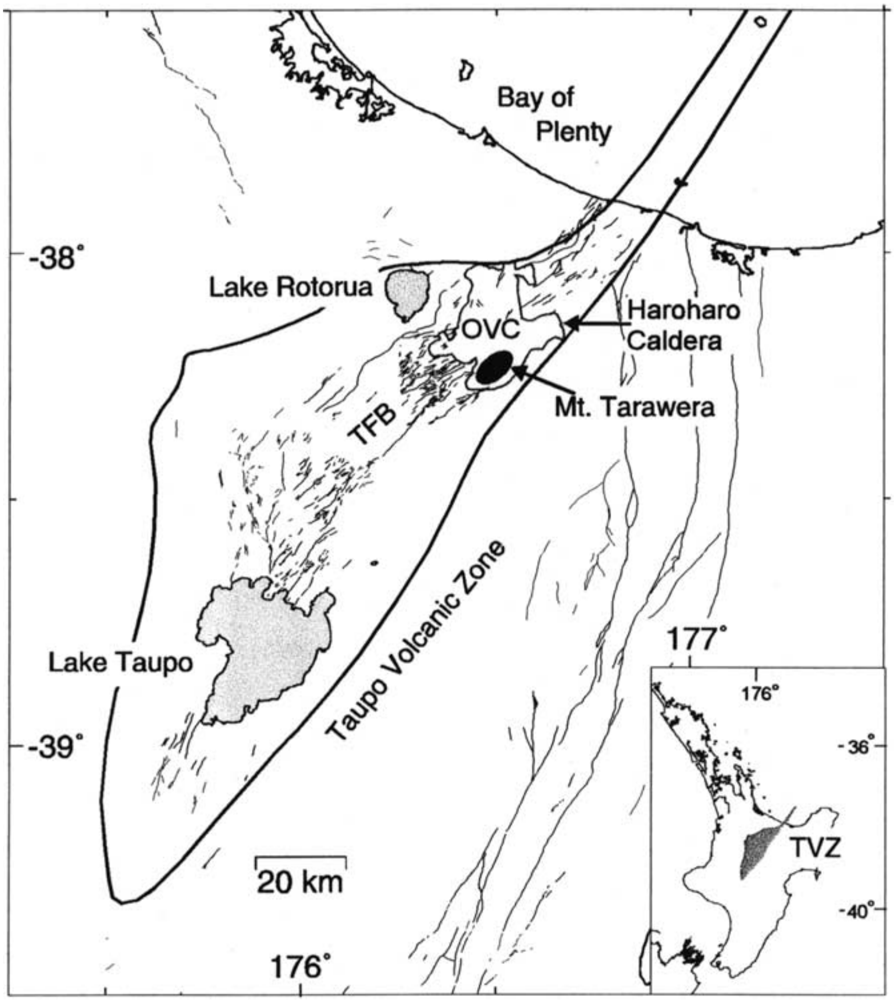

Figure 1. Location of Tarawera volcano, Haroharo caldera, and Okataina Volcanic Centre (OVC) within the Taupo Volcanic Zone (TVZ). TFB is the Taupo Fault Belt.

(Figure 1). It is the largest volcanic episode (>4 km^3 magma) to have occurred in New Zealand during the last 1000 years, and the only one of rhyolitic type. No observations of the Kaharoa episode are recorded, but geological and petrological studies have produced a detailed picture of its eruptive and magmatic processes (Nairn *et al.*, 2001; Leonard *et al.*, 2002). Recognition that the rhyolitic Kaharoa eruptions were primed and triggered by basalt intrusions has provided a key to defining the types of seismic and other activity that likely preceded the episode. If this precursory activity can be characterised, it would provide useful insights into the geophysical signals that will precede the next Kaharoa-type rhyolite episode.

Many of the world's active and potentially active volcanoes are monitored in an effort to detect geophysical precursors to impending eruptions. This study reverses the procedure by working back from the unmonitored Kaharoa eruption to its inferred precursors. A scenario of precursory geophysical events is developed by combining knowledge of Kaharoa magmatic processes and the crustal structure of the Tarawera region with geophysical data recorded from similar modern eruptions. This scenario is used to evaluate the effectiveness of the existing volcano-monitoring system around Tarawera in detecting such precursory activity.

2. Geological Model of the Kaharoa Eruption Episode

Kaharoa eruptives are dominantly rhyolitic in composition, with >4 km^3 of magma erupted from 7 vents (Figure 2) that define an 8 km linear zone across Tarawera volcano (Nairn *et al.*, 2001). Initial vent-opening explosions were followed by generation of a series of high ($>$ 20 km) plinian eruption columns (Sahetapy-Engel, 2002) from which tephra was carried downwind to the southeast across the east coast of the North Island. Collapse of the plinian columns produced pyroclastic density currents of hot gas and ash that flowed over the slopes of the volcano (Figure 2). The early pyroclastic eruptions were followed by extrusion of a small lava dome in the initial plinian vent, and the migration of explosive activity to adjacent vents. Later pyroclastic eruptions from northern vents occurred during winds from the south and southeast, dispersing tephra north and northwest across the North Island. Three large lava domes were then slowly extruded on top of the volcano, with partial collapse during dome growth generating extensive "block-and-ash flow" avalanches of hot gas and lava clasts that flowed >10 km from the vents (Figure 2). An approximately 4-year duration for the Kaharoa episode is estimated from the tephra dispersal relationships, and comparison of Kaharoa lava volumes with the extrusion rates observed at modern silicic dome-building eruptions (Nairn *et al.*, 2001).

Rhyolite magmas in the Taupo Volcanic Zone are considered to be generated by partial melting near the base of the crust. These melts rise through the crust to accumulate in high-level storage zones where magma density equals that of the surrounding rocks. Chemical and mineralogical parameters (Leonard *et al.*, 2002; our work in progress) indicate that the Kaharoa eruptions occurred from a stratified rhyolite magma chamber, located at $\sim$6 km depth in the upper crust (Figure 3). Total volume of the Kaharoa pre-eruption magma body may have been about 10 km^3, of which about half (5 km^3) was erupted (Nairn *et al.*, 2001).

Basaltic inclusions are common in the Kaharoa pyroclastics, as free clasts, and as enclaves within rhyolite pumices. Two main basalt types have been identified (Leonard *et al.*, 2002); (1) hornblende-bearing basalts that had been in contact with the Kaharoa rhyolite magma for sufficient time for small hornblende crystals to grow in the basalt groundmass; (2) other basalt inclusions that lack any hornblende and had been in contact with the rhyolite magma for a much shorter time. The groundmass hornblende-bearing basalts mingled, mixed and hybridised with rhyolite near the floor of the magma chamber (Figure 3). Exchange of xenocrysts,

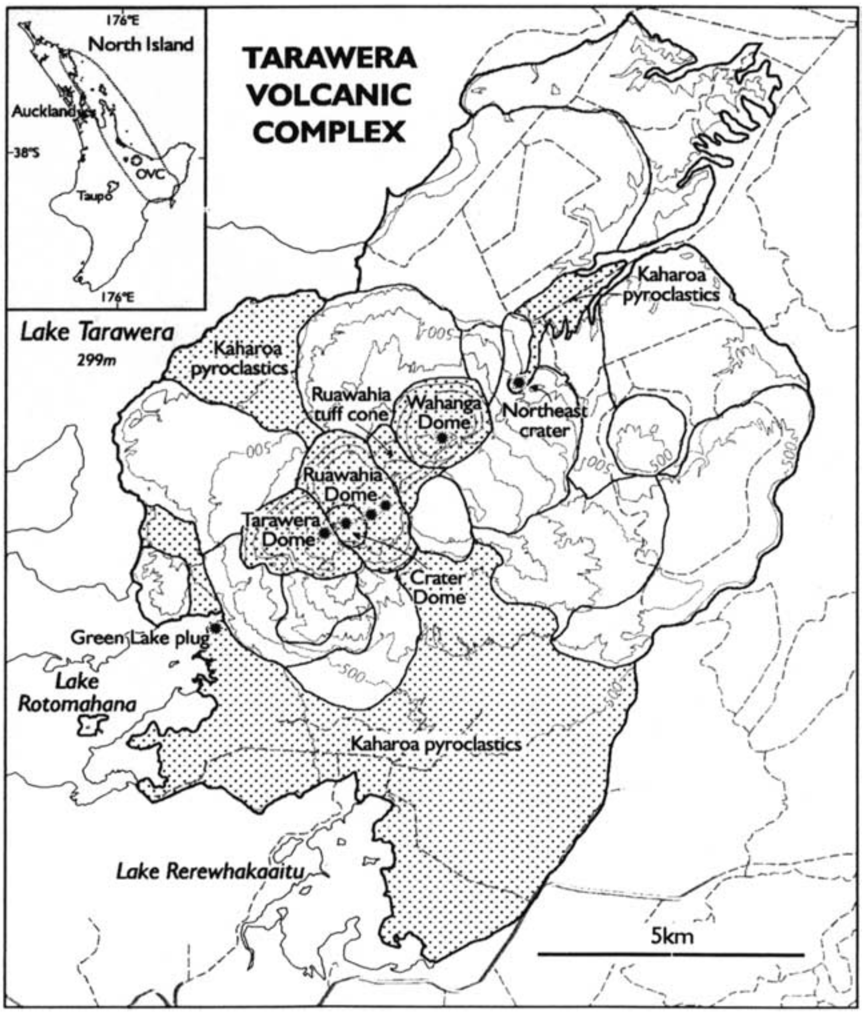

Figure 2. Map of Tarawera volcano, with thick Kaharoa eruptives stippled; stars mark Kaharoa vents. Inset map shows 3 cm isopach for Kaharoa tephra fall deposits.

resorbtion of quartz phenocrysts and zoning of plagioclase crystals shows that multiple basalt intrusions occurred for some time before the first eruptions commenced. The rhyolite magma body was primed by these injections of mass, heat and volatiles until what became the triggering basalt intrusion tipped the balance into eruption (Leonard *et al.*, 2002). The triggering intrusion is represented by the basalt inclusions that lack hornblende; these were quenched by eruption before growth of groundmass hornblende could occur. Petrological features suggest that Kaharoa rhyolite magma reached the ground surface less than 4 days after the eruption was triggered by the final basalt intrusion event.

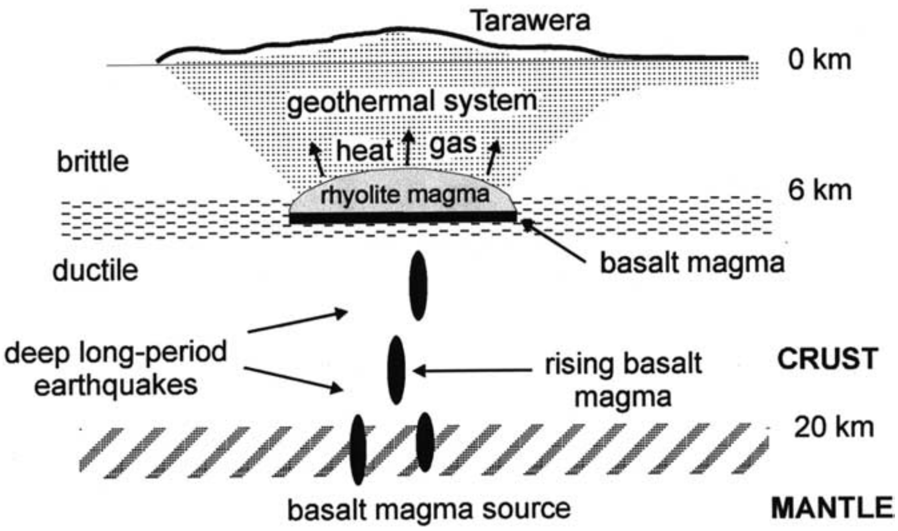

Figure 3. Schematic diagram of scenario crustal structure beneath the Tarawera area before the Kaharoa eruption, based on regional seismicity, and petrology of Kaharoa eruptives.

3. Modern Similar Observed Eruptions

No historically recorded eruption is closely similar to the Kaharoa rhyolite episode, but some aspects of some modern eruptions provide useful analogies.

3.1. SAKURAJIMA 1914–15 (KYUSHU, JAPAN)

Sakurajima volcano, on the southern boundary of Aira Caldera (Kobayashi, 1988), erupted 2.2 km^3 of andesite lava in 1914–15. The eruption was accompanied by surface subsidence of >0.5 m with horizontal displacements of >4 m on the volcano flanks. The ground deformation was modelled as deflation of a pressure source at 7–10 km depth beneath the centre of the caldera (Ishihara, 1988), i.e., about 10 km to north of the vent.

3.2. UNZEN 1990–95 (KYUSHU, JAPAN)

Eruptions of dacite lava in 1990–1995 were preceded by a 12-month migration of seismicity from 15–20 km west of Unzen to beneath the volcano. Isolated tremor occurred from five months before the first eruption, probably at shallow depth beneath the summit. Geodetic surveys revealed continuous subsidence of the western part of the volcano, apparently associated with the lava extrusion at the summit (Ishihara, 1993). The subsidence was modelled from three deflation sources, the strongest at 7 km depth and about 4 km west of the summit. The earthquake migration, and subsidence during the eruptions, strongly implies a magmatic path, or magma reservoir, deep (13 ± 2 km) beneath the western part of the volcano (Umakoshi *et al.*, 1994).

3.3. PINATUBO 1991–1992 (LUZON, PHILIPPINES)

This summary of the 1991 Pinatubo eruptions is based on Wolfe and Hoblitt (1996). The last recognised eruption of Pinatubo occurred about 500 years ago. Small local earthquakes were felt in March 1991 before a phreatic explosion on April 2 1991 was followed by increased steam and SO_2 discharges and minor ash emission. The first seismographs were installed on April 5, at 10 to 15 km northwest of the summit. During the next several weeks these (and additional) stations recorded between 40 and 140 seismic events per day, mostly of $M < 1$. From late-May to early-June subtle changes signalled a trend of accelerating seismic activity, although SO_2 gas emissions, which had increased tenfold from May 13 to May 28, suddenly decreased as if magma had sealed the conduits for gas-escape to the surface. Seismic-energy release increased in early June and became localised beneath the summit. It was accompanied by inflationary tilt on the upper east flank of the volcano, and culminated in the extrusion of a small (mixed-magma) andesite lava dome on June 7. Seismic-energy release continued to increase over the next five days before four brief explosive eruptions of dacitic pyroclastics during June 12–14 were accompanied by significant periods of volcanic tremor. Over the next 24 hours a series of pyroclastic eruptions with increasing seismic-energy release built up to the 9-hour climactic eruption on June 15 when 5 km^3 magma was erupted.

The 1991 Pinatubo eruption was driven by intrusion of basalt magma into a much larger volume of more silicic (dacite) magma. Basalt is present as inclusions within the andesite of the initial dome extrusion, and the andesite is the product of mixing of basaltic and dacite magmas (Pallister *et al.*, 1996). Detailed analysis of the pre-eruption seismic records has identified deep, long-period (DLP) earthquakes, interpreted as caused by injection of basalt magma into the lower crust at Pinatubo (White, 1996).

3.4. RABAUL 1994 (NEW BRITAIN ISLAND, PAPUA NEW GUINEA)

The Rabaul caldera complex has a long history of active volcanism (Nairn *et al.*, 1994), with the latest caldera-forming eruption about 1400 years ago producing the present Rabaul harbour. Precursory activity began in 1971 with a gradual increase in seismicity accompanied by slow uplift of the caldera floor. Seismicity and deformation accelerated during a volcanoseismic crisis in 1983–85. Several thousand earthquakes were recorded each month and up to 1 m of uplift was measured within the caldera (McKee *et al.*, 1985). After 1985, seismicity decreased and uplift slowed. Minor periods of increased seismicity and associated uplift occurred during the next 9 years (Saunders, 2001) but at much less than the crisis rate (Nairn and Scott, 1995). At 3:00 pm on September 18 1994, two intra-caldera earthquakes (the largest M5.1) occurred on east and west sides of the caldera, near Tavurvur and Vulcan volcanoes. These earthquakes were followed by intense, but stable, seismicity near Vulcan. At that time the activity was regarded as typical of a caldera ring-fault earthquake swarm, with tiltmeters showing deflation. At dawn on September 19, uplift near Vulcan (5–6 m) and Tavurvur (1–2 m) was observed to have occurred overnight. Explosive eruptions began at Tavurvur at 6:06 am and at Vulcan at 7:17 am. Post-eruption inspection of the seismograms revealed that several long-period events had occurred in the 12 hours prior to the M5.1 earthquakes. Evidence for basalt involvement has been found in the andesite-dacitic eruption deposits (Roggensack *et al.*, 1996; Patia *et al.*, 1997).

3.5. MONTSERRAT 1995 (WEST INDIES)

Soufriere Hills volcano (on Montserrat island) last erupted about 350 years ago. Seismic crises without eruptions occurred in 1897–98, 1933–37, and 1966–67; an approximate 30-year periodicity (Young *et al.*, 1998). Increased seismicity in 1992 was followed by many relatively deep (10–20 km?) earthquakes in 1994, but no immediate seismic (or hydrothermal) precursors were recognised before the phreatic first eruption in July 1995 (Young *et al.*, 1998). The initial phreatic eruption phase was accompanied by volcano-tectonic earthquakes mostly beneath the volcano and adjacent areas, with events concentrated at 4 km northwest of the eruption vent. Some long-period earthquakes and volcanic tremor were also recorded (Aspinall *et al.*, 1998). A swarm of shallow hybrid earthquakes preceded extrusion of the first lava dome in September 1995, though the relatively distant geodetic network saw no deformation, and no hydrothermal changes were observed (Young *et al.*, 1998). The onset of continuous dome growth and collapse in November 1995 was preceded by a tenfold increase in the seismic event rate and inflation recorded near the dome (Kilburn and Voight, 1998; Voight *et al.*, 1998).

The Montserrat episode was triggered by injection of basaltic magma into a cooled and highly crystallised andesite magma body (Murphy *et al.*, 1998). The intrusion reheated and remobilised the largely solidified andesite magma. It was not possible to determine the number or timing of injection events, but the relatively deep seismicity in 1992 may have accompanied rise of the basaltic magma (Murphy *et al.*, 1998).

4. Structural Setting and Seismicity of Tarawera Volcano

4.1. STRUCTURE

Continuous extension (rifting) of the Taupo Volcanic Zone (TVZ) at about 1 cm per year has produced the intensely fractured “Taupo Fault Belt” to SW and NE of the Okataina Volcanic Centre (OVC – Figure 1). Few faults are mapped within the OVC, which has a long and complex history of volcanism (Nairn, 1989, Wilson *et al.*, 1995). Large pyroclastic eruptions between 350 ka and 65 ka caused major caldera collapse, subsequently infilled with large volumes of low-density eruptives and sediments. The caldera-fill is signalled by low gravity values (-55 μN/kg), and low seismic velocities ($>$10% below average) to 4 km depth. Tarawera volcano is situated across the southeast margin of this low gravity – low velocity anomaly, which is centred near the outlet to Lake Tarawera (Figure 2),

The depth and style of seismicity in the Tarawera area is determined by crustal structure, i.e., the depths to the brittle-ductile transition, and the crust-mantle boundary. Within the TVZ, depth to the mantle is estimated at about 15 km (Stern 1986), or 20 km (S. Bannister and C. Bryan, pers comm., 2000). The brittle-ductile transition occurs within the crust and represents the temperature-controlled boundary at which brittle behaviour above changes to ductile behaviour below. The transition determines the maximum depth to which normal tectonic earthquakes will occur. Earthquakes are common above the transition, but below it the crust does not fracture under normal (tectonic) strain rates, and earthquakes are uncommon. A transition depth of 6 km in the central TVZ has been determined from studies of recent seismicity (Bryan *et al.*, 1999). Few earthquakes have occurred beneath the Tarawera area since seismic monitoring began (see Section 4.2), so that the brittle-ductile transition depth is not precisely known here. The focussing of hydrothermal and magmatic heat flow in the Tarawera area suggests the transition may be shallower here than elsewhere, i.e., at $\leq$6 km depth. Tectonic earthquakes are likely to be uncommon below this depth under the normal strain rates associated with the ongoing tectonic extension across the TVZ. However, should earthquakes occur deeper than the brittle-ductile transition, this may indicate a significant increase in strain rate, a process likely during the rapid intrusion of magma.

Basalt magma in the TVZ is generated below the crust-mantle boundary (Gamble *et al.*, 1990), which the scenario model (Figure 3) assumes to be at 20 km depth beneath Tarawera. Deep, long-period (DLP) earthquakes are expected to occur in the lower crust during the rise of basaltic magma from the crust-mantle boundary (as recorded at Pinatubo (White, 1996)). Such DLP earthquakes occur below the brittle-ductile transition.

4.2. CURRENT SEISMICITY

Permanent and temporary seismic networks installed in the Okataina area (Figure 4) since 1992 have recorded little or no crustal seismicity within about 5 km of Tarawera (Figure 5). In contrast, earthquakes regularly occur on the Haroharo vent lineation about 10 km north of Tarawera, and swarms of shallow tectonic earthquakes are common in the Waiotapu-Waimangu area (Bryan *et al.*, 1999) to southwest of Tarawera. The nearest ‘seismically active’ fault to Tarawera is the Wairua Fault about 5 km to the west (Figure 4).

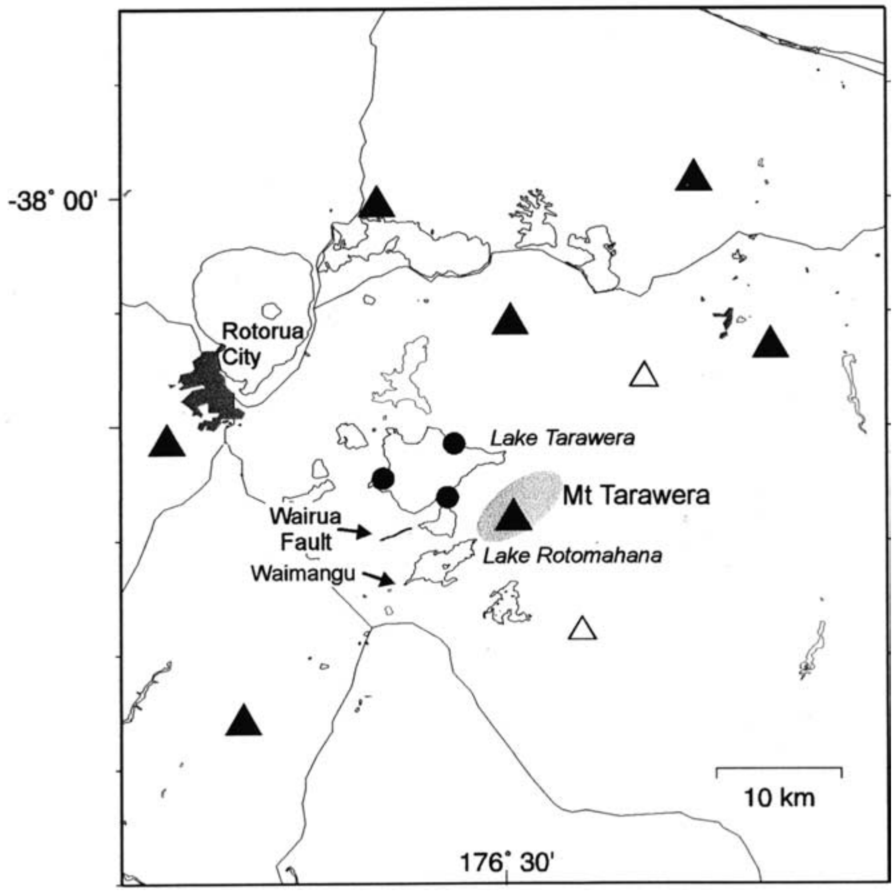

Figure 4. Map of the OVC permanent seismic stations (▲) and ground deformation sites (●) as in 2002. The open triangles (△) show locations of two hypothetical seismographs added during the scenario precursory period (see text). All seismographs are vertical component only. Shaded ellipse marks Tarawera eruptive vent area.

5. Scenario of Geophysical Events Preceding the Kaharoa Episode

In this section, the geological model of the Kaharoa episode is combined with the structural setting of Tarawera volcano to develop a scenario of likely precursory activity (Figure 6), with some events based on observations of similar modern eruptions. The scenario contains relatively ordered changes over years, months and weeks, accelerating to the first eruption. The real precursory sequence is likely to have been considerably more complex and included significant short-term fluctuations in intensity, and/or pauses between the different phases, as demonstrated by some of the historic eruptions described in Section 3 (and others). While there is geological evidence for the Kaharoa magmatic and eruptive processes described in the scenario, little is known about the rates or intensities of the magmatic processes

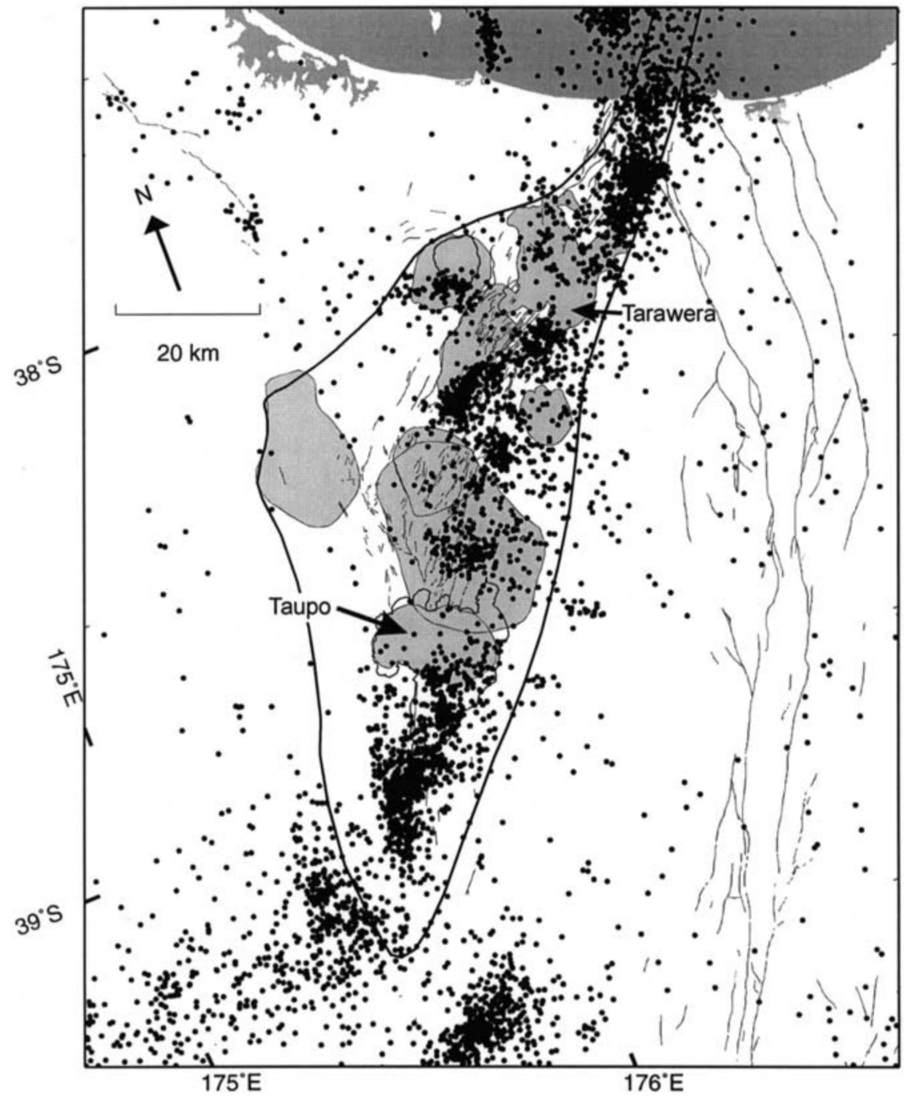

Figure 5. Epicentres of shallow (<20 km depth) earthquakes that occurred in the central North Island between 1987 and 1994. Outline of TVZ is shown (as in Figure 1); major calderas are shaded, and the outlines of lakes Rotorua and Taupo are shown. Note that there are few earthquakes near Tarawera volcano.

so that the event chronology is much less constrained. The scenario timing should not be taken as an accurate guide to a future eruption, but it does reflect that some precursory processes are inferred to occur over several years; others over a few days or hours.

Without relevant data as to location of the Kaharoa magma body the scenario locates it directly beneath Tarawera, rather than laterally displaced (as at

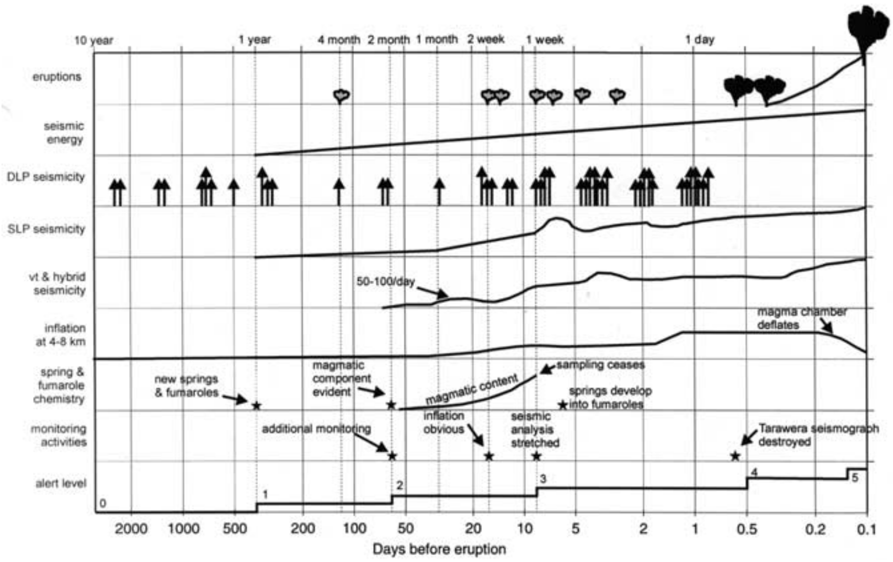

Figure 6. Timeline (logarithmic scale) summarizing the scenario precursory activity and scientific response before the Kaharoa eruptive episode.

Sakurajima and Unzen). Also included here are the scientific observations and recommendations that could be made if the scenario events were to occur at the present time. The active status of New Zealand volcanoes is defined by the 'Scientific Alert Level' (SAL – Table I). Note that the SAL is intended to define the current state of a volcano and does not include any prediction of time to onset of eruption (Scott, 2001).

5.1. ABOUT 5 YEARS BEFORE ERUPTION

Infrequent, small basalt intrusions rise from the base of the crust to pond beneath and begin to heat the rhyolite magma chamber at $\sim$6 km depth (Figure 3). The Tarawera seismograph (Figure 4) records occasional long-period (LP) earthquakes as distinctive monochromatic 2 Hz signals that gradually become more frequent and clustered in time. P-waves are clearly recorded, but S-wave arrivals are poorly recorded by the vertical-component only seismometer, with an uncertainty of 1–2 seconds. Most of these earthquakes are too small ($<$M2.5) to be located by the OVC network, but the larger LP events are recorded on enough seismographs to be placed beneath the Tarawera area at a depth of 15 km. They are classified as deep long-period (DLP) events, with location uncertainty about $\pm$4 km lateral and vertical (Sherburn and Nairn, 2001). No shallow seismicity is observed. Lake-levelling data from Lake Tarawera show a small, long-term trend (up at Tarawera), just recognisable above the $\pm$6 mm noise level over a 1–2 year period, and interpreted as 'regional tilting', of tectonic origin. The SAL (Table I) is at zero.

Table I. The Scientific Alert Level (SAL) table for reawakening dormant volcanoes in New Zealand

0	Typical background surface activity, seismicity, deformation and heat flow at low levels.	Usual dormant, intra-eruption or quiescent state.
1	Apparent seismic, geodetic, thermal or other unrest indicators.	Signs of volcano unrest. No significant eruption threat.
2	Increase in seismicity, deformation, heat flow and/or other unrest indicators.	Indications of intrusive processes. Local eruption threat.
3	Commencement of minor eruptions at reawakening vent(s). Relatively high and increasing trends shown by unrest indicators.	Increasing intrusive trends indicate real possibility of hazardous eruptions.
4	Establishment of magmatic activity at reawakening vents(s), with acceleration of unrest indicators.	Large-scale eruption now appears possible.
5	Destruction within the Permanent Danger (red) Zone. Significant risk over wider areas.	Hazardous large volcanic eruption in progress.

5.2. ABOUT 1 YEAR BEFORE ERUPTION

Small basalt intrusions continue to enter the rhyolite magma chamber. The Tarawera and other seismographs record continuing small (mostly M $\leq$ 2 and unlocatable) DLP events. Some basalt ponds at base of the chamber, some is injected into the rhyolite and mingles and mixes with it (Leonard *et al.*, 2002). Gradual heating of the rhyolite magma body increases heat and volatile flux to the overlying hydrothermal system; the higher base temperatures driving stronger convection in this system so that more heat is transferred to the surface. Measured temperatures and flow rates of hot springs at Rotomahana (Figure 2), and fumaroles on the northeast flanks of Tarawera increase slightly. Several new fumaroles appear on Tarawera summit. Pressurisation of the hydrothermal system generates occasional small, shallow, long-period (SLP) earthquakes, and clusters of earthquakes, between the magma chamber and the surface (McNutt, 2000). The waveforms of events within these clusters are similar, indicating a repetitive, non-destructive source process (Chouet *et al.*, 1994). Lake-levelling data shows that the small, long-term 'regional tilting' continues at normal rates. The minor increase in hydrothermal heat flow, together with the seismic activity, causes some scientific concern, and the SAL is raised to one (Table I).

5.3. ABOUT 4 MONTHS BEFORE ERUPTION

Basalt intrusions continue to rise into the rhyolite magma chamber, to drive enhanced magma convection and increased exsolution of volatiles, which pass into the hydrothermal system. Surface heat flow continues to increase until a small hydrothermal eruption occurs at Rotomahana, recorded by the Tarawera seismograph as a five minute-long volcanic earthquake followed by 25 minutes of continuous, but diminishing, volcanic tremor. Several small, shallow volcanic earthquakes (caused by pressurisation of the hydrothermal system) had occurred during the two days before the hydrothermal eruption.

Volcanologists infer that the eruption and seismicity are related to excess pressure in the shallow hydrothermal system. A possible increase to the SAL is debated but rejected, as no evidence of new magma is found in the eruption ejecta and the eruption may just reflect superficial changes in the hydrothermal system, perhaps caused by the seismicity. Additional seismographs are installed near Tarawera (Figure 4).

5.4. FROM $\sim$2 MONTHS BEFORE THE ERUPTION

Basalt intrusions into the rhyolite magma continue to increase. The enhanced seismograph network initially records increasingly more frequent (average $\sim$1 per week) and larger deep long-period (DLP) earthquakes, with reduced location uncertainties. DLP earthquakes are centred beneath the summit area of Tarawera ($\pm$2 km) at a depth of 15 ± 2 km, i.e., in the lower crust. Some of these are larger than any previous DLP events, and some merge into low amplitude tremor (as at Pinatubo in 1991 (White, 1996)). Magma chamber pressures are increased by transfer of heat and volatiles from the basalt to the rhyolite magma, and by increasing volatile exsolution from the convecting rhyolite (Snyder, 2000). Volumetric inflation of the rhyolite magma chamber now exceeds 1%.

Swarms of small ($M < 2.5$) shallow volcano-tectonic (VT) earthquakes are generated by slip on existing fractures stressed by inflation of the underlying magma chamber. Only the larger events are recorded on more than the Tarawera seismograph and can be located. Temporary overloading of the Tarawera seismograph during the largest events makes timing of S-phase arrivals difficult and depth estimates imprecise. There are two earthquake sources, one at 4 ± 2 km depth beneath Tarawera, and a second source is 7 km to the west at 5 ± 3 km depth. Both sources are characterised by a diffuse cloud of hypocentres with any patterns obscured by the location uncertainty (Sherburn and Nairn, 2001). The western-source earthquakes continue at the same rate ($\pm$10 per week), but events beneath Tarawera increase to 20 per week [as at Pinatubo (Harlow *et al.*, 1996) and Montserrat (Young *et al.*, 1998)]. Swarms of small, shallow, long-period (SLP) earthquakes also become more common as the increasing magmatic gas and heat flux continues to raise pressures in the hydrothermal system.

Re-examination of the lake-levelling data shows the long-term apparent 'regional tilting' trend continues, leading to suggestions that the 'regional tilting' signal may be a 'volcanic' signal related to inflation beneath Tarawera. Several radio-telemetered GPS (Global Positioning System) receivers are installed on upper slopes of the volcano to monitor any ground deformation. Analyses of Tarawera fumarole gases and Rotomahana hot spring waters find new magmatic components. Early in this period, the SAL is raised to two (Table I) based on the continuing seismicity, possible inflation, and the magmatic component of hydrothermal discharges.

Towards the end of this period, a slowly rising overall rate of seismic energy release is characterised by more frequent earthquakes of all types. Improved locations show that the volcano-tectonic (VT) earthquakes centred to west of Tarawera define a NE–SW alignment close to the Wairua Fault – a historic seismic source. It becomes difficult to immediately distinguish shallow and deep long-period earthquakes (as at Pinatubo in 1991) as they have a similar dominant frequency.

5.5. FROM ∼2 WEEKS BEFORE THE ERUPTION

An increased rate of basalt intrusion generates several swarms of DLP earthquakes, including more and larger (to M3) earthquakes than have previously occurred. VT earthquakes reach 50–100 per day (based on the analogous Pinatubo activity), and short swarms of SLP earthquakes occur at least daily, associated with frequent small hydrothermal eruptions at Rotomahana. Significant (>5 cm) uplift and dilation of the ground surface above the magma chamber has now occurred. Volcanologists now accept that the tilt observed across Lake Tarawera results from inflation of the volcano. The new GPS stations provide near-continuous telemetered data that confirms this result.

5.6. FROM ∼1 WEEK BEFORE THE ERUPTION

The final and most intense period of basalt intrusion begins, accompanied by large (M > 3) deep long-period earthquakes and tremor (based on petrological evidence for mixing of the triggering basalt throughout the rhyolite magma body (Leonard *et al.*, 2002)). Seismic activity at all depths continues to intensify, with volcanic tremor, DLP, SLP, VT and hybrid earthquakes all occurring (as at Pinatubo (Harlow *et al.*, 1996)). Some hot springs at Rotomahana dry out to become large discharge, high temperature (>600 °C) fumaroles, with high magmatic gas content. Hydrothermal eruptions at Rotomahana become more frequent. Magmatic pressure at the top of the rhyolite chamber exceeds the lithostatic confining pressure and the tensile strength of the overlying country rock. A NE-trending linear fracture is formed in the magma chamber roof, feeding a growing rhyolite dike that rapidly intrudes towards the ground surface. Shallow seismic energy release is intense, continuous and accelerating (as at Montserrat before major extrusion commenced in November 1995 (Kilburn and Voight, 1998)). Many strongly felt VT earthquakes of M > 4 occur, with continuous volcanic tremor as the dike opens fractures towards the surface. The largest earthquakes cause slumping of lake floor sediments to generate seiches within Lake Tarawera. Uplift and cracking of the ground surface (observed from aircraft) occurs around the summit of Tarawera.

Manual collection of lake-levelling data on Lake Tarawera ceases for safety reasons, but telemetering of GPS data continues to monitor increasing inflation of the volcano. Sampling of hot springs and fumaroles ceases due to increasing danger from frequent hydrothermal or phreatic eruptions. The Tarawera seismograph is often overloaded by the intense local seismicity, while the many VT earthquakes cause the analysis to lag behind real-time so that only the larger earthquakes can be located. The immediate analysis becomes focussed on RSAM and SSAM displays as the analogue seismograms become increasingly overloaded and difficult to interpret.⋆ The SAL is now raised to three (Table I), based on the occurrence of phreatic eruptions.

5.7. THE LAST FEW HOURS

Seismic activity continues to intensify, with seismographs close to Tarawera recording semicontinuous volcanic tremor before the increasingly intense seismic activity prevents any further location of earthquakes. All OVC network instruments are now frequently overloaded, and only the RSAM and SSAM displays are providing any useful data.

A vent-opening phreatomagmatic eruption occurs near the summit (Nairn *et al.*, 2001), with blasts of steam and ash and blocks of old lava thrown more than 2 km from the vents. Ejecta from the initial summit explosions is mostly cold country rock, but a small proportion (1%) of new magma (rhyolite pumice plus rare basalt scoria) shows that the rising magma column has now reached the surface. Signals from the Tarawera summit seismograph and GPS instruments cease due to damage caused by the eruptions, but outlying stations record explosion earthquakes with airwaves, followed by intense local shallow volcanic tremor. A similar but much larger phreatomagmatic explosion occurs 4 km to northeast of the summit vent, as the rhyolite dike reaches the surface through a fumarolic area at the northern foot of Tarawera (Nairn *et al.*, 2001). The SAL is raised to four (Table I) as a hazardous local eruption is in progress, and a large eruption is possible.

5.8. ERUPTION UNDERWAY

A series of plinian eruptions commences from the summit vent, continuing for a few days and generating fluctuating eruption columns that frequently exceed 20 km in height (Sahetapy-Engel, 2002). A significant volume ($>$1 km) of the rhyolite

⋆ RSAM (Real-Time Seismic Amplitude Measurement) calculates the absolute average amplitude for each data channel regardless of the nature of the signal. SSAM (Seismic Spectral Amplitude Measurement) determines the average spectral amplitude at a range of frequencies for each data channel. Both are useful for a quantitative assessment of seismicity when manual analysis is not possible due to continuous signal or overloading.

magma chamber is erupted within a week, with accompanying stress changes resulting in several large ($M > 4$) volcano-tectonic earthquakes (as during the climactic phase at Pinatubo (Wolfe and Hoblitt, 1996)). These events are located close to Tarawera using data from regional seismographs not obscured by the ongoing co-eruption seismicity. Signals from some OVC network seismographs and GPS instruments are lost, either due to the effects of ash falls and pyroclastic flows over their sites, or to telemetry problems caused by ash in the atmosphere. More distant seismographs ($\geq$15 km) are not overloaded and RSAM and SSAM data from these sites are used to follow the progress of the eruption. The SAL is raised to five (Table I) "hazardous large volcanic eruption in progress". The scenario ends here, one week into the eruption, which continues for the next few years.

6. Assessment of the Tarawera Monitoring System

6.1. REGIONAL SEISMIC NETWORK

The OVC radio-telemetered seismic network (Figure 4) can locate with reasonable accuracy, and in near real time, most earthquakes of $M \geq 2.5$ within the Okataina Volcanic Centre. The reliability of the earthquake data used to monitor the Kaharoa scenario has been assessed by estimating uncertainties in the location of the three seismic sources in the scenario (Sherburn and Nairn, 2001). Horizontal uncertainty is greatest (at $\pm$5 km) for the 15 km deep source beneath Tarawera, and depth uncertainty greatest (at $\pm$5 km) for the 5 km deep source at 7 km west of Tarawera. These patterns of uncertainty arise because there are no permanent stations to the southeast of Tarawera to provide control in a northwest-southeast direction.

The uncertainty analysis indicates that although the permanent seismic network is capable of identifying precursory seismicity of the Kaharoa eruption scenario, it would not accurately locate these earthquakes. Deep long-period (DLP) earthquakes comprise the critical seismicity during the early precursory phase, and it is the locations of these earthquakes that would be the least certain. In studies where many earthquakes are available it is common practice to eliminate the poorest locations, usually those rated D on an A–D quality scale (Aspinall *et al.*, 1998). As recorded by the permanent network, 99% of the scenario DLP earthquakes would have D quality locations. Additional seismographs installed to 'plug holes' in the permanent network (i.e., to southeast of Tarawera Figure 4) would significantly reduce the epicentre and depth uncertainties (Sherburn and Nairn, 2001). Data from such an enhanced network would enable accurate monitoring of precursory activity associated with the Kaharoa eruption scenario. Note that data from the Tarawera seismograph is particularly important in determining accurate locations and depths for earthquakes beneath or close to Tarawera. Without such data the depth uncertainty for shallow earthquakes may increase by a factor of as much as 2–3. The Tarawera seismograph is certain to be overloaded late in the precursory phase and would be destroyed early in the eruption.

6.2. GEODETIC NETWORKS

Vertical ground movement across Lake Tarawera is monitored by three water level recorders on opposite shores (Figure 4). Data recorded on-site at 15 minute intervals are manually collected several times a year for processing and analysis. The lake is regarded as a level surface so that averaged daily level values can be used for monitoring any changes in relative height around the lake, and thus interpreted as uplift or subsidence of the Tarawera massif (Scott, 1986, 1989). The long-term resolution is about ± 6 mm, though adverse weather can generate short-term variations of as much as 20 mm. Horizontal strain monitoring networks at Lake Rotomahana and around Tarawera summit were installed in 1983, and measured annually to 1987 to establish a baseline. These networks are not presently monitored, but new measurements can be made when required (i.e., after local earthquake activity). A regional GPS network was established in the OVC in 1990 and resurveyed in 1992, 1994, and 2000. This network would be resurveyed if precursory seismic activity was recognised at Tarawera.

Precursory ground deformation associated with the Kaharoa episode is more difficult to model than the seismicity. Geological and petrological data indicate that a >4 km^3 (possibly up to 10 km^3) rhyolitic magma body had accumulated in the upper crust long before the first eruptions. The rhyolite magma was primed by multiple injections of small volumes of basaltic magma (Leonard *et al.*, 2002). Precursory deformation in the scenario results from inflation of the rhyolite magma body, driven by the addition of basaltic magma and thermal expansion of the heated rhyolite. To calculate the inflation caused by the basalt injections requires knowledge of the shape, volume, temperature, and elastic properties of both the preeruption rhyolite magma body and the intruding basalt magma. In the absence of these data the scenario assumes a minimum 1% volumetric inflation of the rhyolite magma chamber (see below), and evaluates the surface effects of this inflation at the water level recorder sites on Lake Tarawera.

Basalt comprises about 1% of the total Kaharoa eruptives, but only a fraction of the intruded basalt will have mixed with the erupted rhyolite (the rest will have ponded beneath the rhyolite – Figure 3). Thus 1% of the erupted volume represents the minimum intruded basalt volume. For a volumetric expansion of 1% the deformation model predicts a height change of 16 mm across Lake Tarawera (Sherburn and Nairn, 2001), more than twice the resolution limit of the system. Greater inflations produce larger uplifts. The sensitivity of the Lake Tarawera level network to a 1% volume expansion suggests that long-term intrusive deformation would probably be detected. However, if this inflation occurred at a steady rate over several years it may be initially interpreted as tectonic in origin.

In the last few days before the scenario eruption, rhyolite magma (heated and energised by the final basalt intrusion) initiates and occupies a dike that rapidly intrudes towards the surface. If the dike dimensions are 8 km long (from the Kaharoa vent locations) and 10 m wide, extending to the ground surface 5 km above the top of the magma chamber, the final dike volume is 0.4 km^3. Two sources of deformation can be expected to result from the dike intrusion process; one reflecting the rapidly increasing loss of up to 0.4 km^3 of magma from a depth of 5 km, and one reflecting the intrusion of dike magma much closer to the surface. The total deformation signal would then comprise a deep, longer wavelength deflation upon which was superimposed a shallow, short wavelength inflation.

Simple modelling of the loss of 0.4 km^3 of material from a depth of 5 km predicts a maximum deflation, directly above the source of more than 350 mm, producing a height change of about 100 mm across the Lake Tarawera level-monitoring network. Such a large change would clearly be detectable. The effect of the intrusion of this 0.4 km^3 of magma towards the surface is more difficult to model. The time frame is very short, the source is very shallow and elongated, and the exact model used will significantly affect the pattern and magnitude of calculated deformation. What is clear is that dike intrusion will probably generate a large deformation signal close to the source, but that, because of its shallow depth, the wavelength of this signal will be very short. This implies that monitoring sites on the upper slopes of Tarawera will probably record uplift, but that those more distant will probably see only the effect of the deeper deflation source, and measure subsidence.

Regardless of whether sites record uplift or subsidence the scenario predicts that significant changes will occur only in the last few weeks before the eruption, and particularly in the last few days. To successfully record and interpret these changes requires data that are collected and processed in near real-time. In this context, the Lake Tarawera level network is suitable for identifying long-term deformation, but its data availability is inadequate for monitoring precursors in the final days before the eruption. It may be possible to radio-telemeter data from the lake level recorders, but additional monitoring instruments such as GPS receivers with a near real-time telemetry capability could be placed closer to the eruptive vents on Tarawera. Both systems would be required to successfully monitor the final precursory period.

6.3. HEAT FLOW MEASUREMENTS

Hot spring water levels and heat flows (Scott, 1986) are measured in the AD1886 eruption craters at Waimangu (Figure 4), with occasional sampling of other hot springs and fumaroles at Rotomahana and Tarawera. Resistivity surveys (Bibby *et al.*, 1994) show this surface hydrothermal activity to form part of a very large geothermal system, continuous at depth, and extending 15 km southwest from Tarawera across the Rotomahana-Waimangu area to Waiotapu. The present surface activity has been considerably modified by the AD1886 phreatomagmatic eruptions at Rotomahana and Waimangu (Nairn, 1979), and is undoubtedly different to that existing prior to the Kaharoa episode. However, the deep geothermal system must be affected by increased heat flux from the underlying magma chamber, and this will drive significantly increased heat flow from the surface hydrothermal features. The existing hydrothermal monitoring would be able to detect these changes.

7. Key Issues in the Scientific Response

In the period immediately before the scenario eruption commences the overall level of precursory activity rapidly increases. It is at this time that volcanologists will have the most difficulty in making accurate short-term forecasts of impending activity. A real pre-rhyolite eruption crisis will undoubtedly be more complex than that presented here, with recent experience highlighting problems in making an accurate forecast in time to be useful. Intense seismic activity will initially stretch and eventually overwhelm the analysis systems, preventing counting and location of all but the largest earthquakes. Trend assessments will then have to be based on overall aspects of the seismic activity such as the total amount, and any rapid acceleration, of the energy release. In addition, ground-based monitoring studies will be limited by the occurrence of hydrothermal eruptions, seiching on Lake Tarawera, and the threat of sudden eruption onset. In this situation (as at Rabaul in 1994 (Nairn and Scott, 1995)), the availability of telemetered ground deformation data would be invaluable. The escalation of activity while the monitoring systems are diminishing has to be expected, with plans ready for alternative monitoring methods. The failure of proximal monitoring instruments and/or data telemetry links once the eruption is underway must be anticipated, so that eruption monitoring can continue with reduced data sources.

This scenario of precursory activity ends with the first plinian eruptions, which continue for about a week. However, geological data suggests that Kaharoa eruptive activity continued for another 4–5 years (Nairn *et al.*, 2001). Once the initial eruption phase was over, volcanologists would be asked about the likelihood and style of future activity, including the possibility of a build up to much larger pyroclastic eruption. The loss of data from the most important monitoring sites would make these questions difficult to answer. The rapid reinstatement of an effective monitoring network (as occurred at Pinatubo 1991 and Rabaul 1994 following those eruptions) would be vital.

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