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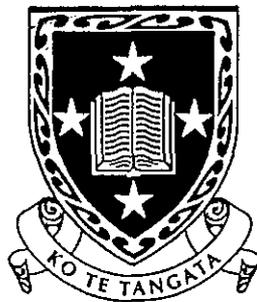
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**Geology, History and Stratigraphy of
Hydrothermal Eruptions in the Rotorua
Geothermal Field**

A thesis submitted in partial fulfillment
of the requirements for the Degree of
Master of Science in Earth Sciences
at the University of Waikato

by

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Abstract

The study area is the Rotorua geothermal field (RGF), which is located in the southern end of the Rotorua caldera. Distribution of surface geothermal activity, hydrothermal eruption (HE) deposits and craters have been mapped. HE deposits formed in geological, historical and modern times were studied to record and describe their distribution, composition, petrography, lithology and stratigraphy.

Locations of all identified HE sites in the RGF have been plotted and shown on accompanying maps. At Ohinemutu and Sulphur Bay, HE breccias have been preserved only where deposits were subsequently silicified by hot spring outflows. At Whakarewarewa two HE breccias outcrop over about 0.5 km² and are up to 23 m thick. Study of stratigraphic relationships with tephras of known ages has determined one as Holocene (c. 20 ka) and one of Late Pleistocene age (c. 65 ka).

Four HE breccias were studied in detail. The mineral composition, physical description, field characteristics and spatial distribution of HE breccias are described and mapped. Clasts and matrix were examined by XRD analyses of whole (67) and clay fraction separates (16). Silica crystallinity indices (14) were determined by XRD to identify devitrification rates of opaline mineral species. The petrography of 67 breccia clasts and matrix samples were studied, and polished sections showed the only sulphide to be pyrite. Geothermal alteration of all prehistorical HE deposits was of advanced argillic to argillic and one modern day deposit was of sub propylitic epithermal alteration.

Study of a HE deposit formed in Kuirau Park on 26 January 2001 allowed properties and mineral composition to be examined and recorded before rapid oxidation and weathering destroyed its physical and mineral composition. Study of this and other twentieth century HE events confirms that these rapidly decompose to leave little or no recognisable deposit in the geological record.

Descriptions and all known historical records of HEs in the RGF have been collated to provide a comprehensive inventory of maps and appendices of these events. This information will greatly assist statutory authorities with mitigation of risk to lives and property from geothermal hazards as well as aid appropriate land use and emergency services planning.

Hydrothermal eruptions are ongoing in the RGF through time and produce craters 2 – 110 m diameter with erupted deposit volumes of 1 – 500,000 m³ that have distributed over <5 m² to >0.5 km². These have occurred throughout at least Late Pleistocene to Holocene times and appear to have been triggered by such events as volcanic eruptions from the adjacent Okataina Volcanic Centre

and related abrupt changes to the waterlevels of Lake Rotorua. Frequency and spatial distribution of HEs in historical times suggest human interference with the geothermal system is also a significant influence.

This study has brought together all records of known hydrothermal eruptions and other unusual geothermal disturbances in the Rotorua geothermal field. The information has plotted into GIS for use by statutory authorities and others. Two prehistorical HE deposits in Rotorua city have also been recognised and described for the first time, together with identification of their likely vent locations and possible eruption initiating events.

Acknowledgements

I am deeply indebted to many people who have spontaneously offered assistance and services, or have provided me with ongoing psychological support and incentive in this study. I am also conscious of the tolerant and patient forbearance of my daughters Sarah and Alannah, who have missed out on other activities as a consequence of my prolonged part time studies. My wife Anna has given me ongoing and unfaltering support and encouragement to undertake this study and to persist with it while juggling work and family time demands. Anna, I am very grateful for your ongoing faith and support.

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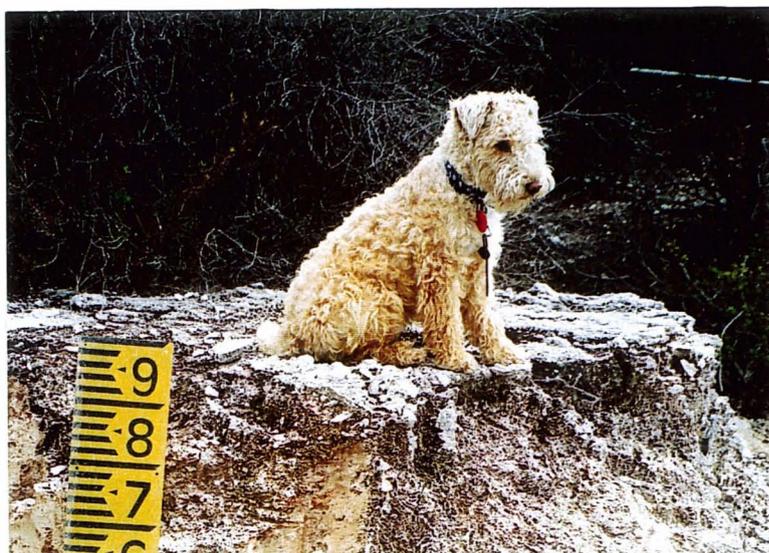


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I like terra firma – the more firma, the less terra

- George Kaufman

Chapter 1

INTRODUCTION

1.0 INTRODUCTION

The Rotorua Geothermal Field (RGF) has a history of hydrothermal eruptions (HEs) that date back throughout the Holocene to at least c. 26,000 years Before Present (BP). Several large hydrothermal eruption craters and breccias of a prehistoric age are still visible in AD 2002, but some evidence of others has been destroyed, possibly by Maori occupation during c. AD 1350-1850 and then by European urban development processes during c.1900s-2000. This thesis is a study and investigation of the relic breccia deposits produced by hydrothermal eruptions in the Rotorua Geothermal Field.

Some of these HE events have been witnessed in historical and recent times, both in Rotorua and Wairakei (Karapiti), as well as elsewhere around the world. Written or photographic records provide additional evidence about the actual processes that occur during such eruptions. In Rotorua city, large steam eruptions have had devastating outcomes for some areas and also individual residential properties, in both recent and historical times.

Considerable work has already been published describing the distribution, mechanisms, characteristics and other aspects of hydrothermal eruptions in New Zealand, and a thorough study and summary is given by Browne and Lawless (2001). Therefore no attempt to model or fully portray the nature and occurrence of HE events is made here. Instead, this work concentrates on

recording and describing some preserved HE breccia deposits in the RGF. They are described here to record such information before all evidence of them is destroyed, by both the combined ongoing effects of geothermally induced hot (<100°C) acid (pH <5) weathering and also the ongoing effects of human urbanisation processes.

Already some well preserved silicified HE breccia deposits in the RGF have been destroyed by urban developments during the 1980s-1990s and it seems likely that more have also been lost in earlier decades. Some simple interpretations and findings are given here, with comment upon possible future occurrences of HEs in the RGF.

Materials involved in these HE events are described, and where possible, attempts are made to compile stratigraphic columns and approximate ages, by identification of either stratigraphically underlying or overlying primary tephra, or their reworked secondary deposits that sometimes have been incorporated into the HE breccias. From identification of associated tephra and accompanying deposits, some time constraints have been obtained on the date of these HE events, which in turn may then be examined for possible correlation with other significant geological phenomena and possible triggering processes. For example, local volcanic eruptions, or the sudden raising or lowering of Lake Rotorua waterlevels by damming or breaching of dams may have triggered HEs, and recognition of such correlative and possibly causative changes may then help define areas of Rotorua city which might be at risk of these natural hazards.

Eruptions that are directly attributed to well casing failures and blowouts are not detailed in this study, although such events are recorded in Appendix 6.

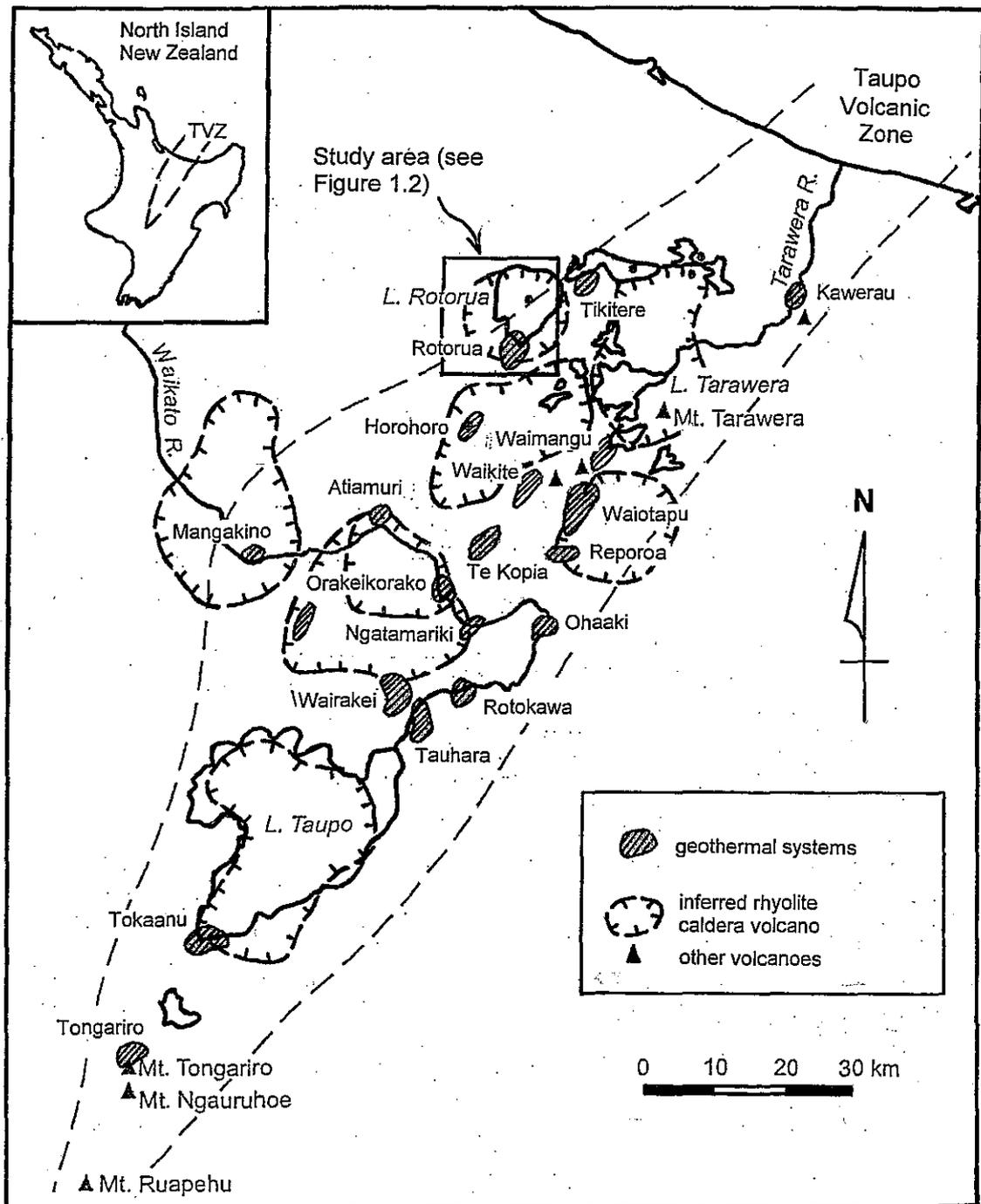


Figure 1.1: The Taupo Volcanic Zone, North Island, New Zealand, showing rhyolite caldera volcanoes and associated geothermal systems, together with location of Rotorua caldera and geothermal system. Adapted from Herdianita, et al. (2000).

1.1 LOCATION OF ROTORUA GEOTHERMAL FIELD

The Rotorua Geothermal Field (RGF) is located within the Rotorua caldera, which is of late Pleistocene age and had its last ignimbrite eruption 220 ka BP (Milner, 2001). Rotorua caldera lies in the present day active volcanic area of the Central North Island of New Zealand known as the Taupo Volcanic Zone (TVZ) (Fig. 1.1). The TVZ is a north-northeast trending volcano-tectonic depression dominated by rhyolitic volcanism, and the Rotorua Volcanic Centre (RVC) is located in the northwest of the TVZ.

Within the RVC, three geothermal fields are presently active, with the RGF being located almost wholly beneath Rotorua city, at the southern end of the caldera (Fig. 1.2). Presently it has a heatflow of about 470 megawatts (Glover, 1992). In the central-eastern portion of the caldera, a separate geothermal system occurs between Mokoia Island and Rotokawa, just east of Rotorua Airport. This is referred to simply as the "Rotorua East" geophysical anomaly by Bibby, et al. (1992). Tikitere is a third geothermal system which lies at the northeastern end of the caldera (Espanola, 1974).

Another geophysical resistivity anomaly is present in the northwest of Lake Rotorua, between Mokoia Island and Ngongotaha and is known simply as the Rotorua West geophysical anomaly (Bibby, et al., 1992); it has no known associated geothermal activity or sediment heatflows (Whiteford, 1992), although it corresponds to several circular depressions on the lake floor that have been detected by echo sounding.

Surface geothermal activity in the RGF extends from Whakarewarewa and Waipa in the south, northeast through the Rotorua cemetery to Ngapuna and northwest into Kuirau Park, Ohinemutu and Koutu (Fig. 1.3). The RGF is also

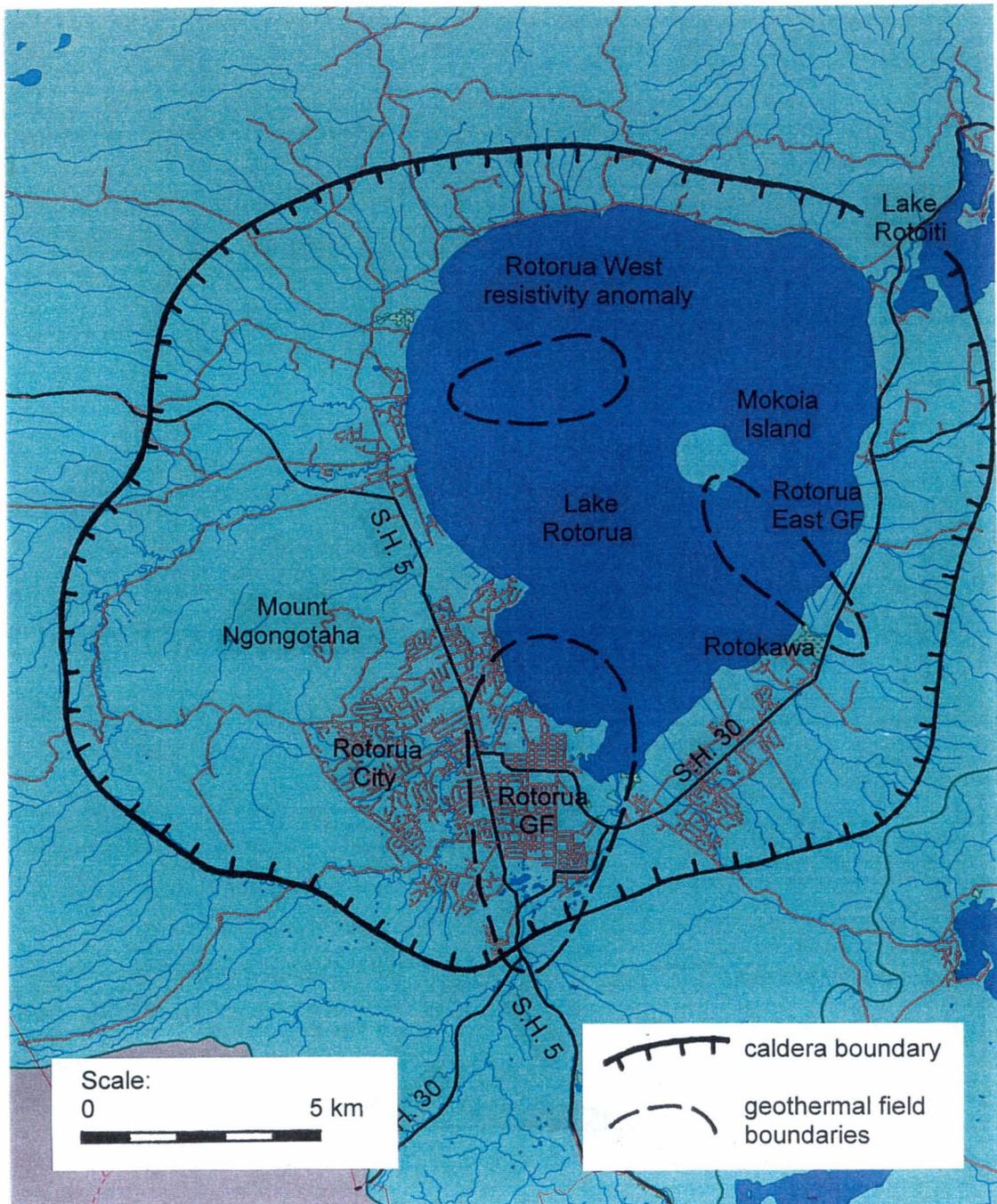


Figure 1.2: Rotorua caldera and geothermal fields (GFs). Caldera boundary is approximate only. Geothermal fields are also approximate, and are defined by resistivity techniques (after Bibby, et al., 1992).

inferred to underlie the southern portion of Lake Rotorua (280 m a.s.l.), where water-borne geophysical work has shown the presence of hot water beneath the lake (Whiteford, 1992). Glover (1992) showed that about 42% of all geothermal fluid upflow in the RGF is rising within Lake Rotorua.

The RGF covers about 12 km² as delineated by the 20 ohmmetre resistivity contour, surface activity and shallow drillholes (Wood, 1992), but extends further outwards to 18-28 km² area at 500 m depth, based upon deeper resistivity soundings (Bibby, et al., 1992). As an example of this deeper extent, an exploration well at 98 View Road (well RR892 at GR 2793150 mE, 6336284 mN) encountered rhyolite to hole bottom at 459 m depth, from where it produced water at about 80°C. The RGF also extends at least 2 km north into Lake Rotorua (Whiteford, 1992) and also south into Waipa, 2 km south of Whakarewarewa and outside the caldera wall (Bibby, et al., 1992).

In historical times up until c.1910s, hot flowing springs also occurred at Koutu, 1 km northwest of Ohinemutu. In 2002 one of these was still outlined by a circular rim of silica sinters (U16 942374). In late Pleistocene to Holocene time an area of hot springs was active up the Utuhina Valley (Fig. 1.5b), several kilometres west of Pukehangi Road (Bayrante, 1984). Both these now cold sites of former hot spring activity indicate the once greater extent of the RGF, perhaps promoted by higher levels of Lake Rotorua at times when those springs were active.

1.2 PHYSIOGRAPHY

The RGF lies at the southern end of Rotorua caldera, which is a near circular feature about 15 kilometres diameter, that is occupied by Lake Rotorua and the prominent rhyolite dome of Mount Ngongotaha (Fig. 1.4).

A series of concentric marginal ring faults delineate the caldera in the north, east and southwest, with the Mamaku Plateau to the west, which is gently down-sloping into the caldera. Lake Rotorua has undergone successive episodes of raised and drained lake levels that have formed conspicuous lake treads now visible around the city and environs (Esler, et al., 2002).

Lake Rotorua may perhaps be the oldest continuously existent lake in New Zealand (p.16 in Lowe and Green, 1987). The RGF is situated upon a series of terrace and lakebed deposits of low to very gentle topographic relief. Lake Rotorua is at 280 metres above sealevel (m asl), and the Central Business District (CBD) is built upon tephra and lacustrine silts and sands which are flat lying to very gently sloping at 290-285 m asl.

Rhyolite lava domes outcrop at six sites within the city and the largest exposed is Mount Ngongotaha, immediately to the west of the city. The lava domes are considered to be of 70-80 ka BP age, although no radiometric ages have yet been published (Shepherd, 1991). Lake Rotorua is a very broad but shallow lake of 79 km² area with mean depth of 11 m. The Utuhina and Puarenga streams enter from the south and southwest through the city and have deposited extensive fans, terraces and lake deposits that today provide the dry land on which Rotorua city now stands. To the north by Ohinemutu, Pukeroa (or "Hospital Hill") (Map 1, Map Pocket) is the exposed promontory of an extensive buried lava dome beneath the city that is well defined by numerous drillholes (Wood, 1992).

Whakarewarewa lies just inside the caldera wall of Pohaturua Hill (Map 1, Map Pocket) and the Puarenga Stream flows through the thermal valley and then on out to its delta at Ngapuna (Fig. 1.3), where about 3 hectares of boiling solfatara occur. Sulphur Bay occupies a broad shallow southern embayment of Lake Rotorua and its waters are characterised by opaque

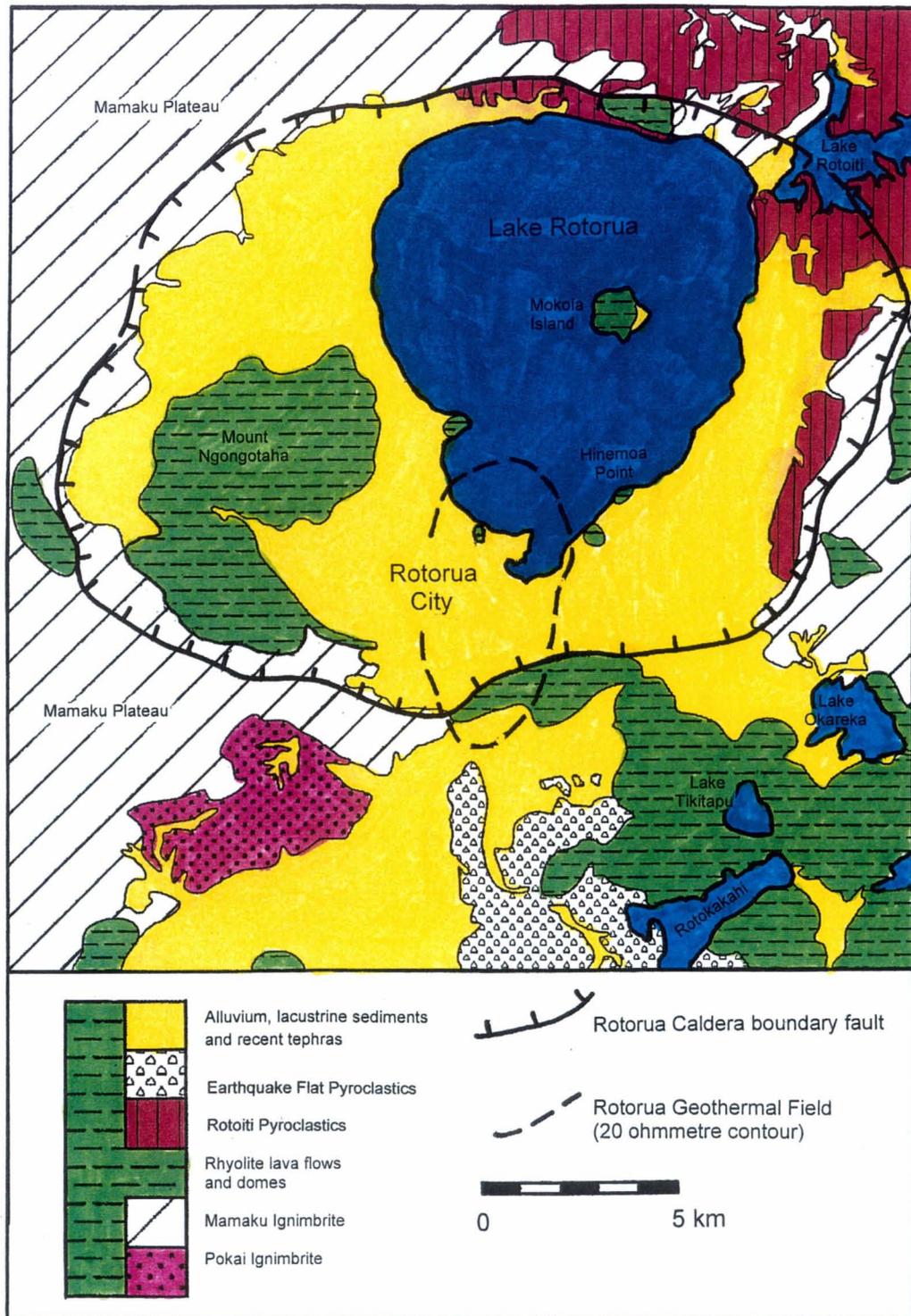


Figure 1.4: Geology of the Rotorua area, showing the outline of the Rotorua caldera and Rotorua geothermal field (RGF). Adapted from Wood (1992) and Milner (2001).

turbid off-white colours and abundant colloidal sulphur in suspension. Continual high heat and gas upflows in Sulphur Bay produce acidic and very deoxygenated waters, with abundant colloidal sulphur production.

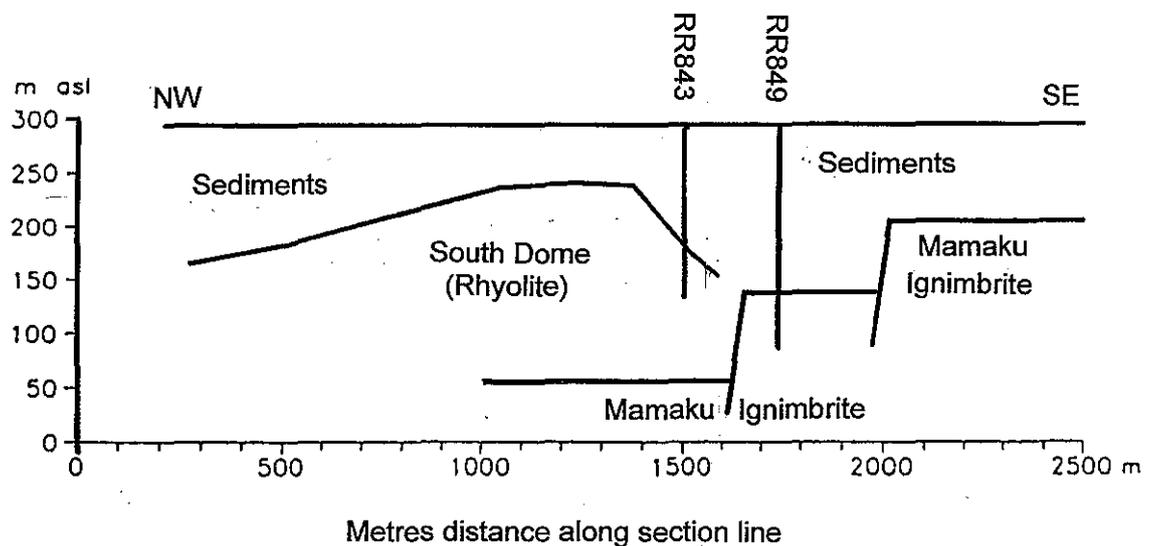


Figure 1.5a: Schematic diagram of the structure along section line NW – SE as shown in Figure 1.5b. Displacement of Mamaku Ignimbrite surfaces are inferred to be due to step faulting downwards into the caldera. Wells RR843 and RR849 are drillholes in vicinity that have contributed data to this model. Depths are in metres above sea level (m asl; Adapted from Wood, 1992).

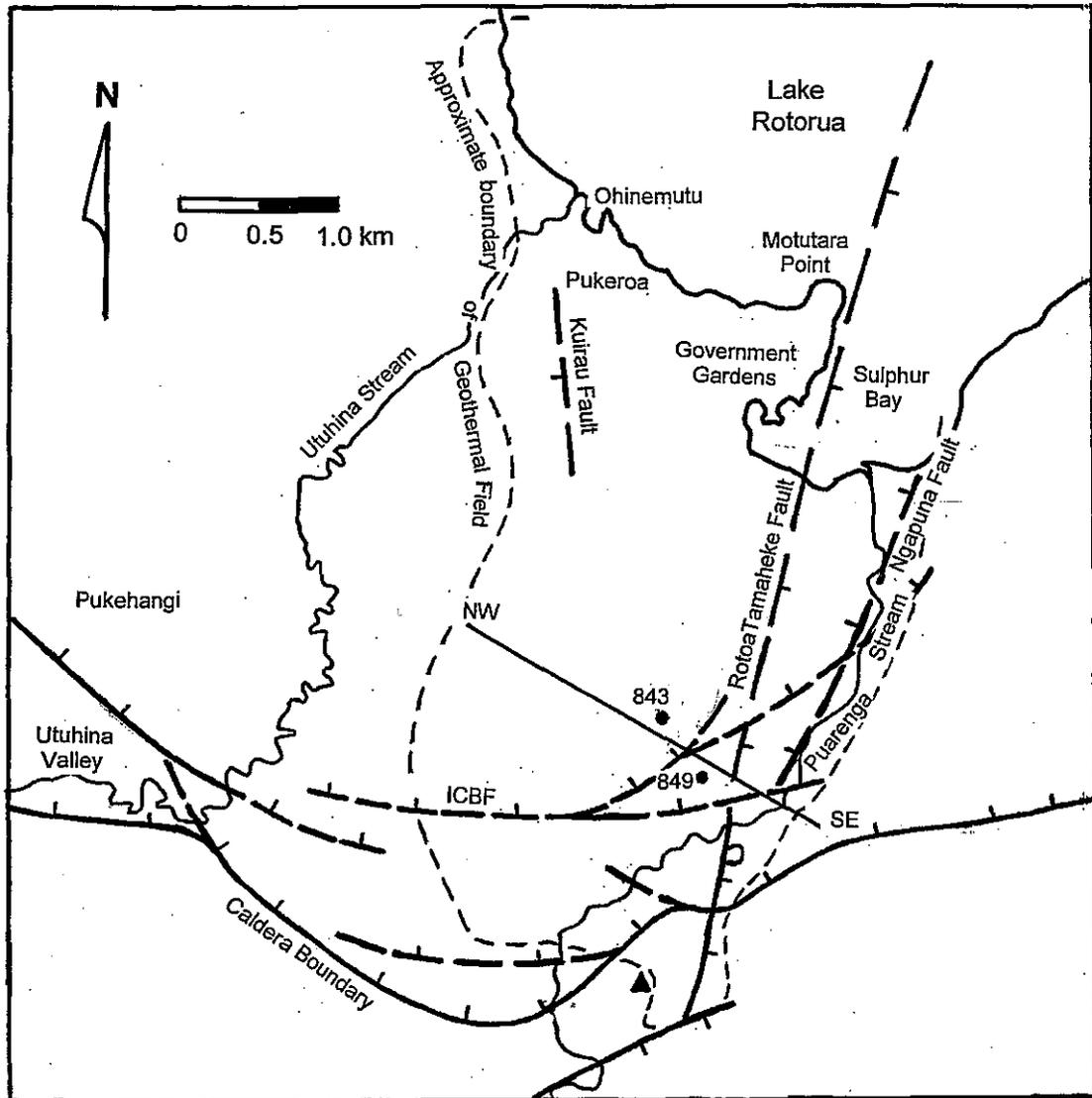


Figure 1.5b: Schematic structural map of Rotorua city area. Caldera collapse scarps and faults are shown as solid lines where visible at the surface and as dashed lines where inferred from drillhole data. ICBF is the Inner Caldera Boundary Fault of Wood (1985). Section line NW – SE is shown in Figure 1.5a. (Adapted from Wood, 1992).

1.3 REGIONAL GEOLOGY AND STRUCTURE

Mamaku Ignimbrite (220 ka BP) is a voluminous partially welded vapour phase altered ignimbrite of 300 km³ (Milner, 2001), widespread around the Rotorua district. Caldera subsidence and ignimbrite backflow has produced a thick infilling of ignimbrite in the RVC. To the west it forms the Mamaku Plateau, but elsewhere it is largely concealed beneath younger unwelded Rotoiti Pyroclastics, which is comprised of rhyolitic ash and ignimbrite of 240 km³ and 64 ka age (Froggatt and Lowe, 1990; Lowe and Hogg, 1995). To the east of Rotorua, the Mamaku Ignimbrite is now concealed beneath many rhyolite domes within the OVC. Holocene tephras and their eroded lacustrine deposits have infilled much of the RVC and blanket the city and surrounding landscape (Fig. 1.4).

Although many drillholes have been made within the RVC, the deepest is only 500 m and nowhere has the Mamaku Ignimbrite been penetrated into any underlying units (Fig. 1.5a). On the Mamaku Plateau the Mamaku Ignimbrite has been drilled through into older ignimbrites, but inside the caldera and to the south of the RVC only volcanic rocks have been penetrated. It is considered that a basement of Mesozoic greywacke exists at about 2-3 km depth in much of the TVZ, based on drillholes at Kawerau to the northeast of the OVC and at Ohaaki to the south, and gravity data (Rogan, 1982).

The RGF has been intensively drilled for hot water extraction, with >1200 wells drilled to date, generally to depths <200 m, and geological profiles and samples recorded (Wood, 1992). Together with much ongoing chemical and isotopic analyses of well and spring waters, the RGF is one of the most thoroughly explored of all New Zealand geothermal systems.

The highest temperatures, pressures and dissolved mineral contents of geothermal waters are all found in the east and southeast of the RGF, in the areas of Ngapuna, Fenton Park and the Wastewater Treatment Plant (WTP) (Map 1, Map Pocket). These springs and wells produce from an aquifer hosted by the Mamaku Ignimbrite, which has its upper surface at about 150-200 m depths (130-80 m asl), although its base has not been penetrated. Upflows are channeled via steeply dipping to vertical normal faults (Fig. 1.5b), with lateral outflows into overlying permeable units within a thick (<200 m) sequence of lacustrine beds.

Two coalesced rhyolite lava domes are present beneath Rotorua city, the northernmost being exposed as Pukeroa ("Hospital") Hill. These rhyolites are well mapped from drillhole geology and contours of their surfaces produced by Wood (1992). The RGF rhyolites are permeable in their outer carapace of highly fractured and pumiceous lavas, through which hot waters flow upwards and laterally.

Deeper within these rhyolites the temperatures increase only very gradually except where rare fractures are encountered. Consequently, most producing wells obtain their hot waters from within the upper 20 m or so of the rhyolite dome surfaces, with little or no increase in temperature deeper within these lavas down to at least 250 m depth. However, no drillhole has yet penetrated through the lava domes of the RGF to any underlying materials.

In the north near the lakeshore at Ohinemutu (Fig. 1.6), Kuirau Park (Fig. 1.7), Government Gardens (Fig. 1.8), Ngapuna (Fig. 1.9) and Sulphur Bay (Map 1, Map Pocket), the land surface and shallow groundwater table nears to lakelevel, with hot spring waters buoyantly rising to just above the groundwater table. Therefore as the lakeshore is approached, hot spring

waters produce nearly continuous hot to boiling groundwaters and many hot springs.

Further south at Sophia Street and Arikikapakapa (Fig. 1.10), the higher elevation of the ground level provides a surface some 7-20 m above the groundwater table. At the south end of the RGF, the Mamaku Ignimbrite surface abruptly lowers northwards into the caldera, which Wood (1992) interprets as step faulting due to caldera subsidence.

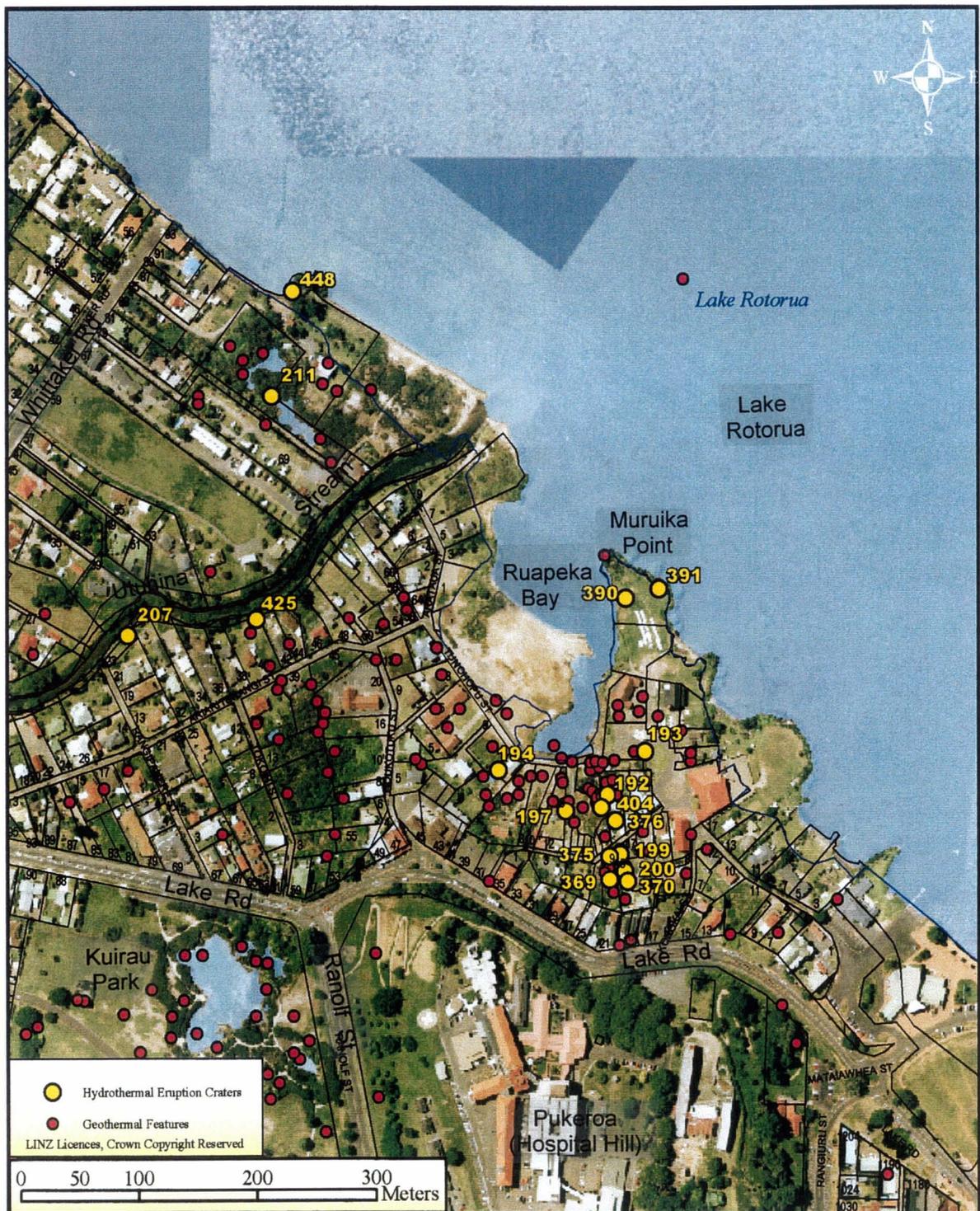
These produce arcuate lineations of inferred faults (Fig. 1.5b), which are also sites of generally poor pressure transmissivity. One of these structures is mapped and named the Inner Caldera Boundary Fault by Wood (1992), with significance in terms of the Rotorua Geothermal Management Plan (RGMP) and utilisation of the hot water resource (Gordon, et al., 2001).

Whakarewarewa is an area of intense geothermal activity and lies immediately inside the southern caldera wall. Surface geothermal features and HE sites here are shown in Figs. 1.11 and 1.12.

1.4 STUDY OBJECTIVES

- To record all hydrothermal eruption sites in the RGF.
- To identify ages of the preserved HE breccias using stratigraphic positions of any recognised and identified tephras or their inclusions within breccias. Ages of these HE events may then allow correlation with other events such as volcanic activity or rapid changes in the levels of Lake Rotorua.

- To identify possible triggering events and mechanisms of HEs. This may provide useful information for management of the geothermal resource and also for landuse planning and emergency services preparation for dealing with or mitigating the consequences of future HE events.



Produced on CIVIC INFO; Rotorua District Council's Geographic Information System

Figure 1.6 Aerial map of Ohinemutu area with all inventoried geothermal features and known hydrothermal eruption craters shown. Numbers given are the EBOP-RDC geothermal database form numbers. See Map 1 (Map Pocket) for location of this figure within RGF.

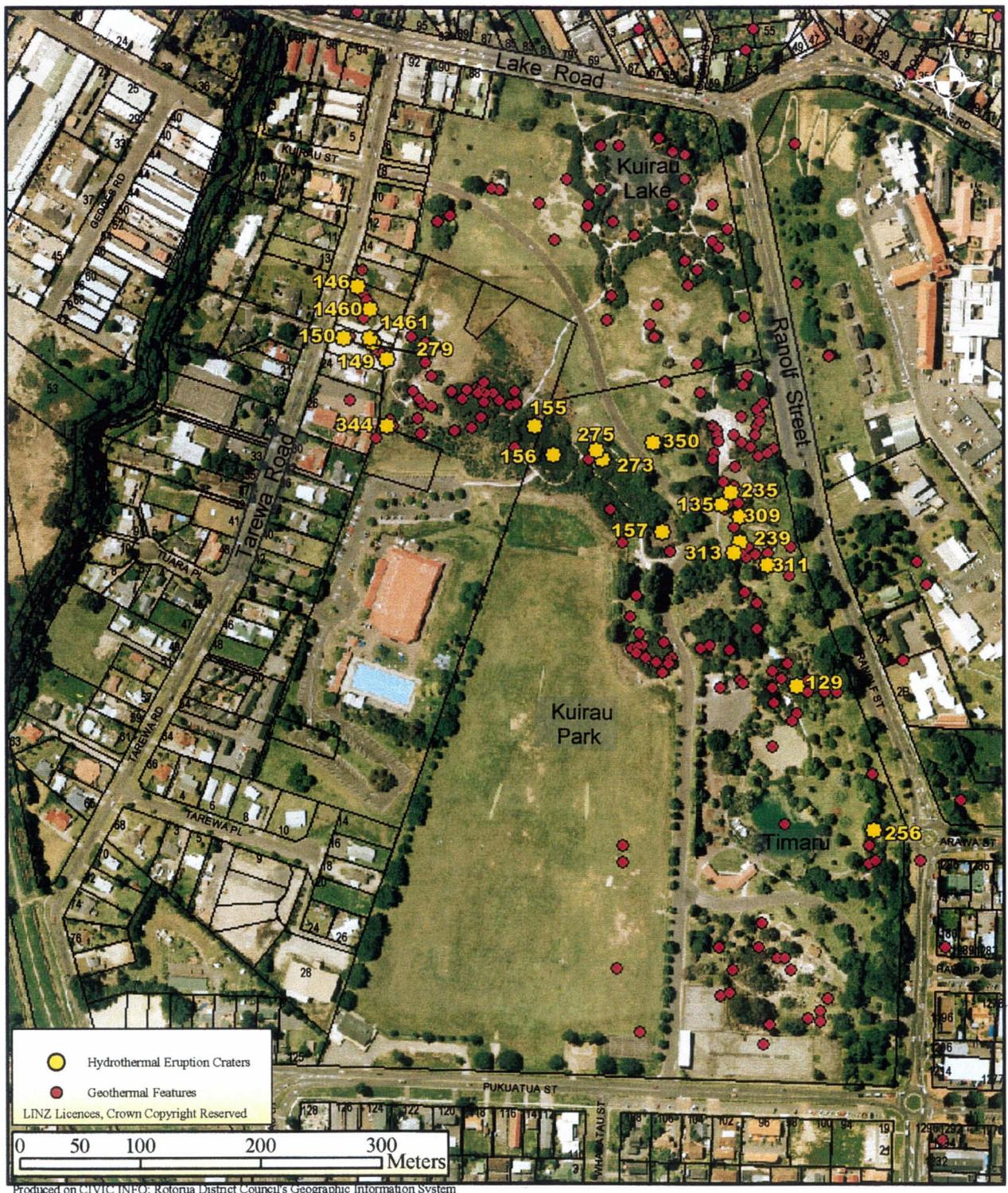


Figure 1.7 Aerial map of Kuirau Park area with all inventoried geothermal features and known hydrothermal eruption craters shown. Numbers given are the EBOP-RDC geothermal database form numbers. See Map 1 (Map Pocket) for location of this figure within RGF.



Produced on CIVIC INFO; Rotorua District Council's Geographic Information System

Figure 1.8 Aerial map of Government Gardens area with all inventoried geothermal features and known hydrothermal eruption craters shown. Numbers given are the EBOP-RDC geothermal database form numbers. See Map 1 (Map Pocket) for location of this figure within RGF.

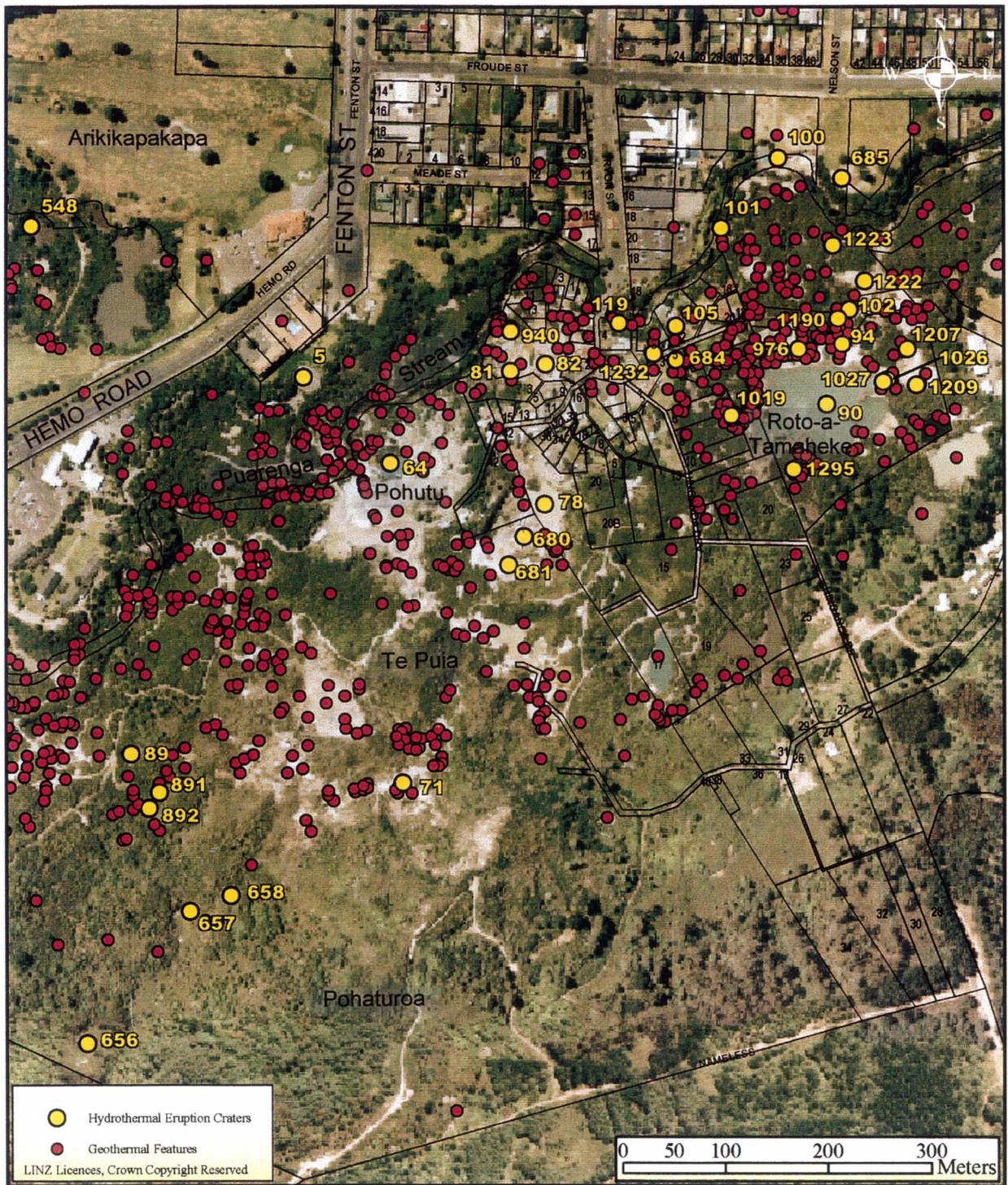


Figure 1.9 Aerial map of Ngapuna area showing all inventoried geothermal features and known hydrothermal eruption craters. Numbers given are the EBOP-RDC geothermal database form numbers. See Map 1 (Map Pocket) for location of this figure within RGF.



Produced on CIVIC INFO; Rotorua District Councils' Geographic Information System

Figure 1.10 Geothermal features of Arikikapakapa Thermal Reserve and golf course, and parts of Whakarewarewa Thermal Valley. Arikikapakapa lake is in centre, Old Taupo Road curving northwards up left side of map, and Hemo Road across bottom of map swings north into Fenton Street, up east edge of map. The yellow sites are hydrothermal eruption craters with their inventory numbers given. Red spots are other types of geothermal features. See also Map 1 (Map Pocket) and the EBOP-RDC geothermal database for additional details.



Produced on CIVIC INFO; Rotorua District Council's Geographic Information System

Figure 1.11 Whakarewarewa Thermal Valley. Arikikapakapa reserve is at top left of map (Figure 1.10). Road at top left is Hemo Road, turning north into Fenton Street. Lake at upper right is Roto-a-Tamaheke, with Whakarewarewa Village to immediate left of lake. Geyser Flat is white ground immediately southwest of F64, the Blue Lake. Hydrothermal eruption craters are in yellow with their database reference numbers given.



Produced on CIVIC INFO; Rotorua District Council's Geographic Information System

Figure 1.12 Close-up of Whakarewarewa central area. Geyser Flat is barren area immediately southwest of F64, the Blue Lake. F71 is Ngawha Crater, with Waikite Mound the barren ground to northwest and Te Puia Hill the bush covered area directly north of F71. Whakarewarewa Village is at top centre-right. Refer to Map 1 (Map Pocket) and the RDC-EBOP geothermal database for additional information about individual geothermal features.

Truth is rarely pure, and never simple

- Oscar Wilde

Chapter 2

DISTRIBUTION AND NATURE OF HYDROTHERMAL ERUPTIONS

2.1 LITERATURE REVIEW

In the RGF there is an ongoing pattern of sporadic hydrothermal eruptions (HEs) throughout historical and modern times. Some of these events were noted in newspapers of the day and others are known by the existence of old photographs or a concise statement within various other writings. It is notable that very few HEs in the RGF have been reported or studied, and that many of these events have never been recorded at all, but are known only from anecdotal accounts or the sparse presence of eruption deposit breccias. Some HE events do not eject any hard rock but only soft muds and silts that are readily incorporated into the ground and soils, so that they do not provide any evidence of their HE origin.

Hydrothermal eruption events are therefore poorly recorded and are almost certainly under represented in both geological records and in written history. The earliest record of what may have been an HE in Rotorua is that of the Sunken Pa at Murihika Peninsula, in Ohinemutu.

“Tradition relates that a large portion of the Point once gave way, from the effects of an earthquake, and all the natives who had lived upon it perished” (p.157 in Taylor, 1959).

Another version describes the pallisade and posts that existed until early European times alongside Murihika Point and in the adjoining lake:

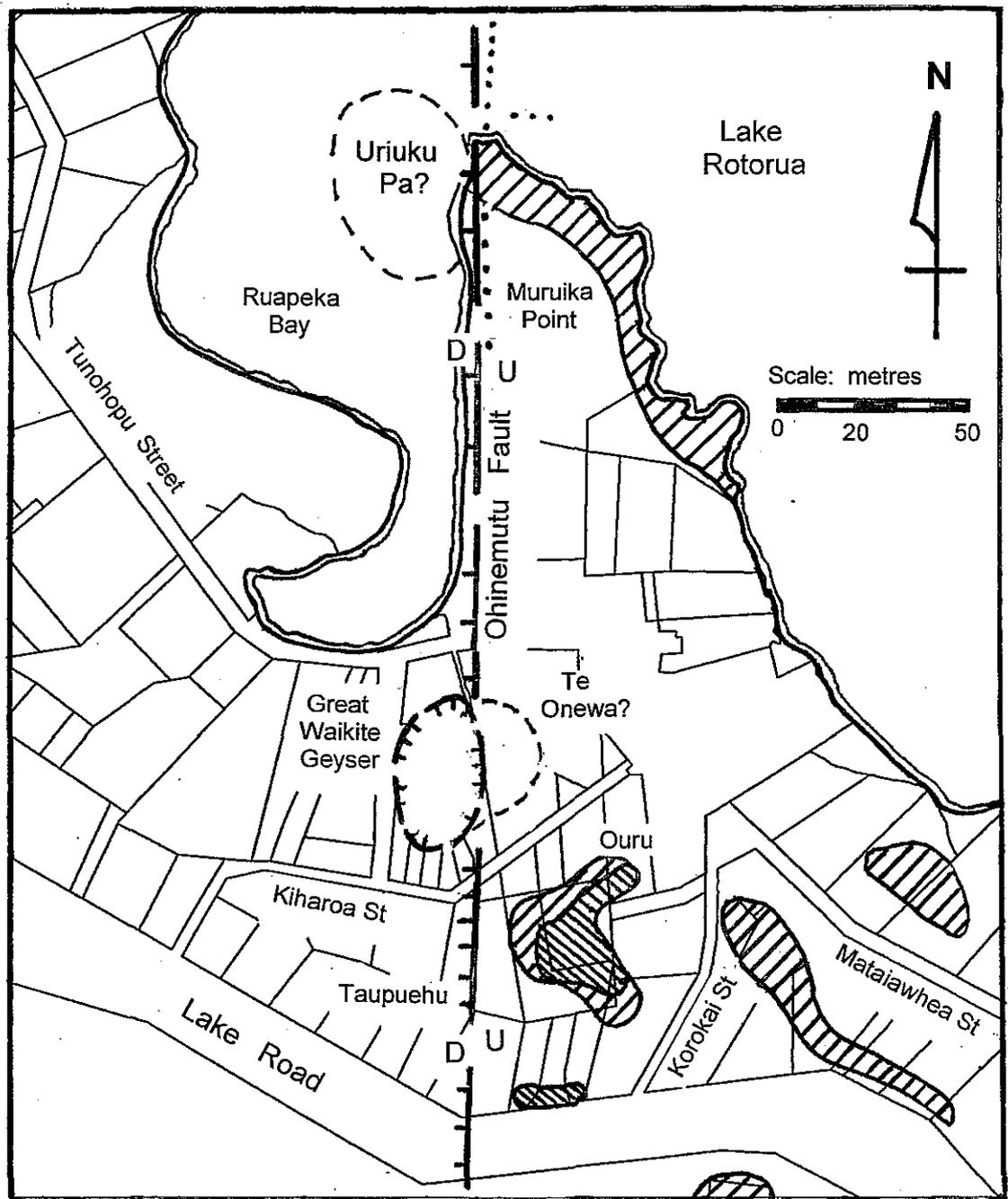
"...and the fact that they were the remains of a populous pa which, some generations ago, suddenly disappeared in the hot waters by which it was then mainly surrounded" (p.286 in Stafford, 1982).

This event occurred several generations before the arrival of Hongi Hika in 1823 and has an estimated date of c. 1760 AD, based upon deductions by the local historian Don Stafford (pers. comm.) and also an account published in *The New Zealand Herald* of 21 April 1886. This submergence of the Muruika Pa at Ohinemutu is described by Gilbert Mair in his version of a personally related account from an elderly chief:

"At midnight the pahi atua resumed their usual forms and surrounded the sleeping village. Conjuring up all the powers of evil, they destroyed the doomed pa. Muruika was suddenly engulfed in the boiling waters of Ruapeka Bay, and all its dwellers perished miserably therein" (Mair, 1923).

The *New Zealand Herald* account stated that this sunken pa was known as Uriuku Pa and about 30 people were scalded to death. It is possible that this may have been a hydrothermal eruption, which could have been accompanied or triggered by a local earthquake, perhaps with movement along the Ohinemutu Fault (Figure 2.1).

At Whakarewarewa, Waikite Mound is a circular silica sinter mound of about 60 m diameter rising 10 m above surrounding ground, to its summit at 315 m asl. Lloyd (1975) described it as being within Ngawha Crater (Map 1, Map Pocket), the site of an HE. He described the breccia from this vent as a subaerial deposit, overlain to the north with terraces cut by Lake Rotorua. From this evidence he deduced that the breccia predated Rotoiti Pyroclastics in age, or before 64 ka.



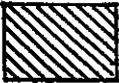
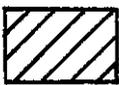
- old posts
-  hydrothermal eruption breccias
-  silicified sediments

Figure 2.1 Geological features and outcrops at Ohinemutu. Details of outcrops by Ouru are shown and described in Chapter 3 text and figures. Sunken pa site is inferred only, as there is no precise description known of its exact location.

The 10 June 1886 volcanic eruption of Mount Tarawera caused great disturbances in the RGF, with many new springs bursting forth throughout the township and muddy eruptions of debris and boiling waters at several sites along Lake Road and Rangiuuru Street (Keam, 1988).

On the morning of Wednesday 22 June 1938, a spectacular eruption occurred in Kuirau Park near the Alum Pool (S613, or Lobster Pool), on the main pathway leading from the park entrance through to Lake Road (Map 3). Mud was thrown to about 45 m distance and part of the footpath was destroyed. A hole about 3 m square was left behind and immense clouds of steam were produced (Rotorua Morning Post, 24 June 1938). However, there were no subsequent descriptions of its deposits or the nature of its occurrence.

Another HE occurred at the Tarewa Road property of Peter Maranui, circa 9th of August 1951. He had been digging a hole to make a hot bath, to which he intended diverting a nearby hot spring. The pool blew up and threw rubble and hot mud over a wide area (Rotorua Morning Post, 9 August 1951).

On 22 August 1966 and over subsequent days through until October 1966, a spectacular HE occurred in Kuirau Park close to Ranolf Street, opposite the King George Public Hospital boiler room building. An eruption column up to about 35 m high blew out from the previously turbid pools S614 and S615 (U16 946360). Some 80 tonnes of mud and other debris was ejected and it was observed by members of the public passing along Ranolf Street, one of whom took a photograph and donated it to the local Tourist and Publicity Office (Fig. 2.2).



Figure 2.2 Hydrothermal eruption at S615 (EBOP Form No. 513) in Kuirau Park on 22nd August 1966. Photograph taken by unknown person standing on Ranolf Street, viewed to southwest. (See also Daily Post, 20/09/66; Healy, 1966).

A report was written about this HE by the resident government volcanologist (Healy, 1966). However, that report was largely devoted to a discussion of various cause and effect processes and possible triggers of HEs together with general changes in local geothermal activity through time. It failed to give any description of the lithology or distribution of these eruption deposits.

In March 1998 the Tarewa group of hot springs (U16 943362) along the western margins of Kuirau Park abruptly recommenced boiling overflows and had a series of large hydrothermal eruptions. Over the following two years sporadic HE events occurred here and led to the removal of four residential houses. The sequence of these events and descriptions of processes and ejecta materials is given in Scott (2000, 2000a), Gordon, et al. (2001) and Suhanto (2001).

On 26 January 2001 at c. 1600 hrs NZST, a hydrothermal eruption occurred from an acid sulphate pool in Kuirau Park, mapped as S721. Some 1200m³ of material (about 2000 tonnes) was erupted within about 4 minutes, with blocks of 1m diameter being thrown 70m to the northeast and blocks to 0.15m diameter being thrown to ~110m, also to the northeast. This eruption was unusual because the eruption column was inclined to the east from vertical, and erupted debris was ejected to the east, with very little being distributed to the west, north or south. Breccia clasts were examined by Slako (2002) and an older hydrothermal eruption event was recognised by its cemented breccia clasts within the 26 January 2001 ejecta, although its source vent was not identified.

2.1.1 Previous Hydrothermal Eruption Studies

Many articles and studies have been made worldwide about hydrothermal eruptions, their occurrence, distribution, ejecta composition and mechanisms of eruption. A detailed study and summary of most published New Zealand HE

events is given by Browne and Lawless (2001). Recent work on modelling these events has been published by Smith and M^cKibbin (1997), who gave a summary of other modelling work to date and how such events might be characterised and differentiated from phreatomagmatic and phreatic eruptions.

The study of hydrothermal alteration minerals found in eruption breccias may provide information about the maximum possible focal depth of the eruption origin, based upon known mineral formation temperatures for depth and pressure. At Waiotapu (Fig. 2.3), HEs have had focal depths of at least 350 m depth (Hedenquist and Henley, 1985); at Kawerau at least 200 m depth (Nairn and Wiradiradja, 1980); and at Rotokawa up to 450 m depth (Collar and Browne, 1985).

2.2 DISTRIBUTION OF THERMAL ACTIVITY

Surface geothermal activity in the RGF (Map 1, Map Pocket) is present in three broad groupings: (1) Whakarewarewa valley (Fig. 1.11, 1.12) and Arikikapakapa (Fig. 1.10) at the southern end of the caldera and city; (2) Ohinemutu (Fig. 1.6) and Kuirau Park (Fig. 1.7) at the northwest and nearby northern shores of Lake Rotorua; and (3) around Ngapuna, the delta of the Puarenga Stream (Fig. 1.9) and the western shores of Sulphur Bay (Fig. 1.8). Other smaller areas of thermal activity also occur in the Rotorua Cemetery on Sala Street and on the banks of the Puarenga Stream opposite Scott Street (Map 1).

From time to time people in boats on Lake Rotorua and various pilots overflying the lake have reported to authorities the presence of conspicuous muddy or bubbling upwellings along the southern lake margins within a few hundred metres offshore, indicating that geothermal activity is also present concealed on the lake floor. This is also borne out by chemical load measurements and fluxes

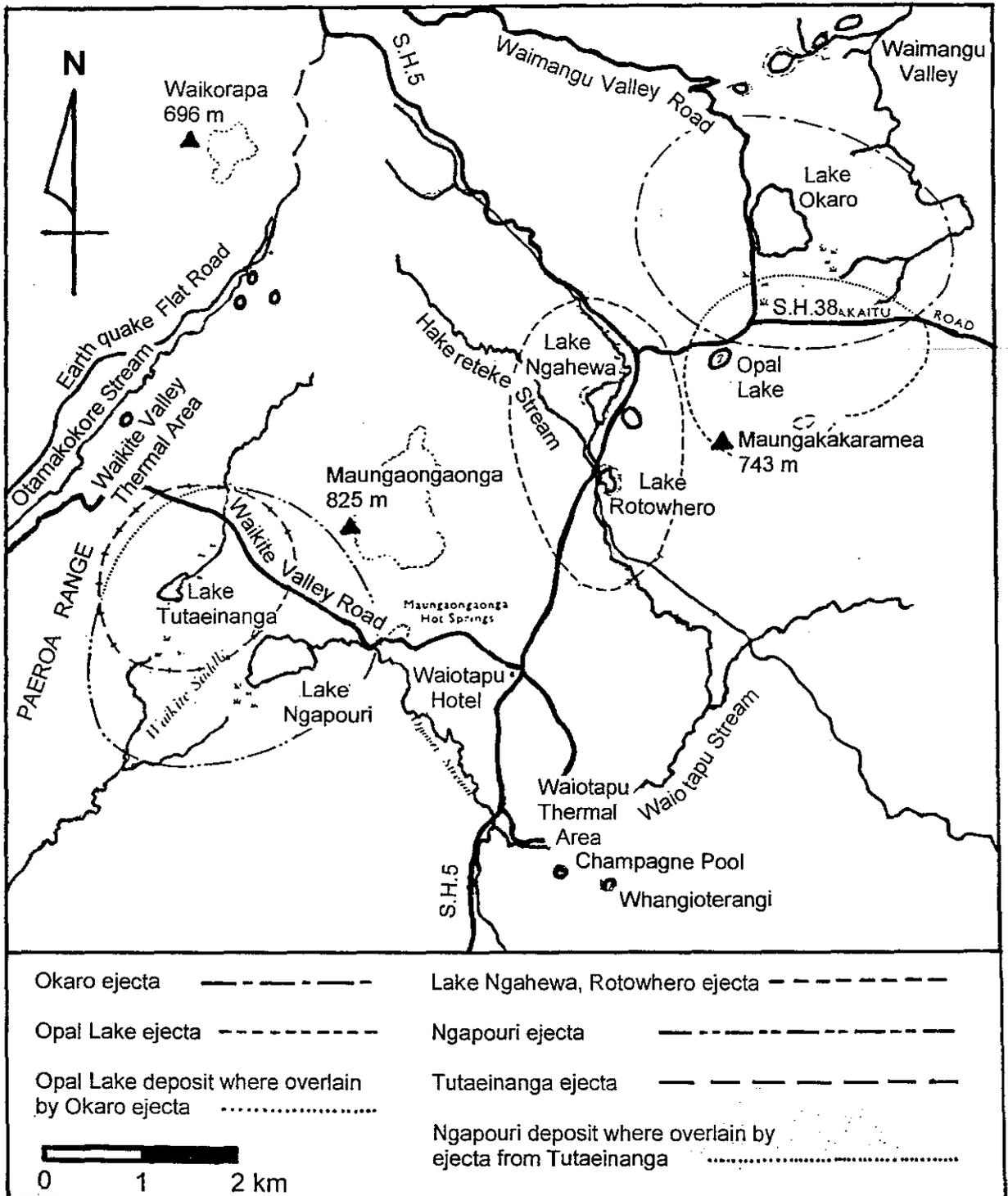


Figure 2.3 Location of hydrothermal eruption (HE) craters in the Waiootapu - Waikite Valley - Waimangu areas. All lakes shown are HE craters, as well as smaller circles. Dashed lines enclose limits of associated HE breccias. Adapted from Cross (1963).

into and out of Lake Rotorua that show 42% of all geothermal outflows from the RGF are occurring within the lake from undetected sources (Glover, 1992). Sulphur Bay is discoloured by colloidal sulphur particles and is deoxygenated; convection cells are also visible from aerial photographs and shoreline vantage points (Fig. 1.8).

In historical time there was also a group of flowing hot springs at Koutu, between the lakeshore and Kawaha Point Road shops (Fig. 1.3). These springs have published descriptions and chemistry that date from 1910 (Skey, 1914) and are also clearly shown on early survey plans for land subdivisions.

In the late Pleistocene to early Holocene, an area of hot springs was active up the Utuhina Valley, a few kilometres west of Pukehangi Road (Wood, 1992; Bayrante, 1984). Today there are outcrops of silica sinter deposits there, some with relict algae and bacterial filaments clearly visible. Rotorua Pyroclastics (13,500 years BP; Kilgour, 2002) overlies a silt or loess on top of those sinters.

2.3 TYPES OF SURFACE THERMAL ACTIVITY

Geothermal systems produce a variety of surface activity types according to the nature of the processes which occur at any particular site. Where geothermal waters reach the surface without any groundwater mixing, clear, hot (70-100°C) and neutral to alkaline (pH ~6.5-8.7) flowing springs occur, with silica deposition from the cooling of waters that are usually saturated or nearly so, in dissolved silica. These types of springs are of clear water, with pale gray, cream or white hard silica deposits of sinter. Rarely these may also contain calcite. These features are of low abundance and generally occur in close proximity to groundwater levels (i.e., nearby streams, close to local groundwaters in elevation, or that of Lake Rotorua in the northern RGF).

Where geothermal waters mingle with groundwaters, weakly acidic and turbid springs occur and have low flow rates, so that longer residence times in contact with the air allow oxidation of sulphide to form sulphates within the pools. This strong acid radical rapidly lowers water pH and the acid waters attack and dissolve adjoining ground to digest many minerals and ultimately form soluble salts and silica residues (Ellis and Mahon, 1977; Corbett and Leach, 1998).

In the absence of any groundwater mingling, geothermal gas upflows attack ground to form viscous mud pools or in drier conditions to build mud cones, due to ejection of mud globules by steam bubbles. Other areas are heated by underground boiling permeating to the surface through permeable materials, so that gases and steam cause barren ground and often alum salts as surface crusts. Salts are water soluble and dissolve during rainfall episodes, but grow again very rapidly after a few days without rain.

All these processes are occurring in all the present day areas of surface thermal activity in the RGF. Areas of very intense boiling without the presence of water form areas of solfatara, where sulphur crystals deposit in permeable ground. This crystal growth pushes apart the ground materials to form bulging mounds of exfoliating yellow sulphurous crusts. The delta of the Puarenga Stream at Sulphur Bay (Fig. 1.8, 1.9) is perhaps the largest onshore example of a solfatara in New Zealand today, comparable only with that of the White Island crater floor in extent.

Occasionally thermally active areas can suddenly commence boiling and erupt through to the surface, forming eruption craters and distributing brecciated, hard or muddy silt ejecta over surrounding ground. This is an infrequent but common and ongoing process in many New Zealand geothermal fields, in both prehistoric, historical and modern times. Types of geothermal features are described more fully in Appendix 7.



Figure 2.4 Blowout at mouth of Puarenga Stream, east side, on 27 February 1973, c.1220 hrs. View is to west across Sulphur Bay to Rotorua city. Eruption crater is EBOP database No. F 515, S 1372; photograph by EF Lloyd.

2.3.1 Geothermal Dolines

Dolines appear very similar to HE craters and are only mentioned to clarify why some circular depressions with crater-like appearances are not included in any discussion or inventory of HEs. Dolines are topographically closed depressions or holes that have developed by internal subterranean erosion, dissolution and subsequent collapse to produce surface features very similar to HE craters. These are formed by either solely physical or chemical erosion processes, or more commonly a combination of both. In geothermal areas where ground materials are comprised of poorly consolidated ashes or alluvium, downward percolating acid ground waters or rising steam and gases lead to the gradual removal of underlying materials until a collapse or subsidence occurs. These collapse features are called dolines and are more typically found in karst limestone terrains.

In the Rotorua Geothermal Field, doline development is most pronounced in Arikikapakapa, where crater-like depressions and holes have formed without accompanying hydrothermal eruptions. Here the land surface is 10 m or more above local ground water level. In nearby Whakarewarewa a large doline is actively developing to the southwest of Wairoa Geyser, and here too there is no evidence of any hydrothermal eruptions associated with this collapse. Several very small dolines also occur in Kuirau Park and one is presently forming just north of the Arawa and Ranolf Street corner (Daily Post, Sat. 18 April 1981). Two other conspicuous and presently developing dolines are within the now abandoned netball courts alongside Pukuatua Street, at the south end of Kuirau Park. These are causing both concentric fissuring and also compressional buckling ridges to form in the hard asphalt surface, which illustrates subsidence processes that occur in natural materials elsewhere, e.g. at Ohaaki Pool and at the Artist's Palette terrace in Orakeikorako.



Figure 2.5 The hydrothermal eruption of 18 May 1992 on the south shores of Sulphur Bay, about 50 m west from the Puarenga Stream delta. Photograph was taken on 30 May 1992 and is viewed to southwest. Crater of ~15 m diameter breached into Lake Rotorua, with muddy dark grey ejecta <0.5 m thick dispersed <10 m from crater margins. Figure is Professor Ron Keam.

Note that when this photograph was taken after 12 days, the solfataric activity in and around the crater has already oxidised the grey-black sulphur muds to white and pale yellow alum salts (e.g., in left and centre foreground).

2.3.2 Prehistorical Eruptions in RGF

Two hydrothermal eruption (HE) craters and associated breccias dating from prehistorical time have been recognised in the RGF prior to this work and very brief descriptions of them have been published (Lloyd, 1975; Bayrante, 1984). This thesis records investigations into three prehistorical RGF HE craters, two of which have never been recorded before; and none of these three sites has ever been previously studied in detail.

Chapter 3 gives detailed accounts of sites, their stratigraphy, settings and appearances. Further information about the mineral content of eruption breccias and analytical results are given in Chapter 4.

Within Whakarewarewa thermal valley along the true right banks of the Puarenga Stream, several low rounded hillocks comprised of HE breccias occur to the south of Whakarewarewa Village and southeast of Geyser Flat. Tourist walkways lead up to a vantage point on top of one (Te Puhunga), an urupa occupies another (Whakarewarewa), and Te Puia pa site is on another. Te Puia is a steep to vertical sided hillock rising some 23 m above surrounding land, to the northeast of Ngawha Crater (Map 2, Map Pocket).

Ngawha Crater has been mapped by Lloyd (1975) as the source vent for an HE, of which Te Puia Hill is the only remaining conspicuous outcrop. Lloyd also suggested these hills of eruption breccias were probably formed penecontemporaneously with the Rotoiti Pyroclastics volcanic eruption out of the Okataina Volcanic Centre c. 64 ka ago (Lowe and Hogg, 1995). His deduction was based upon observed geothermal destruction in Rotomahana, which accompanied the 10 June 1886 volcanic eruption of Mount Tarawera, as evidence that volcanic eruptions disturb nearby geothermal systems.

However, Lloyd's (1975) original date for Te Puia and other hills in Whakarewarewa comprised of HE breccias would require that they have withstood erosion for the last c.26.5 ka, as the Oruanui Formation was deposited into Rotorua basin at a time when Lake Rotorua had begun to rapidly fall from a high stand of at least 360 m asl, to about 300 m asl.

The HE breccia hills of Whakarewarewa are not overlain with any Mangaone Pyroclastics or Oruanui Formations, although they are overlain by both the 13.5 ka Rotorua Pyroclastics and 7.5 ka Mamaku Formations (Nairn, 2002). Neither is there is any evidence on their upper surfaces of water washing, sorting, or erosion, as might be expected in deposits laid down subaerially and then completely submerged by a higher waterlevel stand of Lake Rotorua following the Rotoiti Pyroclastics eruption of 64 ka ago (Kennedy, et al., 1978). Had any tephra of either Mangaone Pyroclastics or Oruanui Formation landed on these hills it would need to have been totally eroded, with no pockets of tephra remaining.

An alternative age for these eruption breccias is suggested to be 26.5 ka ago, at a time when Lake Rotorua water level was rapidly falling, following rupture of the dam at its northeast end. This age would mean the breccias did not exist submerged beneath the higher standing Lake Rotorua for c.40,000 years, as required by Lloyd's hypothesis. It is also significant that the breccias of Te Puia Hill contain strongly silicified siltstone containing many accretionary lapilli, which also outcrop in rocks east of Geyser Flat (U16 962326) and also upstream at U16 948319.

Uncemented brown silty tephra form an extensive terrace fan radiating northwards from Hemo Gorge and comprise the landform of Arikikapakapa Golf Course (Fig. 1.10). This deposit has several collapse and eruption craters that expose massive deposits of a pale gray uncemented silt containing abundant

accretionary lapilli and has been identified as being derived from Oruanui Formation ignimbrites and fall deposits (CJN Wilson, pers. comm.; Wilson and Switsur, 1988). This formation also outcrops at Whakarewarewa, where its appearance is of a similar grain size and accretionary lapilli size and abundance, although thermal alteration and cementing has discoloured it to pale fawn to cream.

Te Puia Hill breccias contain abundant clasts of a strongly cemented accretionary lapilli tephra. If this HE breccia was Rotoiti Pyroclastics age in origin, then no abundant accretionary lapilli bearing tephra deposit has been found of an age preceding Rotoiti Pyroclastics in this area to provide the similar type of material found as cemented clasts. A more plausible explanation presented here is that the accretionary lapilli bearing clasts are of Oruanui Formation that has been alluvially sorted and then silicified before finally being erupted out of Ngawha Crater some time after c. 26.5 ka ago, when Lake Rotorua had begun falling to expose all of Whakarewarewa above lake level. Geothermal alteration of most materials in these HE breccias has been so intense that virtually all common rock forming minerals have been destroyed and it is rare to find any feldspars, amphiboles, pyroxenes or micas.

During site investigations at BP Geyser petrol station, at the corner of Froude and Fenton Streets during 2000, augered inspection holes up to 5 m depth revealed a layer ~0.3 m thick of sticky brick red ochre intermingled with creamy soft clasts. This was underlain by a paleosol of much less weathered fine pumiceous sandy silts. The sticky cream and red pug is comprised of strongly hydrothermally altered clasts, but has been altered prior to deposition at this site, ie. it is an HE breccia. While its source vent was not precisely determined, its location some 250 m north of Geyser Flat and the present day surface thermal activity around Whakarewarewa infers that its source vent was somewhere in that area. Lloyd (1975) describes HE breccia being present at very shallow depths for some 1-1.5 km to the north of Whakarewarewa.

2.3.3 Historical RGF Hydrothermal Eruptions

Newspaper records and other unpublished accounts indicate that throughout historical to modern time (c.1840s to 2002), the RGF has had occasional HEs. The Puarenga Stream delta at Ngapuna (U16 965352) is an area with an ongoing record of spectacular and large HEs having taken place, with at least one having occurred in the 1970s (Fig. 2.4) and two having occurred in the 1990s (Fig. 2.5). During the 1890s, 1900s, 1910s and 1920s, large HEs occurred here and if eye witness accounts are to be accepted, some of these eruptions produced columns up to about 120 m high.

The common occurrence of many large HEs in the Puarenga Stream delta infers that some structure or mechanism is present to allow HE conditions to form. Today this is an area of about 25 hectares of boiling solfatara conditions, where oxidation of sulphide evolved from the boiling process is making a firm sulphur cement to bind the alluvial sediments which are continually deposited across this zone by the Puarenga Stream. This acts as an aquaclude and pressure containing barrier, which leads to temperatures rising above surface boiling point.

Eventually some process ruptures this sulphur-cemented stratum and a sudden loss of pressure induces a flashing of hot water to steam. A hydrothermal eruption then ensues, with rapid pressure drop and the removal of stored energy from the surrounding ground, together with excavation of the nearby ground materials. Triggers for the inducement of HEs here could be quite subtle processes, such as ground shaking following a local (or regional) earthquake, or the seasonal fluctuation in levels for Lake Rotorua creating an unloading of hydrostatic head.

Accounts of thermal activity changes in Rotorua during and soon after the volcanic eruption of Mount Tarawera on 10 June 1886 suggest that ground

shaking in Rotorua city was strong enough to open fissures and conduits sufficiently to allow geothermal fluids to escape to the surface, sometimes flashing to boiling in the process (Keam, 1986). When compared to other volcanic eruptions in the Rotorua district, the Mount Tarawera eruption was quite small in its intensity and quantity of erupted materials. For example, in 1886 Mt Tarawera erupted an estimated 0.7 km^3 of dry rock equivalent, whereas the 1350 AD Kaharoa eruption of Mt Tarawera erupted an estimated 5 km^3 DRE (Hodgson and Nairn, 2000).

However, the 1350 AD event also caused penecontemporaneous widespread destruction of the surrounding geothermal systems at Waiotapu and Waikite Valley (Lloyd, 1959). Steam eruptions then have led to the formation of craters now occupied by waters to give us the present day lakes of: Ngahewa, Tutaeinanga, Opouri, Rotowhero, Champagne Pool, Okaro and Earthquake Flat road craters (Fig. 2.3; Cross, 1963; Lloyd, 1959; Hedenquist and Henley, 1985). This indicates that volcanic eruptions around the Rotorua region are most likely to induce pronounced disturbances in neighbouring geothermal fields and have done so many times in the past.

All known historical hydrothermal eruptions for the Rotorua geothermal field are listed in Appendix 4, which uses a chronological sequence. Appendices 5 and 6 give chronological list of all known collapse holes and well casing and piping failures or blowouts. Grid references are given for identified sites and their Environment Bay of Plenty (EBOP) inventory form number (F xxxx) is also given, where identified (Appendix 3). Some of these events appear to be associated with triggering episodes such as heavy rainfalls, prolonged dry periods of several months followed by sudden heavy rainfall, or by suddenly changing local groundwater (or lake) levels. Other HEs are associated with human activity. Of the latter, two distinct categories are recognised:

1). Digging of channels or bursting of dams causing rapid falls of waterlevel near the eruption site, e.g. July and October 1938 at Roto-a-Tamaheke (N.Z. Geological Survey File U.16/466 General). These eruption events were attributed to human activity in the hours preceding hydrothermal eruptions there. The February 1984 eruption at Roto-a-Tamaheke may also have been triggered by human interference (van der Werff, 1984).

2). More damaging in nature are the eruptions from sites where "dead" springs or mud pools have been filled in. Such sites may be dormant for years or decades before hydrothermal eruptions occur, e.g. the November 1932 eruption in Ohinemutu; the October 1984 eruption in Ariariterangi Street; the May 1985 eruption at Whakarewarewa and the June 1986 event at Ngapuna. This last event may relate to realignment of the riverbanks in c. 1984 having covered over an active vent.

Therefore the infilling of apparently cold spring vents, craters and dolines of hydrothermal origin should be avoided, as they are evidence of conduits from depth having been established at much earlier dates. As such, their future reactivation cannot be discounted and may be enhanced by surface blockage, as this might allow localised over-pressuring of the geothermal aquifer until sudden eruptive boiling can occur to produce an HE.

In Arikikapakapa, some craters and depressions appear to be largely due to internal (tunnel) erosion and subsequent collapse, because breccias have not been identified with any of these. Craters have formed through the 13.5 ka Rotorua Pyroclastics (Kilgour, 2002) and 26.5 ka Oruanui Formation (Wilson, et al., 1988) deposits, but with no significant features known to have formed in historical times.

Map 1 and Figures 1.6 - 1.12 show maps of all known historical hydrothermal eruptions in Rotorua city. From this it is apparent that eruptions have occurred in areas of known surface activity and are not simply random throughout the entire Rotorua geothermal field. There is a pronounced spatial grouping of eruptions at: Ohinemutu, Ngapuna, Whakarewarewa Village, Kuirau Park, Government Gardens and Arikikapakapa..

It is notable that hydrothermal eruptions at Ohinemutu and Ngapuna were particularly prevalent in the 1890s and 1900s-1920s. This may be related to the heavy rainfalls and flooding that occurred then, which was prior to the Ohau Channel being deepened and widened in late 1900 (Smith, 1900) to control flooding and very low water levels at the southern end of Lake Rotorua. The level of Lake Rotorua was controlled from that time and may have reduced the incidence of eruptions at Sulphur Bay and Ohinemutu.

2.3.4 Modern Day RGF Hydrothermal Eruptions

In the mid to late 20th century a number of hydrothermal eruptions occurred in Rotorua, with details of known events being given in Appendix 4. Springs S614 and S615 in Kuirau Park (U16 946360) produced a spectacular eruption in August 1966, which is described in Section 2.4.1. Another notable and conspicuous eruption occurred on 31st October 1963 through until at least 8th November 1963. This occurred alongside a residential house on the lakeshore of Whittaker Road (U16 945369) and was the subject of considerable media attention because of how it progressively excavated surrounding ground to enlarge the boiling and erupting crater (Fig. 2.6). This encroached beneath the house and consumed a bicycle, a large water pump, a small trailer and a garden shed, none to ever be seen again (Healy, 1963).



Figure 2.6 Hydrothermal eruption at east side of lakefront at Whittaker Road on 31st October 1963. This site continued to erupt over several weeks (EBOP data base S1305, F448). See also Daily Post, 31 October 1963; NZ Herald, 1st November 1963; and Healy, 1963. Photograph by EF Lloyd.

Unfortunately the recorded account of this eruption (Healy, 1963) gives much attention to how these events may occur and where they have happened in the past, but almost no description of the deposits ejected. An opportunity to learn about underlying stratigraphy at the site was thus lost. However, Healy (1963) described that initially on the 31st October two craters were in eruption alongside each other, one of 5 m diameter and separated by a land bridge 2 m wide, and another crater of 3 m diameter. Both were frequently erupting 2-7 m high columns of muddy dark grey waters.

By 8th November, ongoing eruptions had enlarged the craters to coalesce into a single larger crater, which had breached to join with Lake Rotorua. The garden shed had then completely disappeared into the crater as well as the house verandah along its western side. The house was later moved away from the crater embayment. Healy (1963) told how most of the ejecta was thrown to the northeast side of the craters and he estimated the deposit to have a volume of 400 m³.

Local residents had recollections of other eruptions in the general Ohinemutu area, but none as large as this event. A shallow hot well at the same property continued to produce clean water without any apparent disturbances during the eruption, so it was not considered to have been implicated in directly causing the blowout. In 2002 this eruption site was still very hot and continually bubbling in the shallow lakeshore margins of Lake Rotorua, about 100 m east of the lake at the north end of Whittaker Road.

2.4 EYE WITNESS ACCOUNTS OF RGF ERUPTIONS

Although craters and breccias produced by hydrothermal eruptions may become preserved to leave evidence of their occurrence, many more leave no record of their presence beyond a few months or years, due to the ejecta being unconsolidated mud or silts. This is due to craters being rapidly infilled (e.g. the Puarenga Stream delta sediments have repeatedly completely infilled and camouflaged HE craters within a few years), or else they become flowing springs that deposit silica sinters up their walls and over surrounding ground and thereby mask evidence of their original formation (e.g. spring S952 at Whakarewarewa; U16 956328). Eruption breccias are generally comprised of geothermally decomposed materials that have been reduced by acid digestion to an unconsolidated clay or silt, usually of largely finely divided silica. This is quickly washed away by surface weathering or is incorporated into surrounding acid ground and leaves no recognisable deposit preserved in the geological record.

Hydrothermal eruptions are typically very short duration events that last only a few minutes or hours, but sometimes recur every few hours or days. They are not persistent enough to allow observation by many people and so any eye witness accounts of actual HEs provide useful information to assist in understanding their formation process.

2.4.1 Spring S615, Kuirau Park

On 22 August 1966 a very brief but spectacular eruption occurred from a turbid hot pool mapped as S615 (Map 3, U16 946360). An unknown member of the public on Ranolf Street took several polaroid photographs of the actual eruption and these were passed on to the Rotorua Tourist Centre, who gave them to the local office of New Zealand Geological Survey (NZGS; Fig. 2.2). Black and white

photographs of this eruption deposit are also held by the Institute of Geological and Nuclear Sciences (IGNS) at Wairakei. They show a mound of fine muds around the vent, out to about 10 m radius from the crater margins. Blocks up to ~0.4 m diameter can be clearly recognised lying ~10-15 m from the vent.

Sam Phillips (Castlecorp; pers. comm.) also witnessed the 22 August 1966 eruption in Kuirau Park. He gave descriptions of its location and deposits as well as the style of the eruption itself. He was on Ranolf Street at the time and recalled it as being very noisy but short lived, lasting only what seemed like a few minutes. Much fine mud was erupted, together with only a few rocks.

Murray Haycock was a young engineer with Rotorua District Council (RDC) in 1966 and was in Kuirau Park at the time and saw part of the eruption. He described the blast as lasting only about 15 seconds total, with a vertical mud column ~50 m high. According to him, it came from a hole by the northwest side of Lobster Pool (pers. comm. 26/04/01). In November 2001, EF Lloyd (retired District Geologist with NZGS; pers. comm.), told how he recalled this eruption coming from a vent by the west side of Lobster Pool and was identified by him as S614 (Figs. 1.7, 2.2).

An unpublished report on this eruption was written by Healy, then District Geologist for the Rotorua office of New Zealand Geological Survey (NZGS; Healy, 1966). He gave a very cursory description of the eruption and its deposits, but a more detailed discussion of its possible causes and an account of other similar recent eruptions. Healy (1966) also estimated the quantity of this deposit at ~80 tonnes of mud, although it is unclear if he meant a volume of ~80 m³ instead, because he does not give any density information. Both his account and photographs published in the Rotorua Photo News (No.37, 24 September 1966) clearly identify rocks amongst the ejecta, but there was no comment upon its composition.

2.4.2 Puarenga Stream Delta, Sulphur Bay

On Wednesday 20 May 1992, John Perry (curator of the Bath House Museum) found the very fresh remains of an eruption on the shore of Sulphur Bay, about 50 m west from the Puarenga Stream mouth. On Saturday 30 May 1992 it was inspected by the author. A 15 m diameter crater was steaming and gently bubbling, with about half of its circumference open into Lake Rotorua (Fig. 2.5).

Muddy dark grey ejecta was dispersed uniformly onshore to 5-7 m distance of the crater rim. Clasts of sulphur cemented quartz rich sands were the only breccia material recognised apart from the coating of fine muds. Several months later the dark muds had all changed to very light brown sandy silts due to oxidation of the sulphur and sulphides to water soluble sulphates, which had then been dissolved and washed out.

2.4.3 Hamiora Place, Ngapuna

On c.7th March 1996 an eruption occurred from the hangi cooking area of boiling barren ground bordering the eastern Puarenga Stream banks (Fig. 2.7; U16 967344). No witness has been found, but several people saw the newly formed crater and ejecta deposits within an hour or two of its formation. Distribution of ejecta to <10 m radius of the crater edge was of sands and silts, with sparse blocks <0.2 m diameter. An oval crater of about 10 m by 15 m area was formed through the flood stopbank, at the southern end of the hangi cooking area, west of the end of Hamiora Place (Fig. 1.9). Blocks up to about 1 m diameter lay in the stream and crater, with some blocks slumping from within the crater walls. Hard blocks of ejecta were comprised of sulphur cemented sands and pumice gravels.

This eruption may have only lasted a few minutes at most, with a column height of perhaps <20 m height, based upon distribution of ejecta. Photographs of the crater were taken by WR Esler and ADC within following days and weeks. By 1997 the stopbank had been repaired again and so no evidence of the crater remains, apart from some large ejecta blocks lying in the Puarenga Streambed.

NB: On the 29th of April 2003, another hydrothermal eruption occurred at this exactly the same vent site at about 0830 hrs. It produced a crater ~3m diameter and evolved a plume of gaseous muds to ~50m high, then weakened after ~2 hrs to a plume of steam and gases ~20m high. A strong westerly wind distributed fine mud and gases to ~200m downwind. (see Daily Post, 30th April and subsequent days).

2.4.4 Tarewa Road HEs

Beginning in March 1998 up until January 2000, the Tarewa Road springs (Fig. 1.7) commenced a series of HEs from several long established hot spring vents that had been dry and cool for about 15 years. The detailed sequence of events and the ultimate evacuation and later demolition of four houses at Nos. 16-20 Tarewa Road is described by Scott (2000, 2000a). One of these events is shown in Fig. 2.8.

2.4.5 S721, Kuirau Park

This HE occurred at c.1540 hrs (NZDT) on Friday 26 January 2001 from a turbid muddy hot pool known simply as S721 (Fig. 3.33) and F350 (EBOP database). Prior to this eruption it was a turbid muddy pool with a water level about 0.7 m below ground surface and at 48-63°C and pH 2.8-4.7 (Cody, 1998).

Several witnesses have given descriptions of the actual eruption characteristics and a large volume of ejecta was deposited, which has allowed detailed investigation of the breccia before it becomes too weathered and assimilated into surrounding terrain. Some witnesses of this eruption are known and include: Jos Nagels (Development Officer with Tauranga District Council); Evan Elms, owner of Lakeside Thermal Holiday Park; and Peter Goodwin, Rotorua District Council

(RDC). Derek Owen (Castlecorp) was using a ride-on lawn mower around the vicinity of S721 on Friday afternoon and he also later saw the eruption of S721 from within the park (pers. comm.). Evan Elms (pers. comm.) also witnessed this eruption from Lake Road.

Jos Nagels was in Rotorua Public Hospital at the time and his room looked out west across Kuirau Park. He and a visitor heard and saw the muddy eruption plume from S721. From his vantage point the eruption appeared to be a vertical column and from his account it reached about 75-100 m height. Rocks could be seen spilling out of the muddy column, which was all enveloped in steam clouds.

Evan Elms was driving west along Lake Road at the time, in an open topped sports car. The noise of the eruption drew his attention and he stopped on the side of Lake Road bordering Kuirau Park to watch. He described how the eruption made a very loud steady hissing noise. His height estimate was of about 150 m, judged from angle of view up to the column top. Most informative though was his information of how the plume was strongly inclined to the east, at an angle of about 70 degrees from horizontal. He also said he timed the eruption at four and a half minutes. Big boulders were shooting out of the dark grey muddy eruption column up to three quarters of its height and steam clouds swirled off to the east, together with a fine mist of dark grey mud. All throughout it made a loud and steady hissing noise (pers. comm. 26 July 2001).

Peter Goodwin (RDC) was in the Aquatic Centre at the time and a colleague called out to him to look at the eruption. He indicated an angle at which he looked up to its top, which equated to 25° or 30° over a distance of ~250 m. This gives a height range of 117-144 metres. From his vantage point it appeared to be a vertical column, with big rocks falling out of the dark muddy column, which was surrounded in white steam clouds.



Figure 2.7 The 7th March 1996 hydrothermal eruption on the Puarenga Stream stopbank, alongside hangi cooking area. Photograph view is to west and stream is flowing from left to right. Crater is ~15 m diameter, but note the sparse amount of ejecta.



Figure 2.8 The 19 January 2000 hydrothermal eruption from an unnamed vent in the Tarewa Road springs group. Centre fence is the boundary between No.20 to left and No.22-24 to right. Two houses were present on No.20 until only a few months before this photograph was taken.

*I kept six honest serving men,
They taught me all I knew;
Their names are What and Why and When,
And How and Where and Who*

- Rudyard Kipling (Just So Stories)

Chapter 3

LANDFORMS, STRATIGRAPHY AND LITHOLOGY

3.1 INTRODUCTION

Hydrothermal eruption (HE) deposits generally have a poor chance of preservation in the geologic record. Unless the deposits are preserved by either silicification or burial, they tend to quickly dissipate and become incorporated into the soil horizons.

In hot acid conditions, HE materials are not distinguishable from surface materials produced by acid alteration unless they were already cemented into hard blocks of durable materials. For example, the 26 January 2001 eruption of S721 in Kuirau Park consisted of blocks with a high proportion of montmorillonite clays, which have undergone rapid slaking to fall apart after only 18 months since emplacement.

Field sample numbers are used in the text, but corresponding catalogue numbers of samples held in the Earth Science Department, University of Waikato collection are given in Appendix 1. The individual geothermal features identified as being hydrothermal eruption craters and sites are listed in Appendix 2 and an example of the Rotorua District Council (RDC) and Environment Bay of Plenty (EBOP) geothermal database entry form is given in Appendix 3.

3.2 NGAWHA CRATER AND TE PUIA HILL

A widespread deposit at Whakarewarewa has been mapped by Lloyd (1975) as a hydrothermal eruption breccia (Map 2, Map Pocket). Lloyd did not give it a formal name but mapped it as being continuous to the east and north of Ngawha Crater (U16 953323) and extending up to one kilometre to the north. He also mapped it as being present across Te Puhunga and Whakarewarewa hills and north across Meade Street to Froude Street. He gave no description of composition or thickness of the deposit.

3.2.1 Location and Distribution

Te Puia Hill (U16 954324) is a prominent steep sided small hill at the southernmost end of the Te Puia Fault lineation of hot springs and geysers at Whakarewarewa (Figure 3.1). It is the remnant of an eroded HE breccia deposit, the vent of which is now occupied by the conspicuous 15 m high silica sinter pile known as Waikite Mound, located at the centre of Ngawha Crater (Map 2, Map Pocket; Lloyd, 1975). The crater is a near circular basin of about 100 m diameter at the northeast foot of Pohaturoa Hill and the whole site has ongoing intense geothermal activity.

Te Puia Hill stands about 23 m high (328 m asl) above the surrounding valley floor (305 m asl) and has a steep to vertical north face with steep east and west flanks. A narrow spur connects south from its summit onto the northeastern end of the Pohaturoa Hill ridge (Map 2, Map Pocket). The spur and surface of Te Puia Hill have been incised and leveled by human activity to form the defensive pa site of Te Puia, which features in oral history of the local Ngati Taoi (Stafford, 1994). Rotorua Pyroclastics (Kilgour, 2002) of 13.5 ka are present upon its surface, but any younger tephra that may have once been present upon Te Puia Hill could

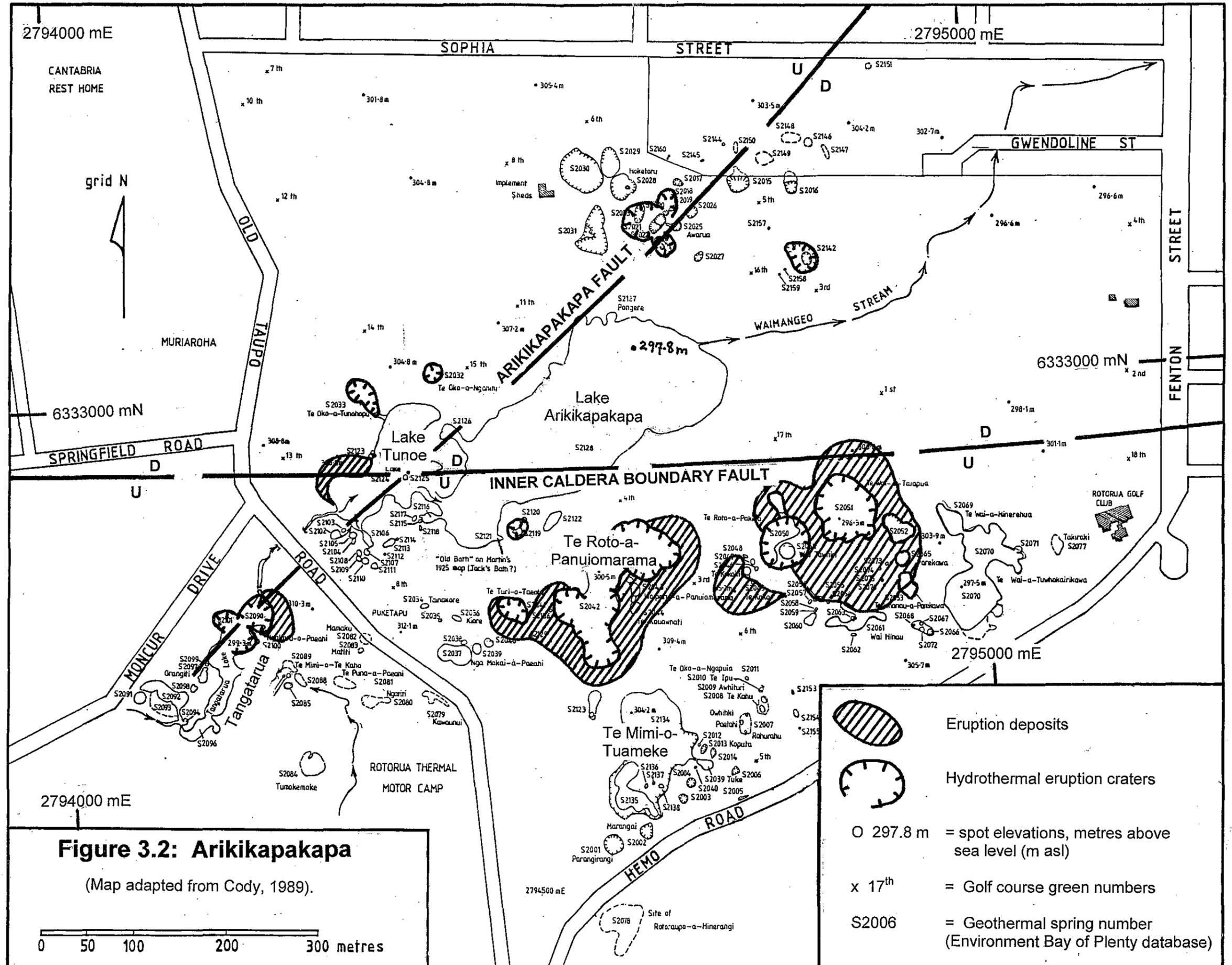


Figure 3.1 View north across Ngawha Crater, at Whakarewarewa. Mount Ngongotaha at far left skyline. Hill to right middle distance is Te Puia Hill, with its top and connecting ridge modified to construct a fortified pa site. The hill is comprised of an unsorted, matrix supported hydrothermal eruption breccia. In the central and left areas, shrubland covers decaying and collapsing silica sinter sheets occupying and infilling Ngawha Crater. At distant left the barren steaming dome is Waikite Mound, a silica sinter pile surmounted by Waikite geyser. In the foreground and right, hot steaming ground and pools are located around the southern and eastern margins of Ngawha Crater.

have been removed or remoulded by human activity. Today the hill is a sacred site as an urupa (burial ground) for warriors killed there. This has resulted in restricted access for study, excavation and sampling of Te Puia Hill and has constrained the detail of work done.

HE breccia associated with Ngawha Crater is confined to the east, southeast and south sides of the crater, with no recognised eruption deposit to the west or immediate north. However, on the north side of the Puarenga Stream, an intensely hydrothermally altered breccia deposit is present and this can be mapped northward into the south end of Rotorua city (Lloyd, 1975). Meandering of the Puarenga Stream across Ngawha Crater and the neighbouring valley floor has removed all traces of any HE breccia. Recent Holocene tephras found elsewhere in Whakarewarewa Valley are not present north of Ngawha Crater to the Puarenga Stream, but immediately to the north of the stream a high terrace at 310-315 m asl comprised of alluvially reworked Oruanui Formation (26.5 ka) (Froggatt and Lowe, 1990) ignimbrite and fall deposits forms an extensive terrace that continues north and west through the adjoining Arikikapakapa Reserve (Fig. 3.2).

Excavations along Fenton Street and in surrounding properties have exposed a highly altered deposit which was identified by Lloyd (1975) as being the Ngawha Crater HE breccia. At the corner of Froude and Fenton Streets beneath the BP Geyser petrol station, this breccia is present as a bright red and cream to fawn clay pug that is wet, plastic and sensitive to liquefaction. No diagnostic minerals are present in the breccia at that site but its stratigraphic relationship with the overlying Rotorua Pyroclastics make it likely to be a Whakarewarewa sourced breccia predating 13,500 years BP. However, it is not known if this is from Ngawha Crater, or is instead an HE breccia sourced from the vicinity of either Whakarewarewa or Te Puhunga Hills.



3.2.2 Stratigraphy and Age

The Ngawha Crater breccia is overlain by Rotorua Pyroclastics along the saddle connecting Te Puia Hill to Pohaturoa, with no apparent paleosol present between them. North of Waikite Mound, hot spring sinter deposits have an exposed basal contact along the west side of Te Anarata Cave and also in the base of Tukutuku Cave, along its east wall. This unit underlying the sinters is a silicified silt, which is the widespread basal unit beneath present day sinters and breccias in Whakarewarewa.

3.2.3 Lithology

Stratigraphy of the Ngawha Crater breccia exposed at Te Puia Hill is shown in Figure 3.3. The most vertical exposure of this breccia is exposed on the north face of Te Puia Hill (Fig. 3.4, 3.5). The stratigraphic column (Fig. 3.3) is from the southeast saddle outcrop (U16 953323). The breccia at Te Puia Hill is characterised by protruding boulder and coarse gravel sized clasts of silicified and pyritised silts and pugs, with a fine gravel to coarse sandy matrix of comminuted materials similar to that seen in the larger clasts. Some vertical grading of clast sizes is apparent through the exposure, with the largest blocks occurring in the lower 10 m. This indicates a progression of weakening energy flux during emplacement of the breccia.

Clasts from Te Puia Hill are predominately of light grey to pale yellow grey massive silicified silts and muds, usually without any bedding or internal grain size sorting (Fig. 3.6). The whole of the Te Puia breccia outcrop also shows conspicuous iron staining of limonite or brown oxide-hydroxide-ferrihydrate colours and occasional internal iron alteration products producing intense purple to ochre red and orange colours. No visible crystals are present, or any opaque

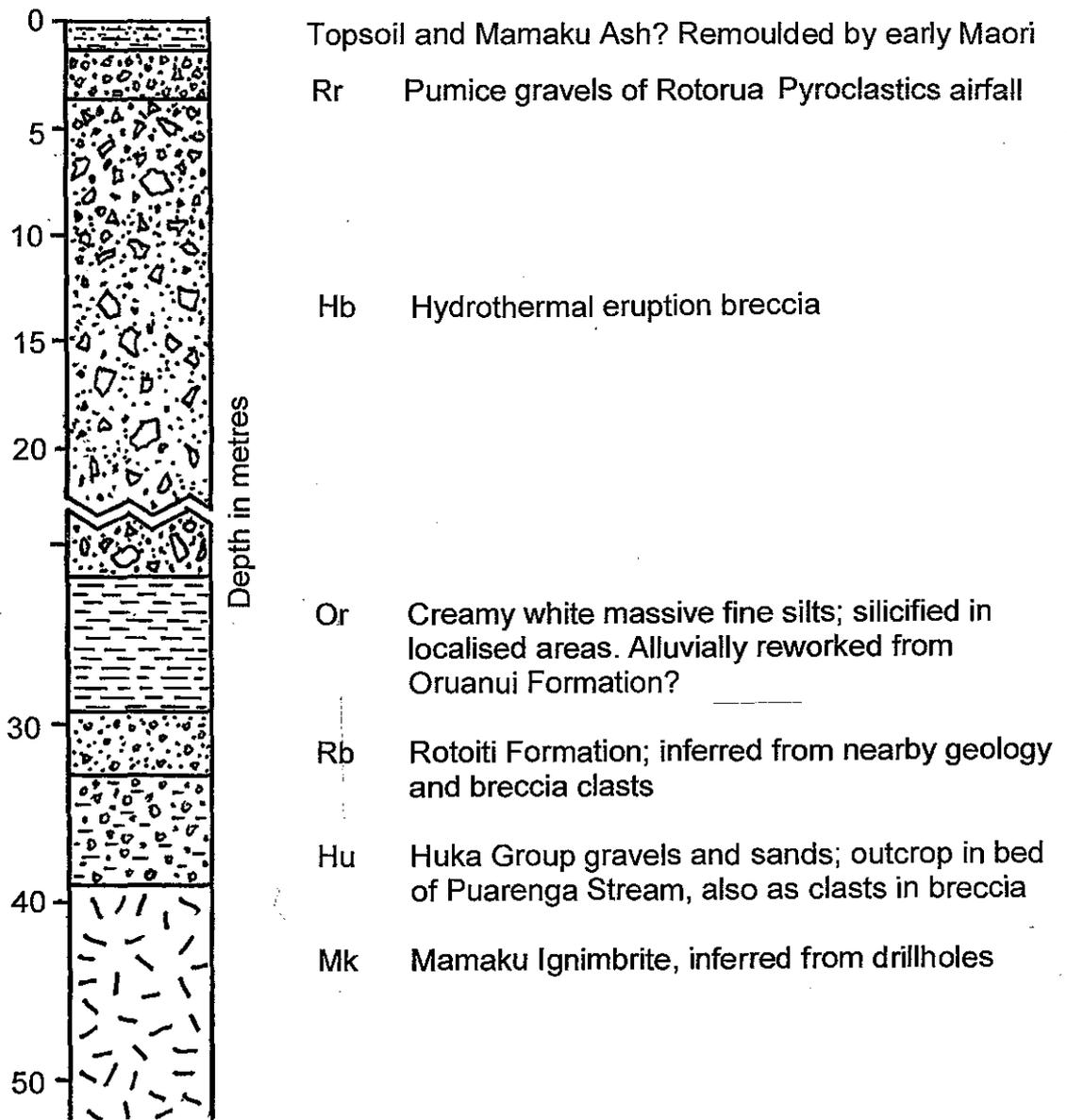


Figure 3.3 Stratigraphic column for Te Puia Hill, Whakarewarewa (U16 954324). Geology below 23 metres elevation is inferred, based upon nearby outcrops, breccia clast composition and drillhole geology.



Figure 3.4 View due south to the north face of Te Puia Hill. Summit has been leveled by human activity to form a fortified Maori Pa. Height from track across foreground to summit is 23 metres. Outcrops of rhyolite lavas at top right are on Pohaturua Hill, which forms a portion of the south wall to Rotorua caldera.



Figure 3.5 Close view of lower north face of Te Puia Hill. One metre scale bar at lower right. Outcrop consists of strongly silicified blocks <0.7 metres diameter, comprised of siltstones, pumice gravels and altered ignimbrites or pumice clasts.

or dark mineral grains. Accretionary lapilli up to 20 mm diameter are common in some silicified silt clasts (Fig. 3.8).

Other clasts have strong iron oxide and ferrihydrite staining on their outer exposed surfaces, with dark grey pyritised internal colouration. These occasionally show evidence of size grading and bedding (Fig. 3.10). Very rarely, some clasts of a white vesicular pumiceous texture are present, which have the appearance of a geothermally altered ignimbrite (Fig. 3.7), or perhaps a pumice breccia (Fig. 3.9). Several rare blocks up to 250 mm long of pale yellow grey to white silicified silt also occur, and these show no visible inclusions, vesicles or crystal content. They are very well bedded into 3-5 mm thick bands of laminated silts. There are also rare clasts of fresh and well rounded rhyolite that may be derived from an underlying deposit of Huka Group sediments and gravels.

3.3 WHAKAREWAREWA AND TE PUHUNGA HILLS

These two hills are situated some 230-300 m northeast of Ngawha Crater (Map 2) and are mapped by Lloyd (1975) as being of the same HE breccia as that sourced from Ngawha Crater. It is considered here that there are at least two breccias present of widely separate ages sourced from two or more vents, which overlap with those from Ngawha Crater.

3.3.1 Location and Distribution

Whakarewarewa Hill (U16 953326) and Te Puhunga Hill (U16 955325) are located within the Whakarewarewa Thermal Valley, along the south side of the Puarenga Stream (Map 2, Map Pocket). Intense thermal activity, in the form of



Figure 3.6 Te Puia Hill breccia at outcrop on lower western face. Vertical scale is one centimetre bands. The large centre clast is about 0.3 m high and wide and is comprised of hard, silicified angular fine white pumice gravel in a matrix of dark grey sandy silts.

boiling ground with numerous open steaming vents, surrounds the base of both these two hills, although their upper slopes and summits are near ambient temperatures with only weak conductive heating. They are comprised of an angular unsorted blocky matrix supported breccia unit that is present only in these two small neighbouring hills, and it does not form any continuous deposit that can be mapped or correlated away from these hills. No other outcrops of breccias occur nearby that might correlate with these deposits.

3.3.2 Stratigraphy and Age

The HE breccias that comprise Whakarewarewa and Te Puhunga Hills are comprised of intensely thermally altered materials of silicified silts that are uniformly white to creamy yellow, and without any visible crystalline inclusions or any dark coloured mica, titanomagnetite, ilmenite or ferromagnesian minerals. There is a total absence of any iron weathering products such as iron stained brown or limonite-ferrhydrite colouration. No basal exposure is present but both hills have residual covering beds of airfall volcanic ashes. Rotorua Pyroclastics (13.5 ka; Kilgour, 2002) is recognised by its coarse gravel pumice, which is the only such thick recent tephra in Rotorua city, and Mamaku Formation (7.5 ka; Nairn, 2002) is present as a greasy orange brown cohesive clay.

Ground near the base of these hills exposes a compact white mud of silica residues and opaline silica, which are considered to be alluvial sediments derived from Oruanui Formation and washed into Rotorua Basin by the Puarenga Stream. This ground has also been intensely hydrothermally altered and no diagnostic minerals are preserved in it, although beds of accretionary lapilli up to 20 mm diameter are present and are of the size range typical of Oruanui Formation materials.

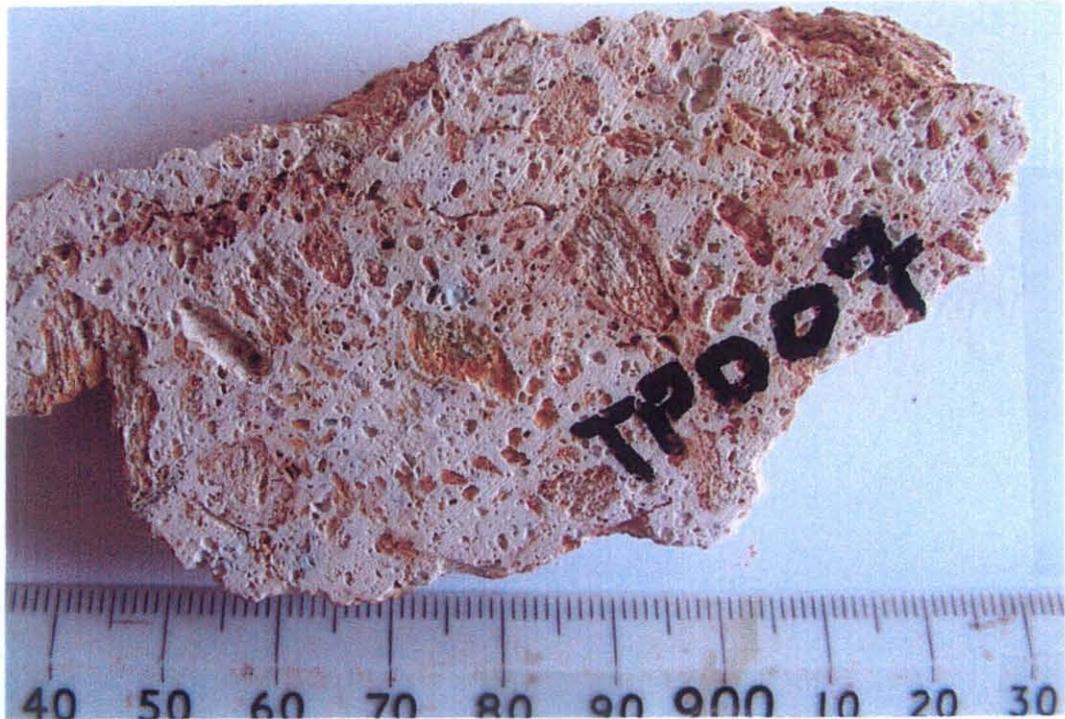


Figure 3.7 Clasts of unidentified ignimbrite from Te Puia Hill HE breccia. Sample No. TP-007, scale units in millimetres.

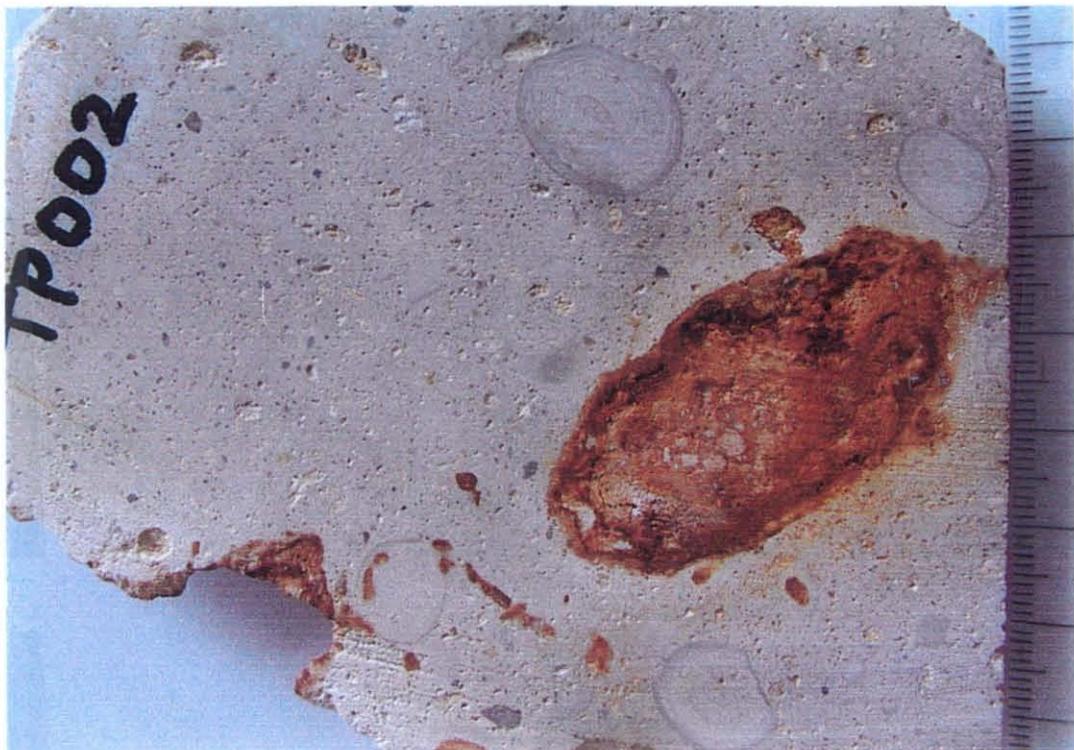


Figure 3.8 HE breccia clast from Te Puia Hill of silicified siltstone containing accretionary lapilli and a large decomposed pumice. Sample No. TP-002, scale units in millimetres.

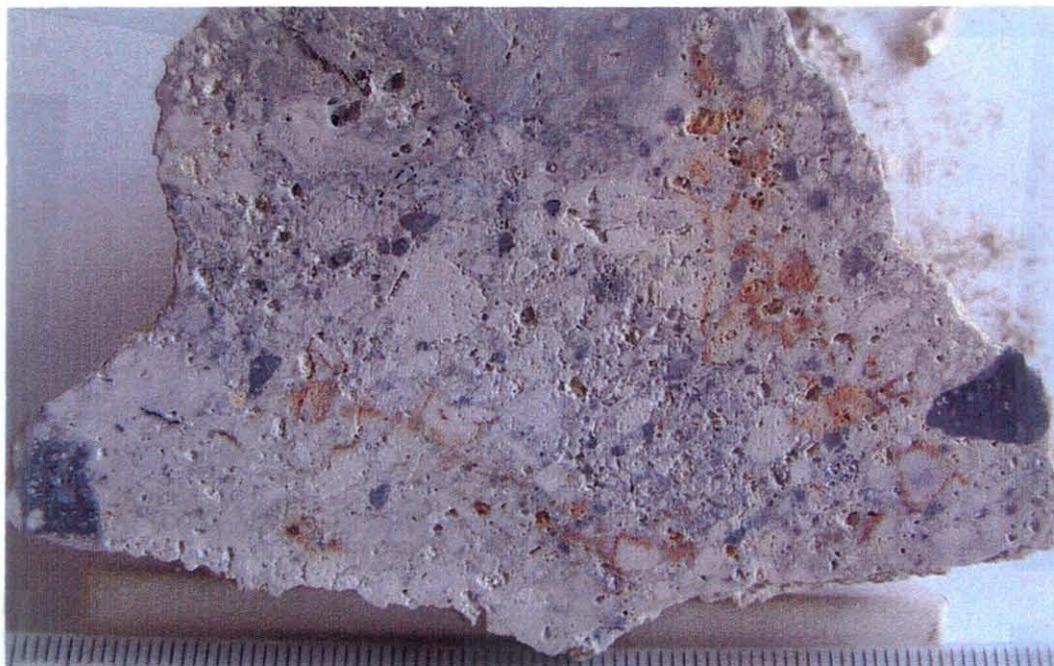


Figure 3.9 Clast of autoclastic rhyolite from Te Puia Hill HE breccia. Sample No. TP-003, scale units in millimetres.



Figure 3.10 HE breccia clast from Te Puia Hill, showing internal and external views. Silicified pumiceous sediment with alternating fine sand, sand and vesicular pumice. Scale in millimetres.

These accretionary lapilli are comprised of fine silt sized particles. The only other accretionary lapilli bearing material occurring in Rotorua Basin is the Rotoiti Pyroclastics (Nairn, 2002), which outcrops several hundred metres upstream (U16 948319). That site it is characterised by accretionary lapilli >30 mm diameter that are comprised of sand-sized glass shards.

3.3.3 Lithology

The HE breccias of Whakarewarewa and Te Puhunga Hills are geothermally decomposed to amorphous silica and silica residues, with sparse quartz and no feldspars or other common rock forming minerals remaining. Breccia clasts are supported by a fine sandy silt and the whole deposit is uniformly white, with no visible inclusions of other minerals.

3.4 WHANGAPIPIRO (CRATER) BAY

3.4.1 Location and Distribution

Whangapipiro (Crater) Bay (U16 958355) is an embayment on the western side of Sulphur Bay (Figure 3.11). It has several characteristics of an HE crater but has never previously been known of or described as such. Its eastern shoreline is comprised of silicified lacustrine pumiceous gravels and quartz sands that form an outcrop 1.5 m high (Fig. 3.12). Along its western side the shoreline is comprised of a pale brown thixotropic silt overlain by an angular unsorted HE breccia >3 m thick (Fig.3.13, 3.19).



Figure 3.11 View due west across Whangapipiro (Crater) Bay. Polynesian Spa at left and Mount Ngongotaha in distance. Foreground is of silicified sediments and weak steam and gas heating. Far shoreline is comprised of cemented eruption breccias and lake sediments.



Figure 3.12 View due east across Whangapipiro Bay into Sulphur Bay and the eastern rim of Rotorua caldera on skyline. Crater is 110 metre diameter. Note the convection cell in centre of bay.

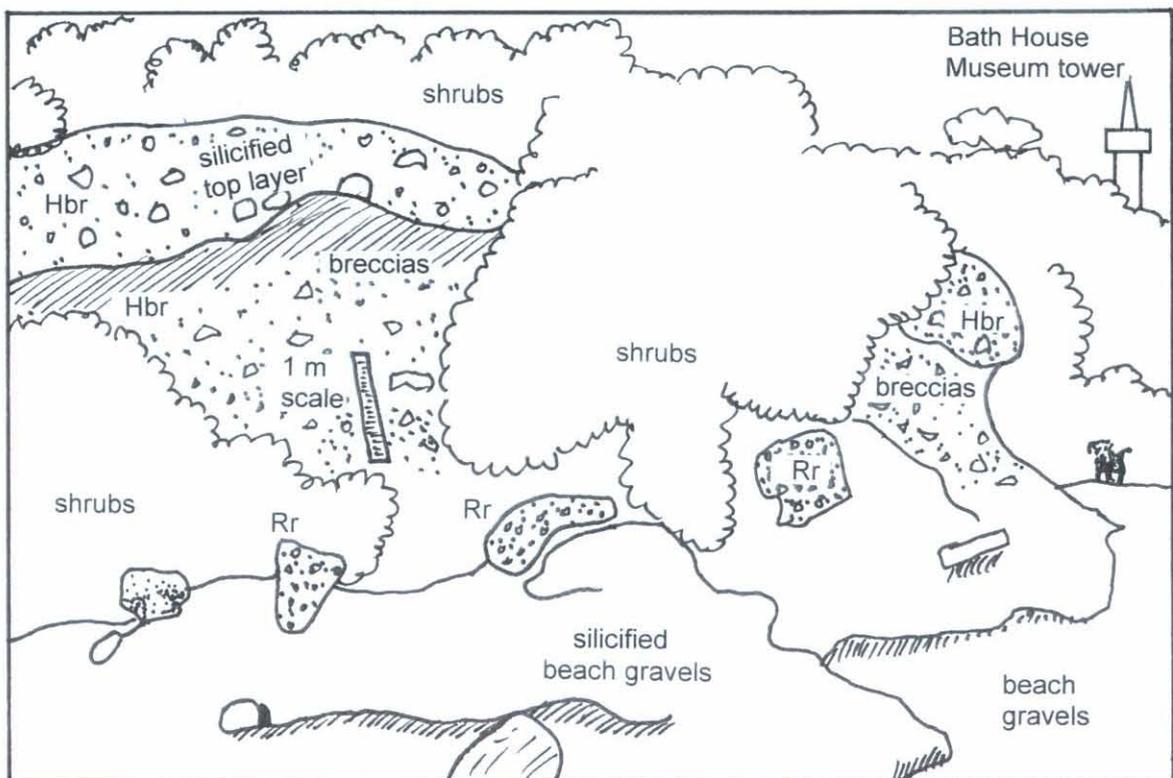


Figure 3.13 Site F184, Whangapipiro Bay breccias, samples F184.1a.001-008. Silicified breccia (HBr) deposit with foreground of overlying cemented Rotorua Pyroclastics (Rr) gravels.

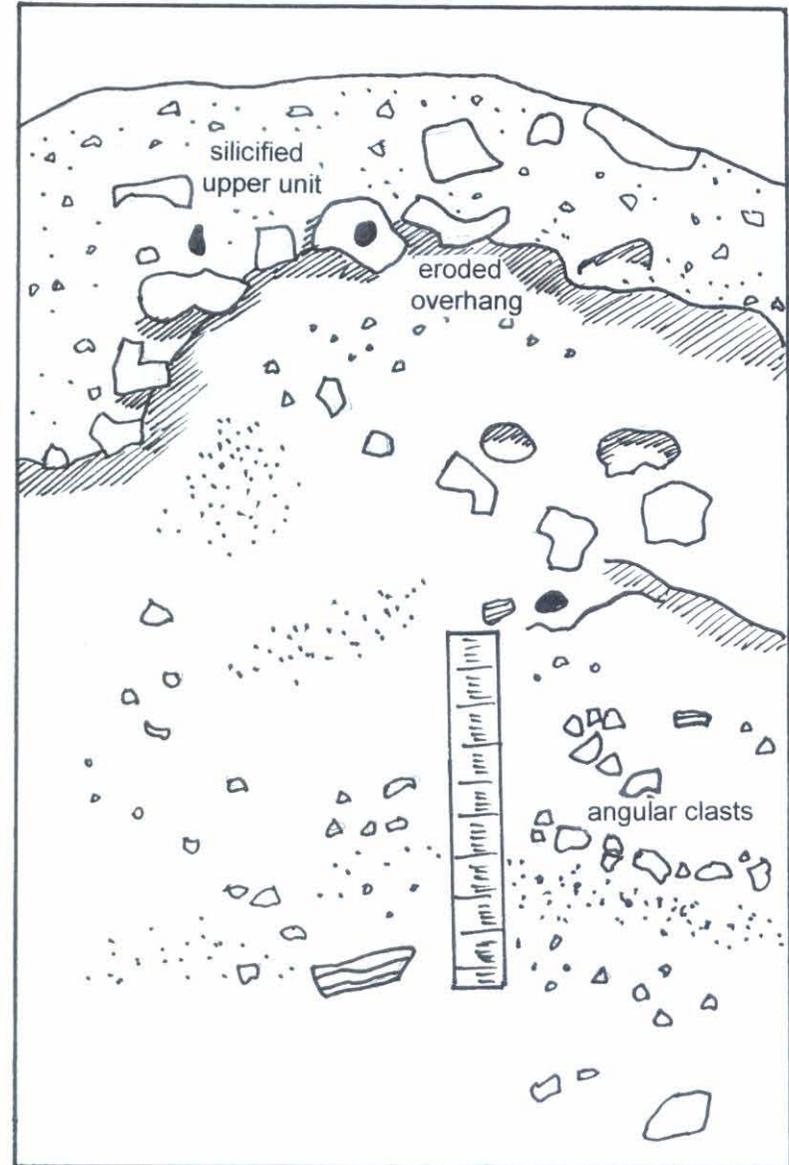
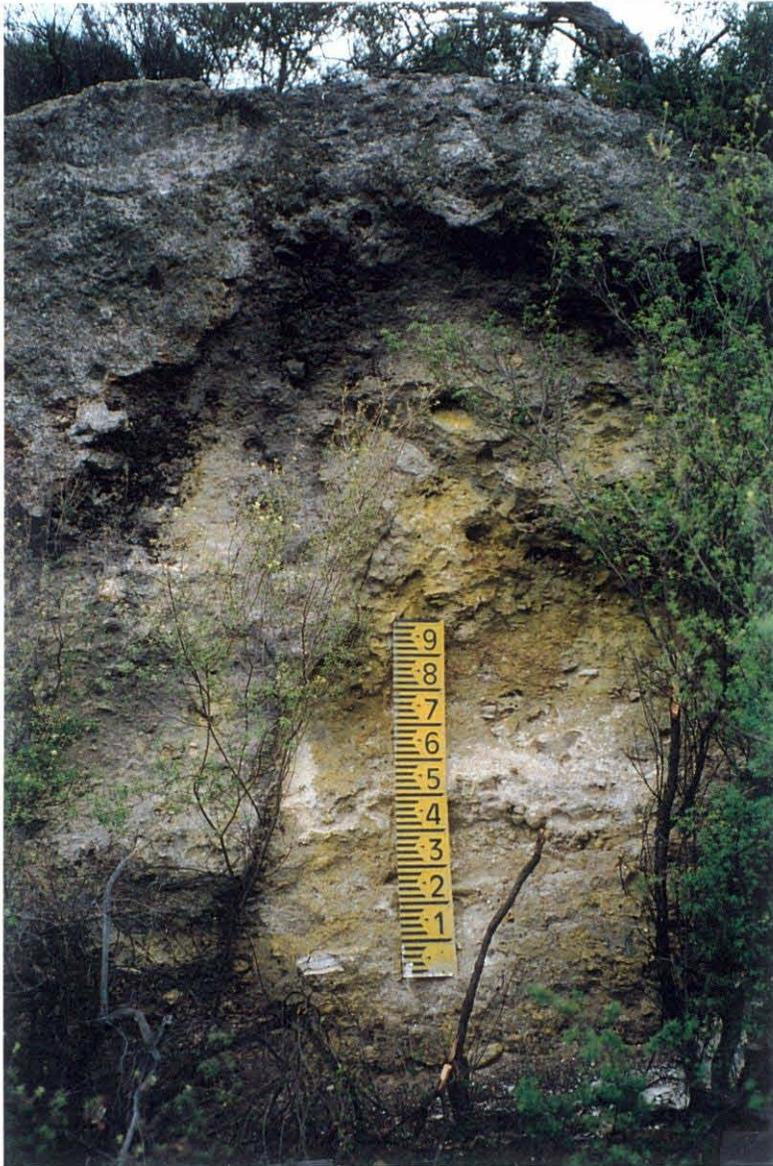


Figure 3.14 Vertical face ~3.5 metres high of cemented eruption breccias, Site F184 (Crater Bay). One metre scale bar.

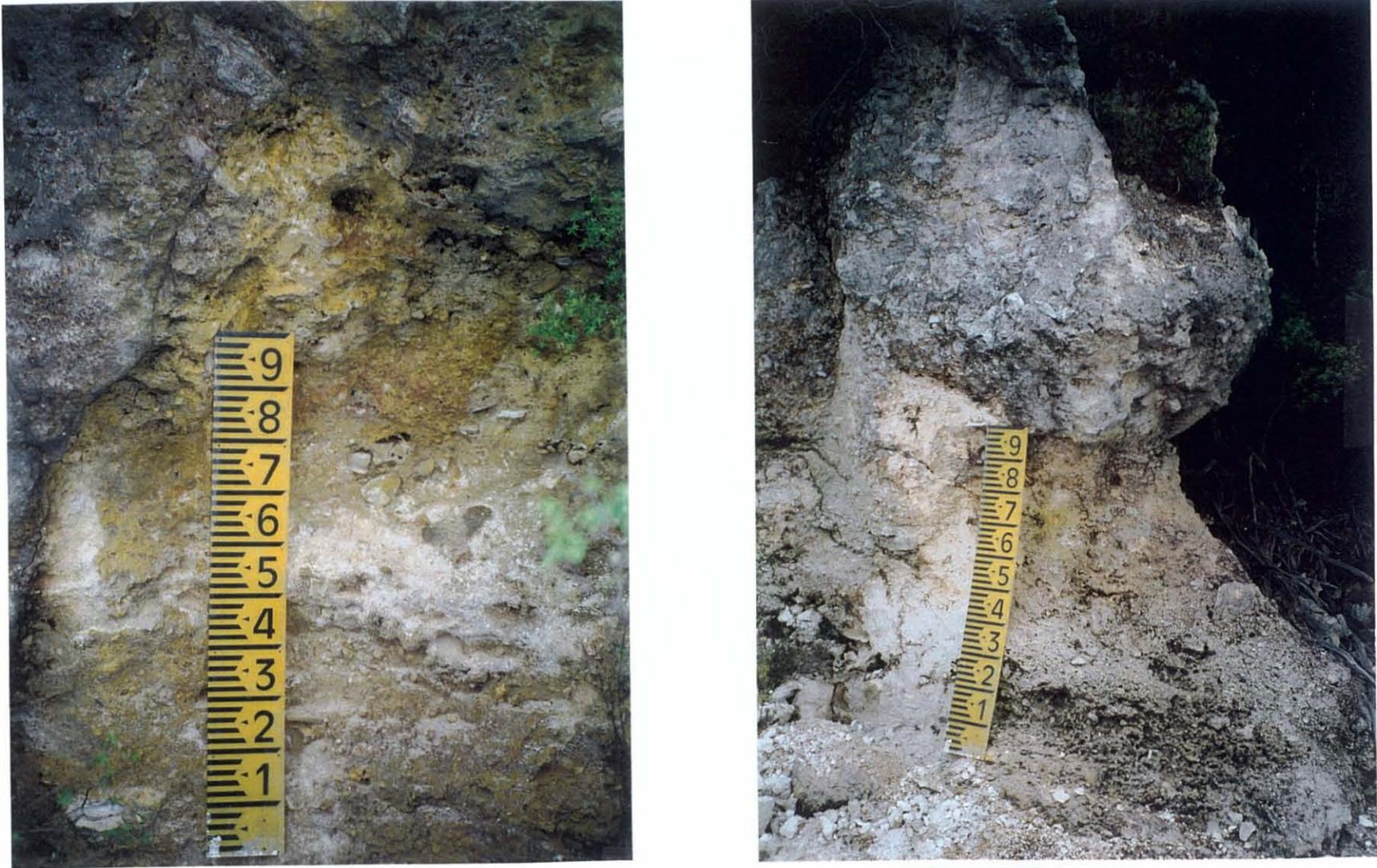


Figure 3.15 Whangapipiro (Crater) Bay site F184.1 (left) and site F184.2 (right). Both sites expose weakly cemented breccias overlain by strongly silicified breccias. One metre scale.

The crater is a nearly circular shape of 110 m diameter and is filled with lakewaters. Its open central vent has continual upwelling that has prevented siltation infilling and produces a visible central convection cell. This produces discoloured water that disperses out across the whole bay. However, any geothermal fluid upflow is masked due to inundation of the crater by Lake Rotorua. The bay has not yet been sounded to establish its bathymetry.

Whangapipiro Bay is catalogued as Form F184 in the EBOP and RDC geothermal database for the RGF. On its western shoreline, a vertical wave cut bank 1-4 m high extends along about 50 m of shoreline and exposes a sandy matrix-supported gravelly to blocky angular breccia, that is not present in outcrops 30 m further west. No breccias are present along its northern and eastern shores, although silicified pumice gravel sediments on the eastern shoreline form vertical banks 1-1.5 m high which might preserve HE breccias below water level. All surrounding shorelines of this bay also have ongoing hydrothermal activity, which is producing sulphur deposits that are actively cementing recent lake sediments. Breccias occur only along the western shoreline in a marginal strip <10 m wide.

3.4.2 Stratigraphy and Age

The age of breccia deposits around this bay is unknown precisely. However the HE breccia is directly overlain by silicified, water rounded pumice gravel clasts of Rotorua Pyroclastics, identified by the size and abundance of the pumice gravels which can be mapped away from here into unsilicified loose fall deposits. No other tephra has supplied any similar thickness of gravel-sized pumice into the Rotorua Basin in Holocene times. The presence of this pumice fall deposit indicates that the HE breccia predates Rotorua Pyroclastics in age (i.e. is >13,500 yrs BP; Kilgour, 2002).



Figure 3.16 Pumice gravel conglomerate from Whangapipiro Bay. Sample No. F184.1c. Scale in millimetres.



Figure 3.17 Clast of pumice containing large quartz crystals. Sample No. F184.1a.008, of Rotoiti Pyroclastics? Scale units in millimetres.

A hot spring once outflowed from a now extinct vent about 15 m northwest of the southernmost breccia outcrop (Figure 3.13) and has formed a dense overlying deposit of algal silica sinters alongside the walking track. This hot spring outflowed over the Rotorua Pyroclastics, which in turn overlie the HE breccias (Fig. 3.14, 3.16). The hot spring outflow also coincided with a high-stand of Lake Rotorua following the 9,000 years BP Rotoma Formation volcanic eruption.

Mingling of the spring waters downwards into a cold ground or lake water would have allowed dilution and dispersion of the dissolved silica and its ultimate polymerisation into non-cohesive colloidal spherules, as opposed to the dense and coherent cemented sinter groundmass that forms wherever these fluids cool undiluted (Herdianita, et al., 2000). Consequently, no strong silica cementation would have occurred below the local groundwater level (Fig. 3.15). In all NZ geothermal fields, present day silica deposition processes around hot acid seeps and alkaline hot spring outflows produce two distinctly different types of silica deposit (Herdianita, et al., 2000).

With the later fall of Lake Rotorua water-level some time since 9,000 years BP, the hot spring also ceased flowing at that elevation as it too retreated to a lower elevation outlet. Consequently the silica deposition and cementation process at the higher elevation also stopped, leaving the breccia with its upper portions strongly cemented and its basal outcrops only weakly cemented (Fig. 3.18).

The breccia is directly underlain by a clay-sized and highly thixotropic mud deposit of pure silica lake sediment in the south, but this material overlies the breccia 30 m further north along the western shoreline (Fig. 3.19). This is considered to represent subsequent remobilisation of the muds after their initial deposition following a lake level rise at 9,000 yrs BP, when the Rotoma Formation (Nairn, 2002) tephra that erupted from the Okataina Volcanic Centre, raised Lake Rotorua water level by about 10 m (WR Esler, pers. comm.).

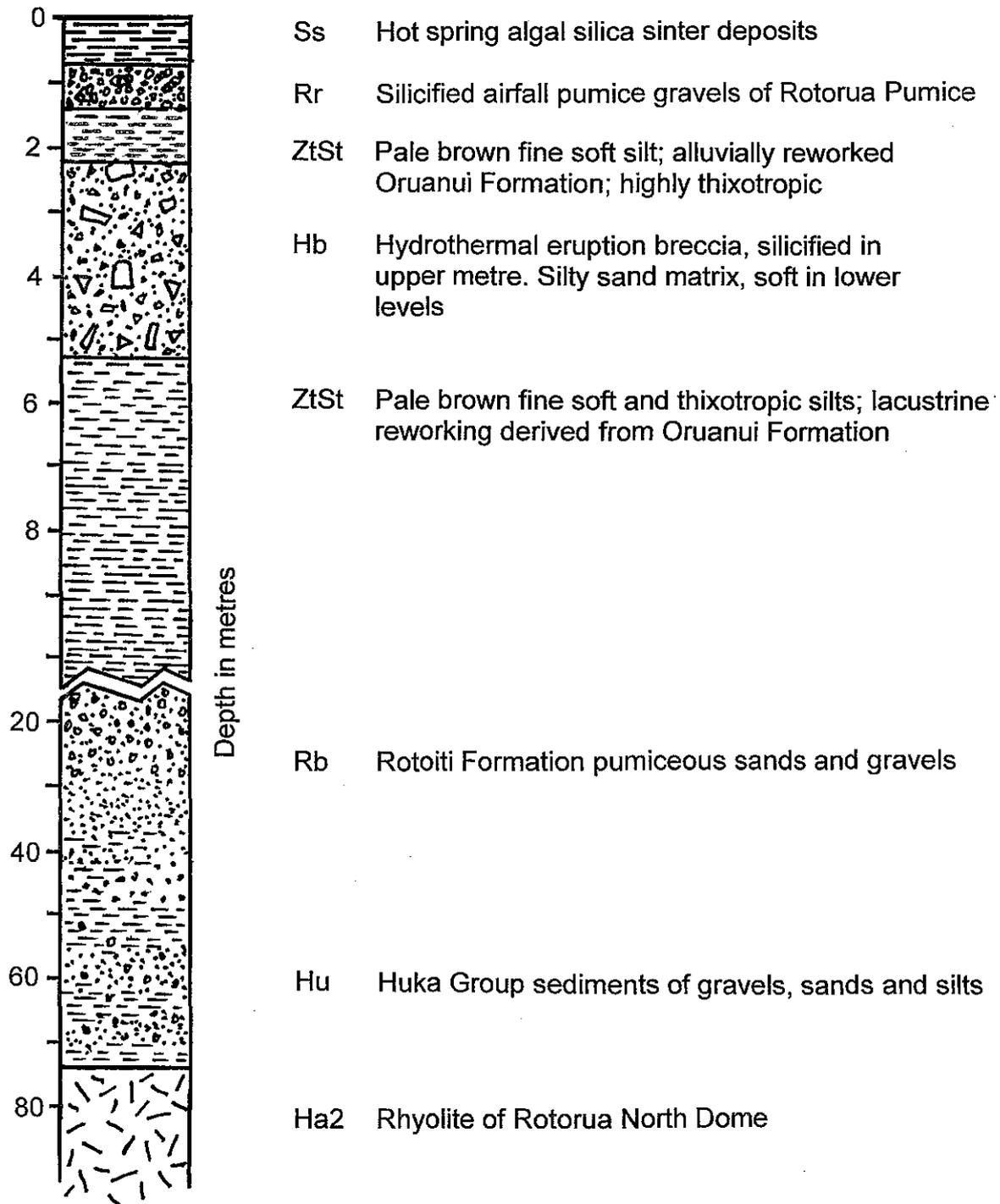


Figure 3.18 Stratigraphic column for Whangapipiro Bay (U16 958355). Geology below 3-8 metres is inferred, based upon nearby drillhole geology. See also Figs. 3.14 and 3.15.

The nearly pure amorphous silica composition of this lake mud, its highly thixotropic character, and its stratigraphic relationship to the Rotorua Pyroclastics deposits, infers that it was initially sourced from the Oruanui Formation ignimbrites and tephras. The lake muds have been alluvially reworked by the Utuhina and Puarenga Streams, inwashing it as erosional material from outside and south of the Rotorua Basin to form lacustrine deposits (Fig. 3.18).

3.4.3 Lithology

The breccia deposit has an increasing hardness to the south, due to an increased degree of silicification caused by percolating geothermal fluids. The upper 1-2 m thick top of the breccia is everywhere more strongly silicified than the underlying deposit. This infers that the cementation probably occurred while Lake Rotorua was at a higher elevation than its present day 280 m asl.

Silica saturated water from a neighbouring hot spring has rapidly cooled to deposit a dense and tough silica cement within permeable sediments and tephras and the HE breccias in the subaerial zone. The sinters are very porous and show wavy banding and density variations, with spicular structures typical of surface silica deposition incorporating algae and bacteria (Jones, et al., 2002).

Acidified rainwaters and condensates have locally dissolved and remobilised silica, and still do so today. This has deposited a weak thin cement that has bound the sandy breccia matrix over its exposed faces. At the present day, continual degassing and warm water upflows within the lakewaters of Rocky Point and Whangapipiro Bay produce visible convection cells, with discolouration due to upwelling fine sediments and formation of colloidal sulphur and minor pyrite by sulphide oxidation.

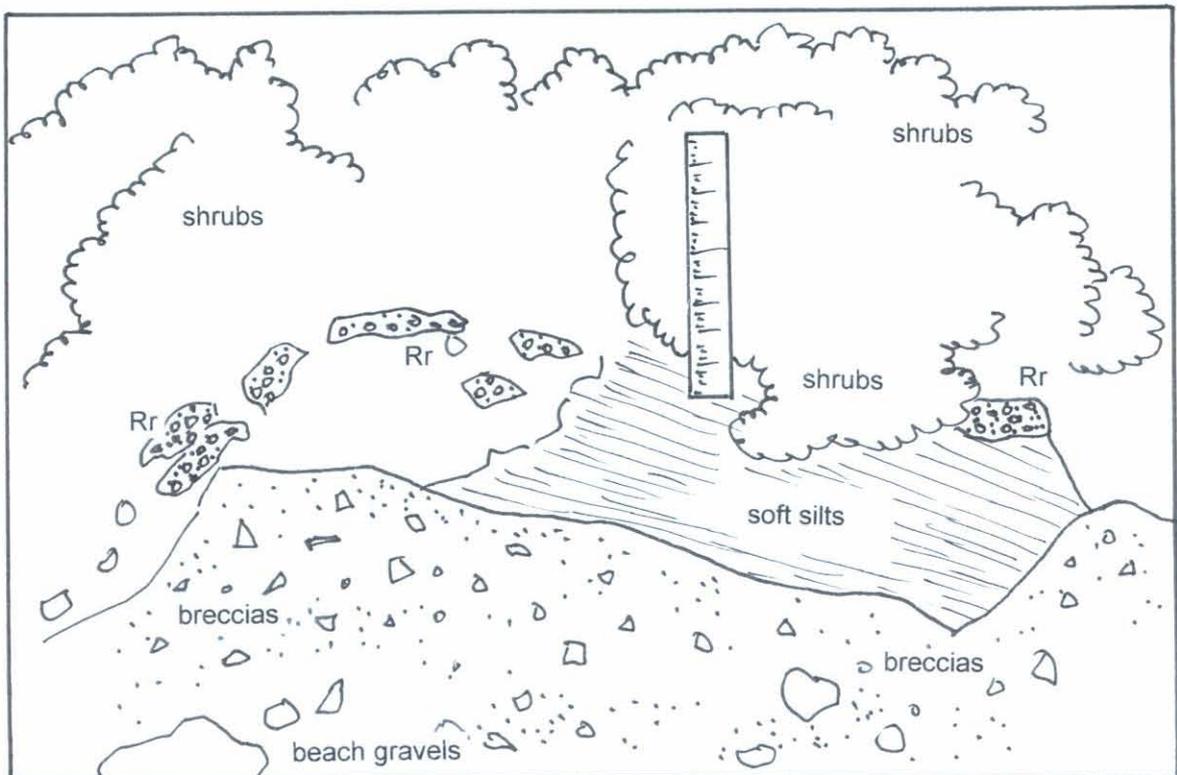


Figure 3.19 Whangapiro Bay, sample F184.3, 17 metres north of site F184.1a. HE breccias dipping at $\sim 25^\circ$ to north, overlain by fine light brown lake silts. In shrubs a thin veneer of silicified Rotorua Pyroclastics (Rr) gravels forms a protective cap that has resisted erosion. Scale bar is one metre.

Geothermal acid gases rapidly oxidise in the presence of dissolved oxygen in fresh waters, or the mingling of oxygen from the atmosphere being mixed by wind and wave action into surface waters. These oxidation products form strong acids, notably sulphurous and sulphuric acids, that rapidly attack most rock forming minerals.

Depending upon critical factors such as abundance of water, frequency of wetting and drying, temperature and permeability of the sediments, acid surface conditions can produce silica cementation. However, this type of silica remobilisation is much less robust or vigorous in its ability to form thick and strongly silicified sediments, in comparison to that produced by outflows of alkaline mineralised spring waters. Present day silica deposition from hot spring outflows in many geothermal fields provide a wide variety of modern analogues for the deposition of silica from mineral waters (Herdianita, et al., 2000).

The silica deposition process within breccias along the western shores of Rocky Point Crater Bay is consistent with alkaline fluid deposition, due to the high density of the silica cements, the laminar surface forms and the preservation of many breccia clasts that are without any evidence of clast edge corrosion, as would be expected in strongly acidic warm waters.

Some silicified clasts in the breccia are themselves breccias and may be from earlier HEs out of this same vent having produced similar deposits. Clasts in this breccia show lithologies of thin laminar siltstones, massive siltstones and sandstones, gravelly conglomerates and rare pumice and ignimbrite clasts, all of which are silicified, some strongly so. Colours of clasts vary from white to very light grey and rarely to grey, with all micas and ferromagnesian minerals altered and leached out. One pumiceous clast (Fig. 3.17) of 120 mm diameter was of stringy glass containing quartz clots up to 5 mm diameter, although no ferromagnesian minerals were found. This clast may be of Rotoiti Pyroclastics

that could have been water rafted into Whangapipiro Bay.

A soft light brown mud underlies the HE breccia in the south but overlies it in the north. This is a lacustrine silica-rich silty clay containing abundant interstitial water, and although usually dry and crumbly on exposed outer surfaces, it is highly thixotropic. In drillholes and surface excavations in Rotorua city this unit is found throughout most of the city and is >10 m thick, although locally it may contain thin sandy bands.

Based upon the presence of accretionary lapilli <20 mm diameter (as compared to lapilli >20 mm diameter from Rotoiti Pyroclastics), and the fine silt-sized particles within these lapilli, it is considered that these materials are derived from alluvial reworking of Oruanui Formation and has been repeatedly reworked with subsequent lake-level rises, so although it mostly underlies the HE breccia at Whangapipiro Bay, it also overlies the breccia further north along the northwest shore (Fig. 3.19).

3.5 OURU, OHINEMUTU

Te Papa Ouru is the Maori land name for an area of about 2000 m² around the Tamatekapua meeting house in Ohinemutu (Fig. 3.20; U16 948364). It is dominated by a southward rising topography to Lake Road, with many outcrops of silica cemented sediments, which also include an overlying blocky unit of hydrothermal eruption breccia (Fig. 3.21). The site was used by pre-European Maori as a burial ground (urupa), with bodies interred into fissures and holes beneath the hard cemented sediments and breccia banks. Because of its sacred status as an urupa, thorough excavations and samplings of the outcrops was not

permitted, although local residents were very helpful in allowing some cursory studies and samplings. Since the 1980s some large blocks of silica cemented HE breccias have been removed during construction of townhouses at 19-21 Lake Road. This has removed evidence of the extent of these breccias around Ouru and it is likely that urbanisation processes of earlier years may have removed other outcrops of HE breccias in the Ohinemutu area, as hard rock supplies are scarce in the Rotorua city area.

3.5.1 Location and Distribution

Little surface exposure of the HE breccia remains today and it is now confined to a small plateau about 900 m² south of Kiharoa Street, up towards Lake Road (U16 948364) in the land area known as Ouru (Fig. 20). It is present only east of the Waikite hot springs lineation, along a north-south line through these springs, which have a prominent vertical scarp exposed south of Kiharoa Street. This has been mapped as Ohinemutu Fault (Fig. 3.20).

3.5.2 Stratigraphy and Age

Outcrops of hard rocks along the south side of Kiharoa Street are exposed as several discrete banks of rock with up to 2.5 m vertical sections and up to 20 m in length (Figs. 3.21, 3.22, 3.23). The basal exposure is of coarse angular pumice gravels cemented to form a unit 0.3 – 0.8 m thick at the base of the outcrop. Because of the size of these pumice gravels (<30 mm diameter), their massive character, angular subrounded edges, and only weakly weathered nature, they are inferred to be a subaerial deposit of Rotorua Pyroclastics dated at 13,500 years B.P. (Kilgour, 2002).

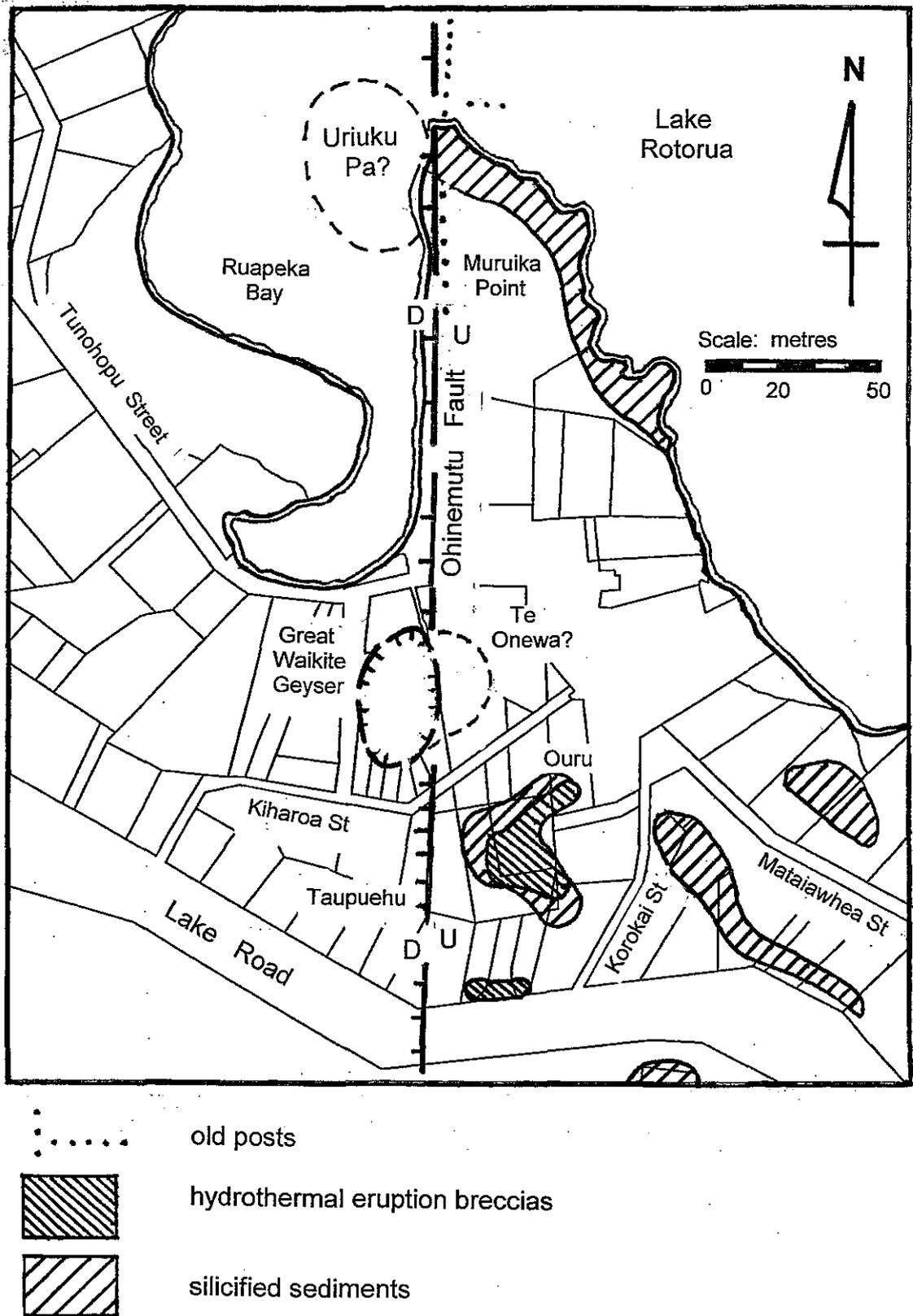


Figure 3.20 Geological features and outcrops of Ohinemutu. Details of outcrops by Ouru are shown in Figures 3.21 and 3.22. Sunken pa site is inferred only, as there is no precise description known.

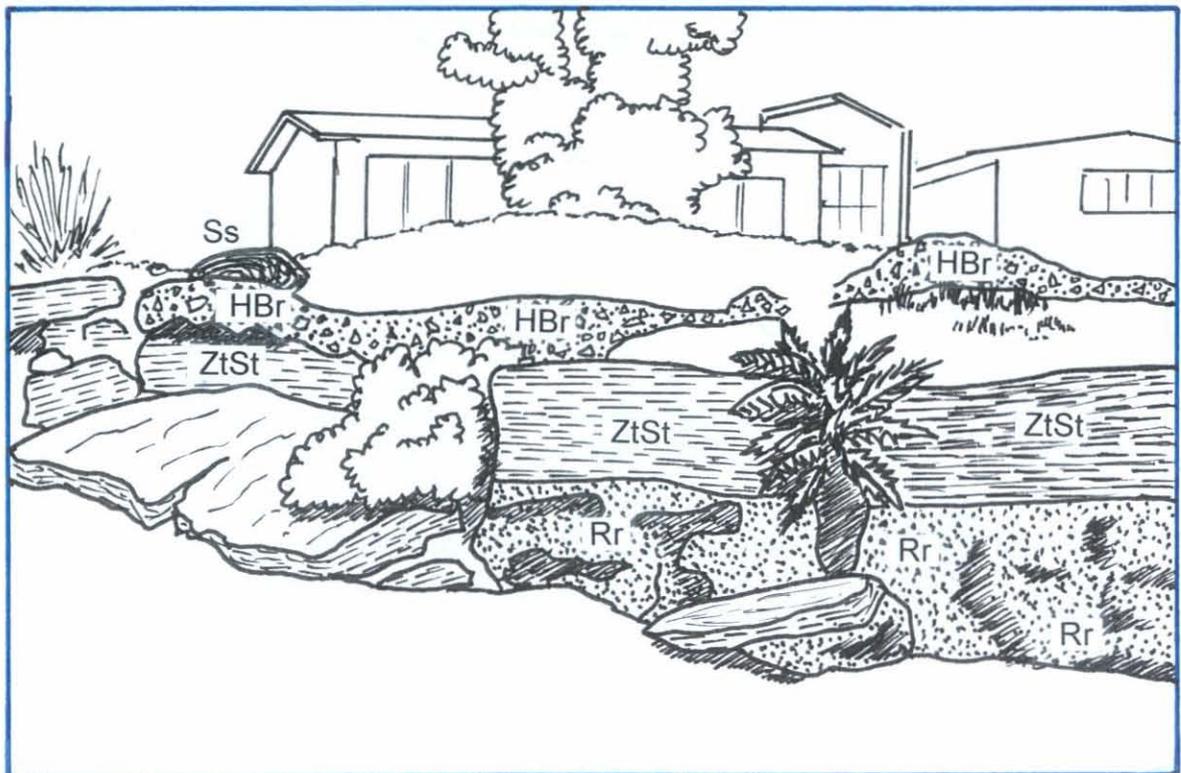


Figure 3.21 Outcrop at Ouru, Ohinemutu (U16 948364). View south up to Lake Road, beyond houses. Yellow one metres scale bar against silicified pumice gravels (Rotorua Pyroclastics, Rr), overlain by silicified lake silts (ZtSt), hydrothermal eruption breccias (HBr) and silica sinters (Ss). Slumped slabs along base of outcrop.

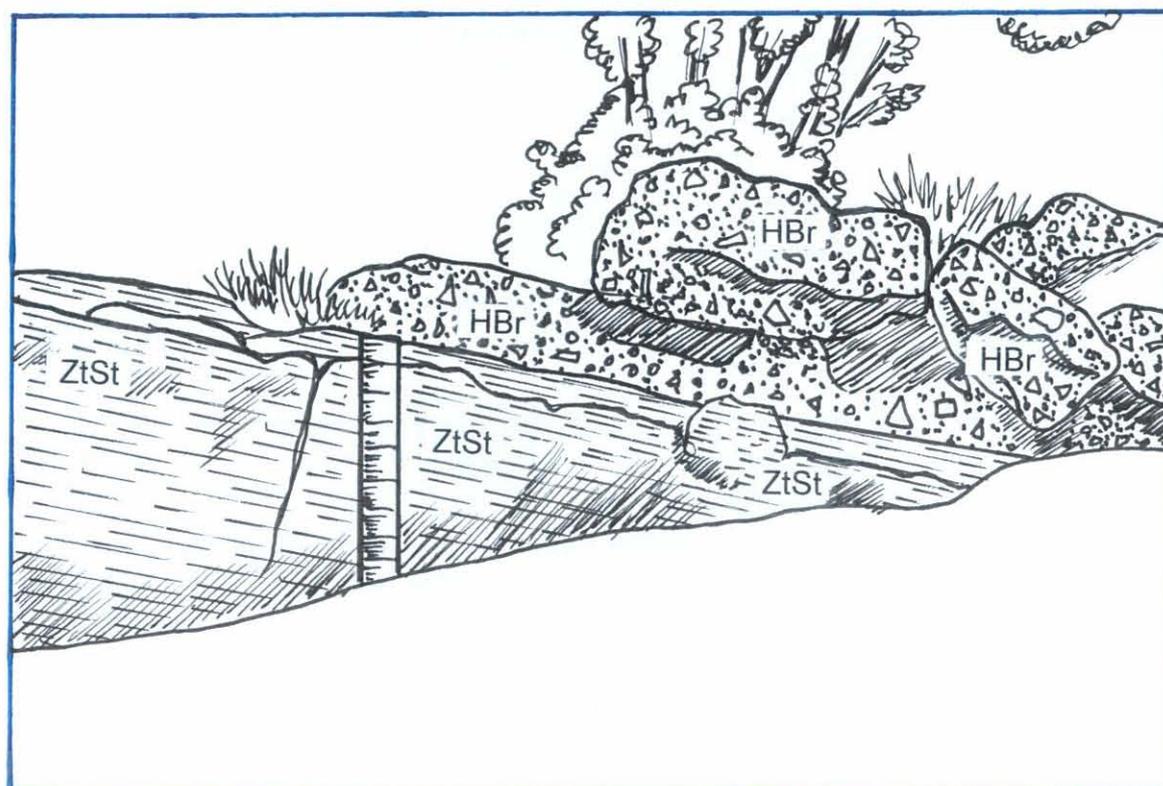


Figure 3.22 Outcrops at Ouru, Ohinemutu, immediately west of Figure 3.21. One metre yellow scale bar against silicified siltstones (ZtSt), overlain by silicified hydrothermal eruption breccias (HBr); all dipping $\sim 10^\circ$ to west.

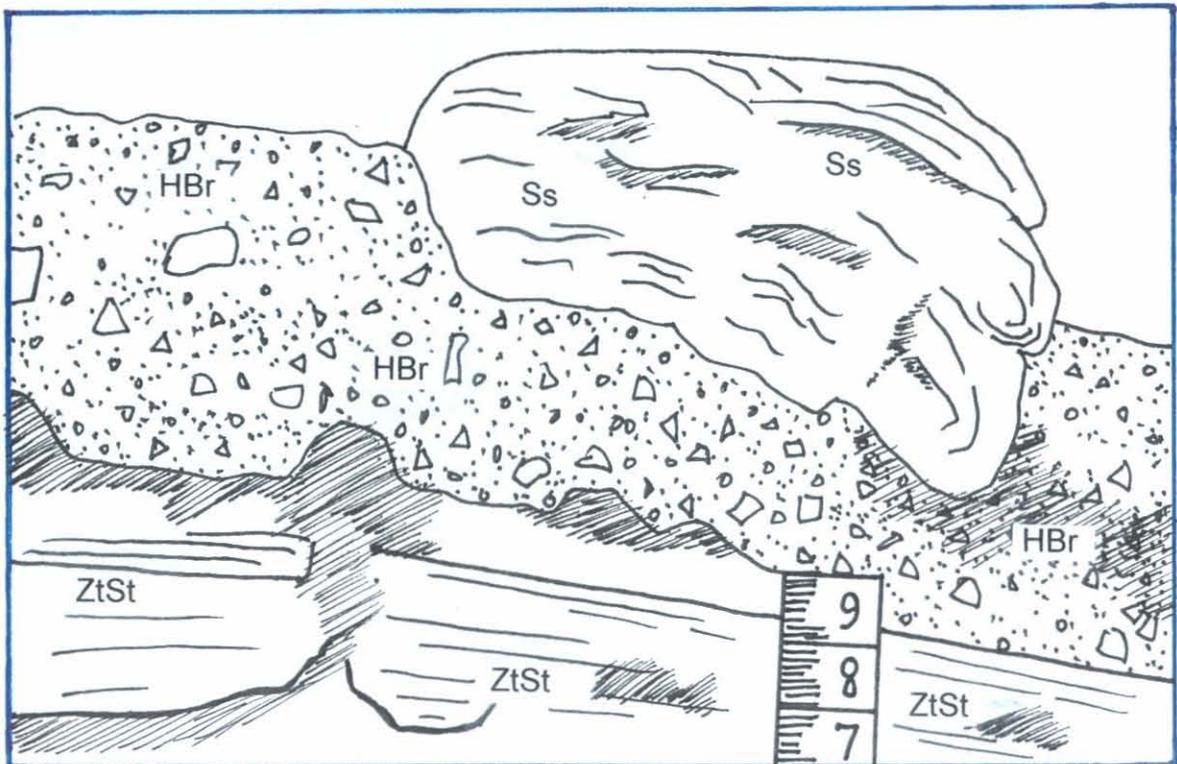


Figure 3.23 Closeup of lefthand view in Figure 3.21, Ouru, Ohinemutu. Scale bar divisions are in centimetres. Top mass is algal silica sinters (Ss) from hot spring outflow; underneath are hydrothermal eruption breccias (HBr); and underneath is silicified lacustrine siltstone (ZtSt).

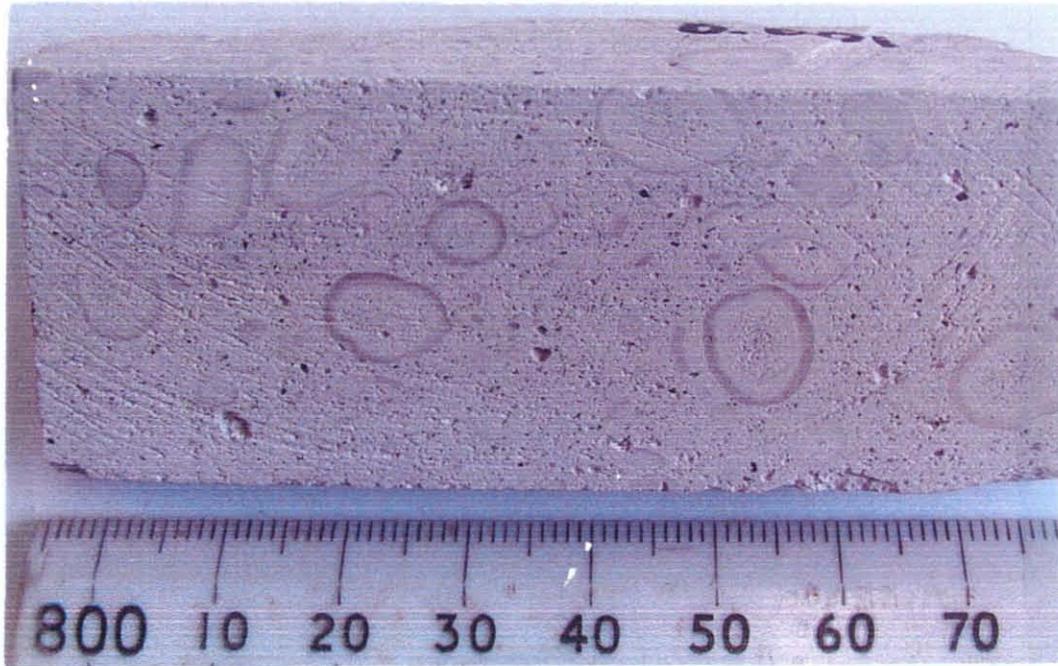


Figure 3.24 Ouru sample No. O.001 of silicified sandstone with accretionary lapilli. Scale in millimetres.



Figure 3.25 Ouru sample No. O.008 of fine sandstone and a silica sinter upper layer. Scale graduated in five millimetre intervals.



Figure 3.26 Clast of unidentified ignimbrite from Ouru HE breccia. Sample No. O.013, scale in millimetres.



Figure 3.27 Clast of pumiceous rhyolite from Ouru HE breccia. Sample No. O.010, scale units in millimetres.

The pumice gravels are overlain by fine silica-cemented silts and fine sands about 1 m thick, which are lake sediments laid down following the Rotoma Formation eruption from Okataina Volcanic Centre 9,000 yrs BP. Immediately following that eruption Lake Rotorua rose by about 10 m to about 290 m asl. At that high stand, fine silica-rich silts derived originally from Oruanui Formation were redeposited as lacustrine sediments, which were subsequently silicified by percolating hot spring outflows (Fig. 3.23).

These siltstones are in turn overlain by a silica cemented, unsorted and angular HE breccia. A hydrothermal eruption has then deposited a breccia with clasts of cemented silts and sands (Fig. 3.24, 3.25), pumice, ignimbrite (Fig. 3.26) and a pumiceous rhyolite (Fig. 3.27), which in turn has been covered by the outflow of hot, alkaline and silica saturated hot spring waters that have laid down an uppermost layer of algal silica sinters. A stratigraphic column for this site is given in Figure 3.28.

3.5.3 Lithology

The Ouru outcrops are comprised of primary and secondary tephra, lake sands and silts, silica sinters and HE breccias (Fig. 3.28), all strongly silicified by percolating hot spring waters. Clasts within the HE breccia contain a variety of volcanoclastic and geothermally altered materials (Fig. 3.26, 3.27).

Fine, massive, light brown lake silts are exposed at least 3 m thick on the vertical eastern wall of the Waikite springs (Fig. 3.29). This location (U16 947364) is rendered inaccessible by a large (~4 m x ~8 m) deep hot spring along the cliff base, so only visual examinations from the opposite side were possible. Immediately east, the same unit outcrops at the base of the sequence on Ouru (Fig. 3.22). The silt is a fine uniform grain size and texture, with no bedding seen.

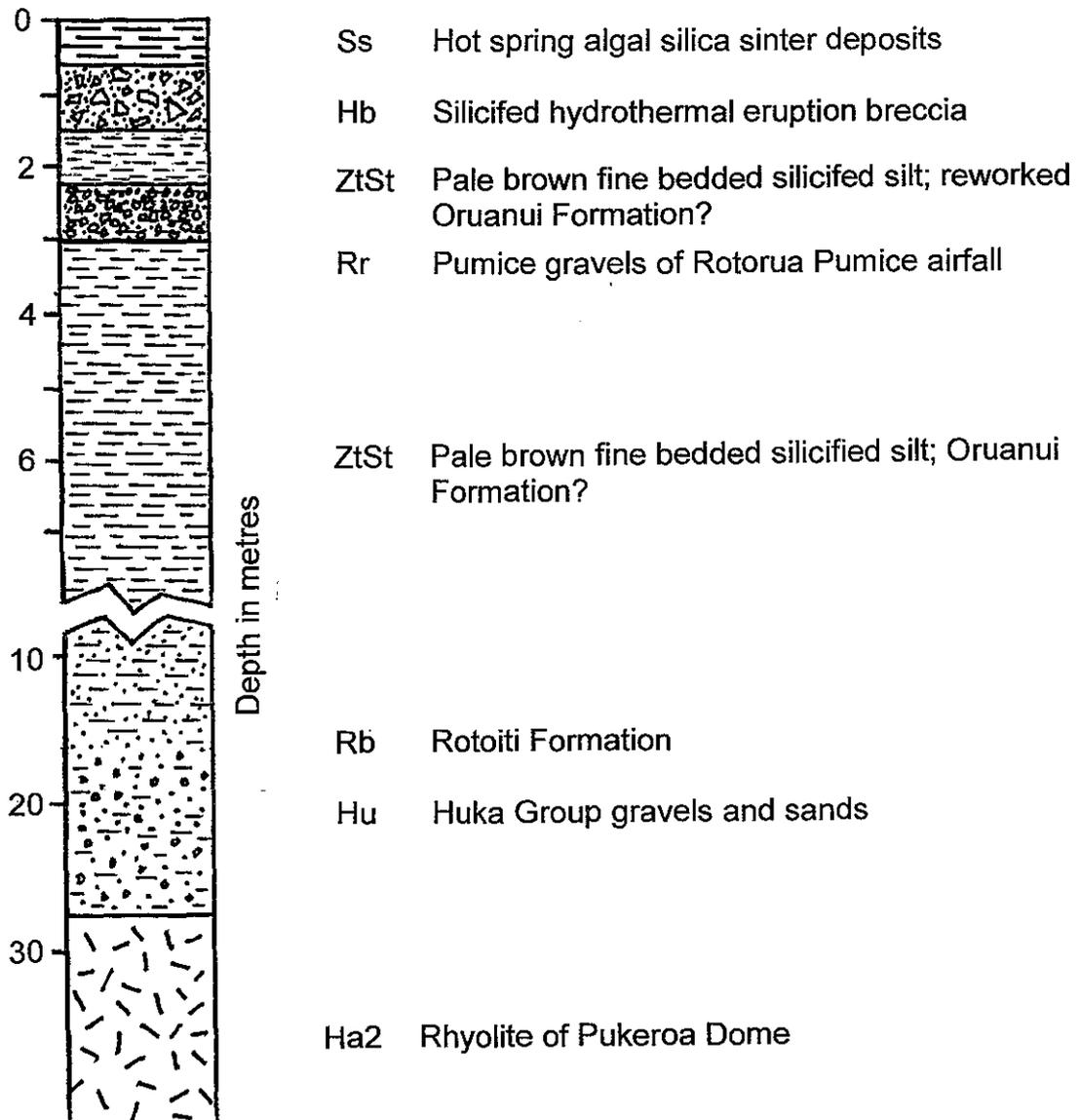


Figure 3.28 Stratigraphic column for Ouru, Ohinemutu (U16 948364). Geology below 7 metres is inferred, based upon nearby drillhole geology. Rotorua Pyroclastics is primary airfall which has been silicified.

It does however have areas of mottled colouration between very light brown and light brown, which show no apparent relationship to any bedding or penetration of weathering in relation to surface exposures. Occasionally it has oval and elongated holes 7-10 mm diameter that are thought to be laval insect drillings.

The weakly silicified pumice gravel bed is about 0.6 m thick (Fig. 3.21) and has a dark brown to orange-brown outer skin and a pale yellow interior. No micas, titanomagnetites or ferromagnesian minerals were visible in hand specimens. Pumices were still strong and had good resistance to finger crushing, suggesting that they had been only mildly weathered by geothermal activity. They are considered to be Rotorua Pyroclastics due to their thickness, relative freshness and because no other pumice gravel tephra is known at the near surface in Rotorua city.

The fine silt bed overlying the cemented Rotorua Pyroclastics is uniformly light brown and of fine sand to silt size. Weak bedding was present but not conspicuous. No visible crystals or black particles were visible in hand specimen. It is a lacustrine sediment, perhaps derived from Oruanui Formation silts washed off the adjoining Hospital (Pukeroa) Hill following eruption of Rotoma Formation and the consequent damming and raising of Lake Rotorua.

The HE breccia is about 0.8 m thick and contains blocks that reduce in maximum diameter with increasing distance eastward away from the Waikite springs. At Ouru the blocks were <0.5 m diameter at the western end of the outcrop and <0.15 m diameter about 25 m further east. The breccia is comprised of abundant angular clasts that are matrix supported, the matrix being sands and silts of quartz and pumiceous fragments and of a very light brown colour. Rare clasts of ignimbrite (Fig. 3.26) and pumice (Fig. 3.27) were present, but most commonly the clasts were of very pale cream to white silicified siltstones and sandstones.

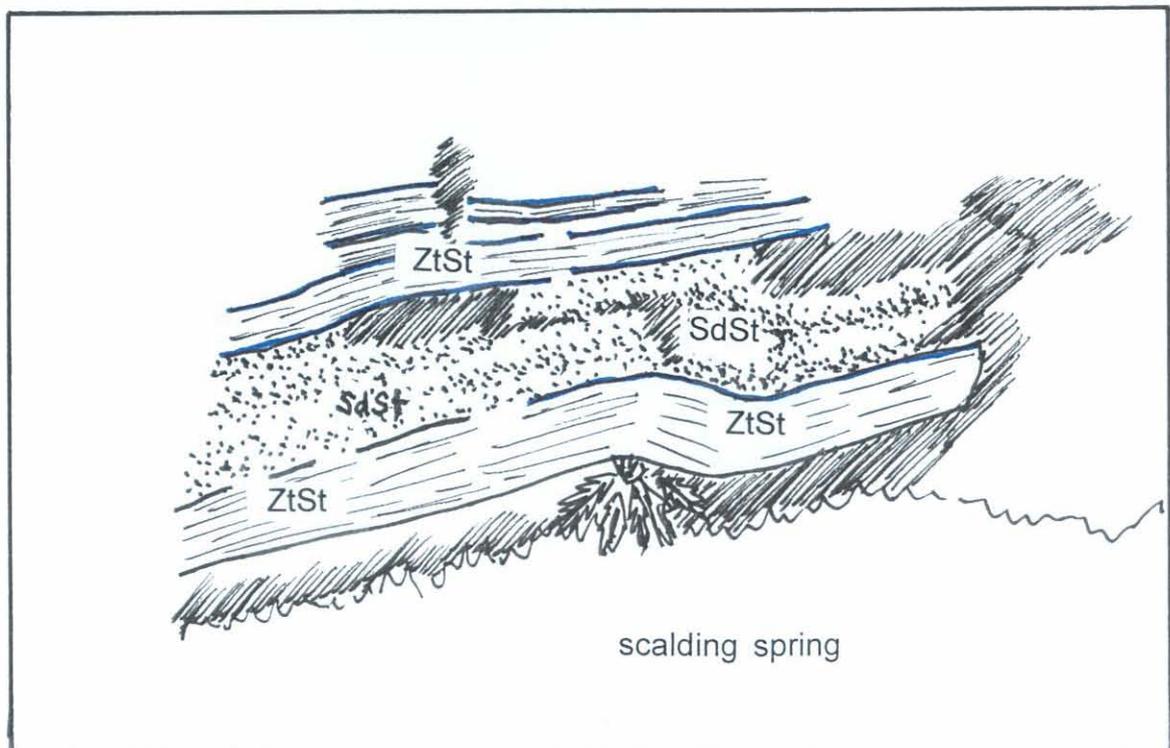


Figure 3.29 Outcrops on east wall of hot spring Taupuehu (S1207), a scalding spring making outcrop inaccessible. Visible wall is ~2 metres high and ~6 metres long, comprised of silicified silts (ZtSt) and sands (SdSt). See Figure 3.20 for location. This wall is considered to be a fault scarp (see text for details).

The ignimbrite was not identified, but the pumiceous rhyolite may have been sourced from the uppermost carapace of the buried Pukeroa Hill rhyolites, which are found in drillholes in Ohinemutu at 30-50 m depths. The outer layers of the buried lava dome is commonly brecciated and pumice rich.

A dense tough grey to white sinter unit ~0.6 m thick drapes over and down the HE breccia unit (Fig. 3.23), indicating that a flowing hot alkaline spring had existed on the uppermost terrace of this outcrop for some hundreds of years. Eruption of the Rotoma Formation dammed Lake Rotorua around the Ohau Channel and raised its waterlevel by 10 m (Eslar, 2002).

It is postulated that while at the higher elevation, the lake deposited silts along its margins in Ohinemutu. After deposition of the presently preserved siltstone, a hydrothermal eruption centred in the Waikite Group springs blew out a crater, the remnant of which persists as part of the historically larger Great Waikite Geyser spring embayment of Ruapeka Bay. Raised lake-levels would have also buoyantly raised the geothermal hot spring upflows there, so that boiling point for depth conditions were exceeded and a HE resulted. The raised lake-level would also have established the once existent flowing hot spring above the Ouru outcrop, which subsequently produced the dense surface sinter deposit over the top of the HE breccia.

3.5.4 Volume of Ejecta

Outcrops of HE breccia are 0.25 m thick at the east end of Ouru, about 75 m from the postulated source vent of the Great Waikite Geyser (Fig. 3.20). Blocks of silicified breccia <1 m thick are preserved on Ouru and were also present until c.1987 on the north edge of Lake Road, about 100 m south of the suspected vent (Fig. 3.20). Assuming a uniformly radial distribution of breccia around the Great

Waikite Geyser and a crater diameter of 20 metres, then calculated volumes of erupted material are as follows:

Crater diameter	= 20 metres
Extent of 1 m thick deposit	= 10 – 50 m from crater centre
Extent of 0.3 m thick deposit	= 50 – 75 m from crater centre
Volume of cylinder	= $\pi r^2 h$
Volume of crater	= 314 m ³
Volume of 1 m deposit – crater	= 7857 – 314 = 7543 m ³
Volume of 0.3 m deposit	= 5303-2357 = 2947 m ³
Total erupted volume	= 10,490 m ³

This calculation assumed a radial distribution of ejecta, because there is no compelling evidence of a directional distribution. Although no ejecta outcrops to the west of the postulated Ohinemutu Fault (Fig. 3.20), a long history of human occupation and modification of the land here could have removed any other outcrops outside of the urupa. The other likely change to ejecta volume since emplacement is that of compaction and perhaps erosion of some material, which would have removed part of the original deposit volume. By comparison, the 26 January 2001 eruption of S721 in Kuirau Park (Section 3.6.4) produced 1200 m³ of erupted materials and the 20 June 1981 HE at Taupo Pony Club (Scott and Cody, 1982) produced 6800 m³.

3.6 S721, KUIRAU PARK

Kuirau Park is a public recreational reserve lying to the west of Ranolf Street and is bounded by Tarewa Road in the west (Fig. 1.7, 3.30, and Map 3). It is an area of numerous boiling and flowing alkaline springs and many acidic warm turbid pools. Spring S721 (database No. F350) has no known name and is a muddy water, acid sulphate, gas and steam heated pool (Fig. 3.30). It erupted on Friday 26 January 2001 and produced a spectacular eruption column and ejecta deposit, which has been described by Slako (2002; Fig. 3.31).

3.6.1 Location and Distribution

S721 was quite unnotable and without any progressive change throughout several spring surveys spanning 1920s until 1998. It is located at about U16 946361 (Map 3, Map Pocket), and on the afternoon of Friday 26 January 2001 at c. 1645 hrs it suddenly erupted into a powerful hydrothermal eruption. The eruption column was unusual in that it was strongly inclined off the vertical towards the east. It rose to about 100 m height and persisted for about 4-4.5 minutes, with large blocks emitted from amongst a dark muddy column and white steam cloud. A steady loud roaring noise accompanied the eruption, which appeared to be steady in its emission of fine ejecta.

Fortunately the Rotorua District Council (RDC) agreed to requests for the eruption deposits to be left unmodified for a few weeks to allow examination of ejecta. The extent and nature of this was systematically mapped and sampled for laboratory analysis during February and March 2001 by ADC, and soon after also by Slako (2002). During this interval the deposit compacted and dried significantly, so that its volume reduced with loss of water and settling.

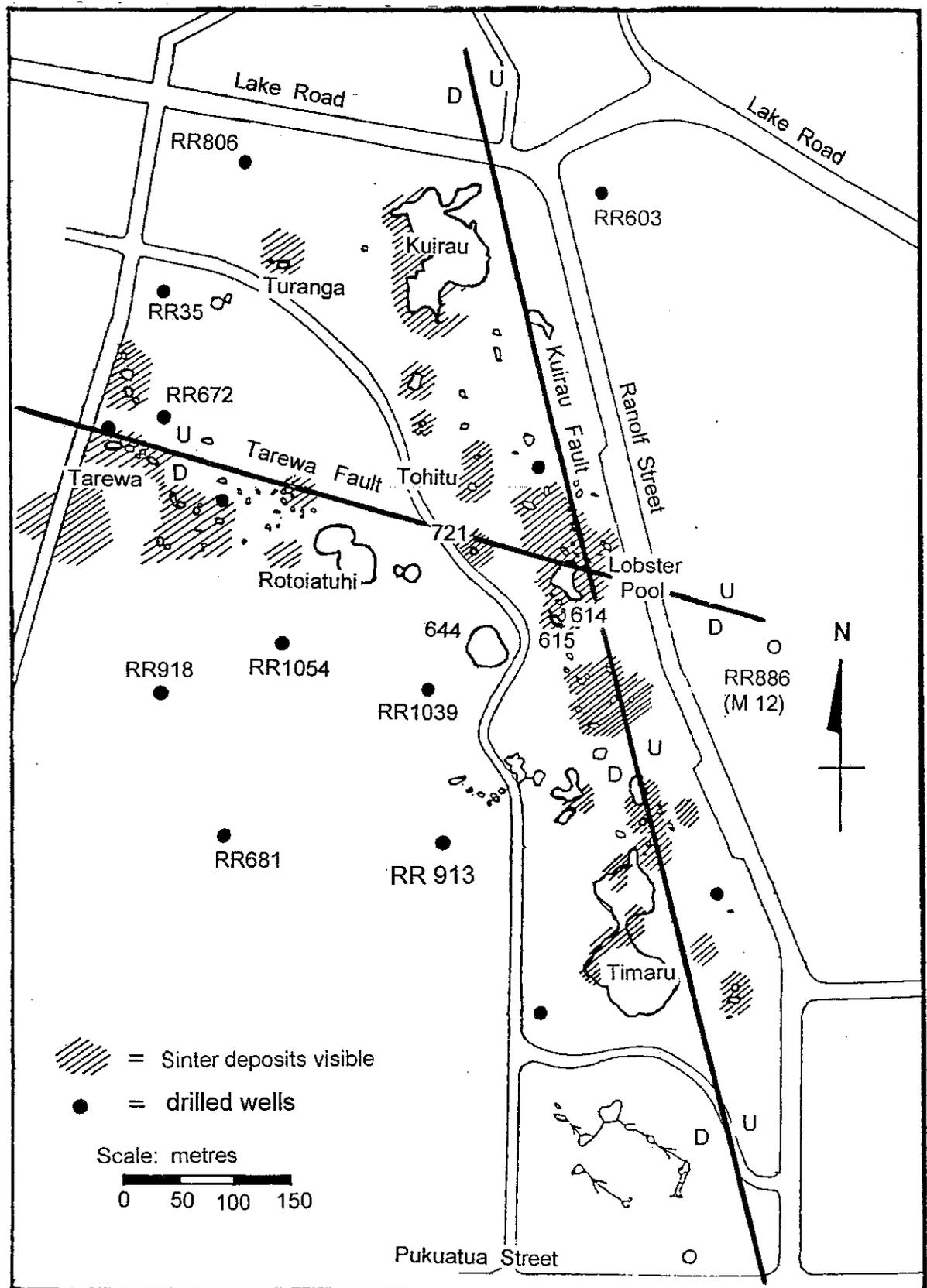


Figure 3.30 Location of prehistorical and modern day sinter deposits. Evidence of once flowing alkaline hot spring sites and areas where such activity might resume. Faults are postulated on evidence of rhyolite surface elevations and the position of flowing springs.



Figure 3.31 Ground view of eruption debris from S.721 in Kuirau Park on 26 January 2001. Photograph taken same day from Ranolf Street, viewed due west. Vent is steaming central site. Note shrubs bent over in right foreground. (Daily Post, photograph).

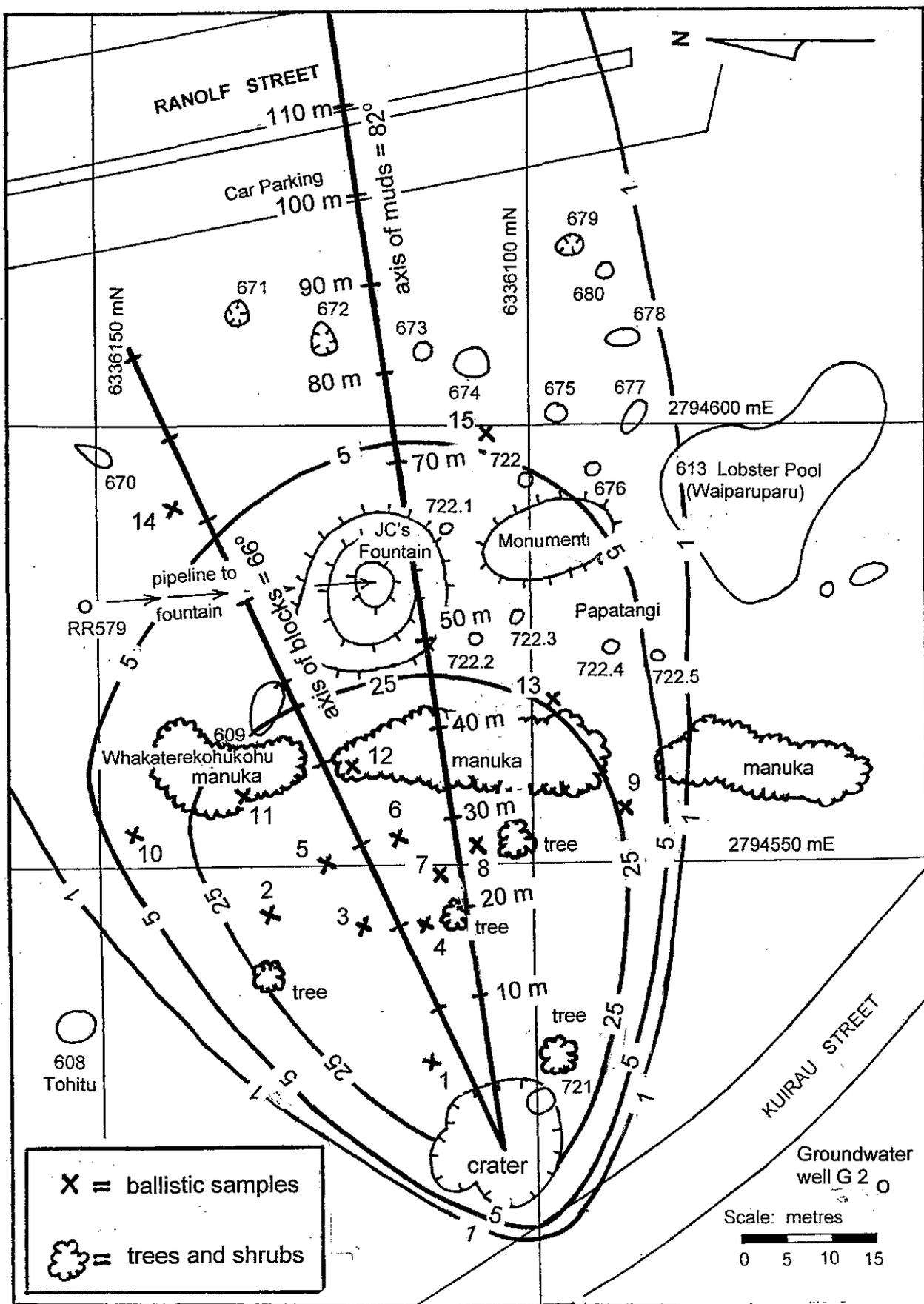


Figure 3.32 Diagram of S721 and its HE deposits of 26 January 2001. Ballistic block sample locations are marked with "x" (Table 3.1) and isopachs of the deposit thickness are given in centimetres. Dispersal axes of muds and ballistic blocks are shown.

At the time of eruption the weather was overcast and showery rain, with a strong westerly wind of about 20-30 kilometres per hour. It is estimated that 99% or more of eruption ejecta was dispersed in an easterly direction, with very little material landing to the north, south or west of the crater (Fig. 3.32). This ejecta deposit was aligned strongly to the east with two conspicuously separate axes of distribution.

A fine wind borne plume of grey mud composed of silt to clay size particles was swept off along an axis of 082° . This formed a continuous ground cover to at least 200 metres distance, over and beyond Ranolf Street and over the Fletcher Challenge Rescue helicopter at its helipad up on Hospital Hill. The mud plume coated cars parked at Queen Elizabeth Hospital, about 1.5 km to the east. Aerial photographs and field studies confirmed the block ejecta dispersed along an axis of about 066° , with the wind-borne mud dispersed along about 082° (Fig. 3.32, 3.33).

3.6.2 Stratigraphy

The eruption deposit was mapped to record its thickness, nature of materials and their distribution (Fig. 3.32). Radial lines were measured from the crater margin and then at right angles every 10 m to form a grid system covering all ground to 100 m east and 100 m wide along that line. Information measured at each 10 m grid intersect included: thickness of deposit, description of materials, measurements of block width, length and thickness, sequence of erupted lithologies and any other notes and observations, as well as sampling of ejecta for XRD, density measurements and thin section preparations.



Figure 3.33 Aerial view to east showing eruption ejecta and debris from the Kuirau Park hydrothermal eruption of 26 January 2001 from S721 crater at lower right. Ranolf Street at top left. Note that the axis of white, aerally dispersed fines is east of the dark grey blocky ejecta. (Daily Post, photograph). See also text Section 3.5.

The deposit when fresh had a conspicuous surface layer of dark grey to black mud, which also overflowed from the western side of the crater to about 5 m distance (Fig. 3.33). It also underlaid much of the blocky ejecta and appears to have been a watery mud produced throughout the eruption. Some blocks had impacted into this mud and sometimes the mud covered blocks.

Stratigraphy of this area of Kuirau Park is given in Figure 3.34, which shows the pre-eruption sequence based upon crater wall outcrops of infill and sinter, and the downhole stratigraphy as found in nearby drillholes. A summary of calculated ballistic block distribution, range and launch velocities is given in Table 3.1.

Table 3.1 Summary of ejecta block size and distribution, with launch velocities calculated from tables of Wilson (1972).

Sample No:	Rock:	Block radius, m	Range, metres:	Density, kg.L ⁻¹ :	Launch Velocity m.sec ⁻¹ at angles	
					of 66°:	87°:
1	SdSt	0.38	9	1.86	10	30
2	SdSt	0.17	27	1.91	30	100
3	ZtSt	0.30	22	1.36	30	100
6	ZtSt	0.25	29	1.55	30	100
10	SdSt	0.21	48	1.64	30	100
14	ZtSt	0.12	72	1.39	30	300

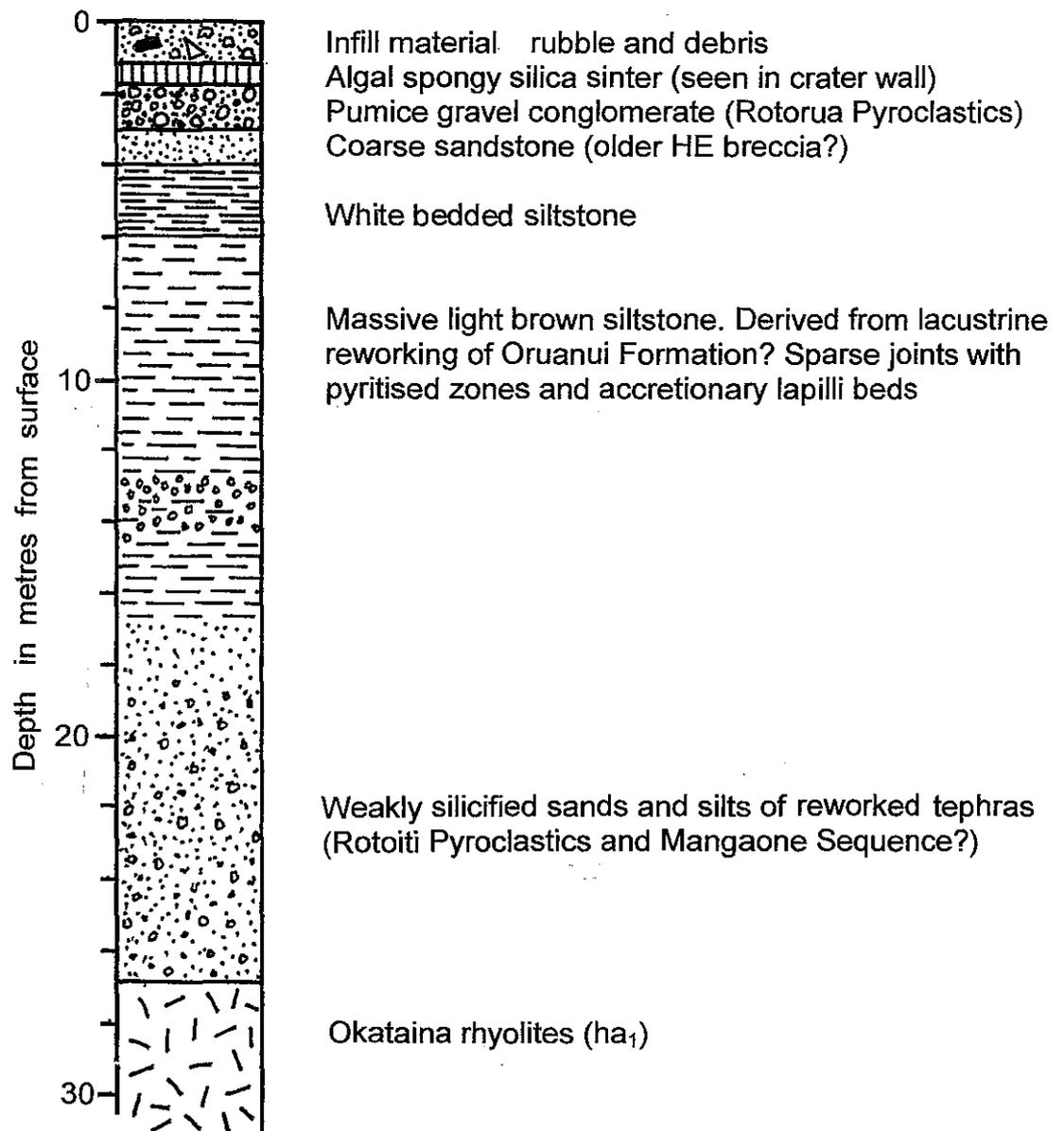


Figure 3.34 Stratigraphic section for S721 HE site, Kuirau Park. Lithologies are known from ejecta and drillholes, but thicknesses and sequence is inferred only. Rhyolite elevation is known from nearby drillholes. HE breccia of 26 January 2001 is not shown here, but is above zero metres on depth scale.

3.6.3 Lithology

3.6.3.1 Ballistic Blocks: The most abundant material was a light brown to light grey moderately firm siltstone. This occasionally contained joints with dark grey margins <20 mm wide each side of the joints (Fig. 3.36), and sometimes contained pyrite crystals visible in hand specimens. However, this siltstone underwent rapid weathering and several months after emplacement the surface of the deposit was covered in variously white fluffy salt crusts and yellow-brown salts. Blocks also began slaking to pieces due to continual wetting and drying.

The light brown siltstone is considered to be a lacustrine silt derived from Oruanui Formation ignimbrite on the basis of its fine silt to clay sized particles comprised of Opal-A, quartz and montmorillonite by XRD, and the abundance and size range of accretionary lapilli, the primary deposit being dated at 26.5 ka (Wilson and Switsur, 1988). A strongly cemented dark grey coarse sandstone was ejected but this was of low abundance. It is considered to have been derived from beneath the Oruanui Formation siltstone unit, as it was not exposed in the crater walls and was much less abundant than the brown siltstone. It contained abundant quartz and feldspar crystals in a matrix of clay and glass fragments.

A few clasts of hard silica cemented sands and pumice gravels are of a much older hydrothermal eruption breccia (Fig. 3.35). However, this may have originated from a nearby vent other than that of S721. Also present as a few sparse blocks was a strongly cemented gravel breccia with angular clasts of andesite and pumice in a matrix of carbonate. This was interpreted as being badly weathered concrete debris that had been dumped into the pool. Density and sizes of ballistic blocks is shown in Table 3.2, with sample locations shown in Figure 3.32.



Figure 3.35 A breccia clast of pumice gravel (Rotorua Pyroclastics?) in silica cement. Sample No. S721.9, scale units in millimetres.



Figure 3.36 Weakly silicified silty sandstone showing vertical joint and pyritised margins alongside joint. Yellow areas are alums produced by oxidation of sulphides. Sample No. S721.7, scale units are in millimetres.

3.6.3.2 Mud Matrix: The whole sequence of this HE deposit was dominated by a fine dark grey mud of Opal-A, quartz, pyrite and sulphur as determined by XRD. This mud was the first material to be deposited, but continued to be erupted so that it covered many ballistic blocks, although others later landed into this mud. A final stage of the eruption was a surge of dark grey muddy waters out of the crater to about 5 m distance. During subsequent months this mud lost its glutinous consistency and became light brown with conspicuous areas of white to yellow and orange salt crusts, as pyrite and sulphur oxidised to gypsum, jarosite and other alums.

3.6.4 Eruption Characteristics

Contouring of the eruption deposit thickness and distribution (Fig. 3.32) allowed estimation of its volume and weight to be made. At 100 m distance east the deposit had thinned to 15 mm thick of continuous mud and with blocks of 100 mm maximum diameter confined to +/-20 m of the central eastern axis. A volume of 1195 m³ was estimated and from 14 density measurements of block samples an average result of 1.375 kg.m³ was found. The dry weight densities ranged over 1.36 – 1.50 kg.m⁻³ for the siltstones and the sandstone blocks were consistently more dense at 1.64 – 1.91 kg.m⁻³ (Table 3.2). This equates to a total ejecta mass (ballistics plus muds) of 1643 tonnes as air dried material, although on site the whole deposit was erupted wet and contained much rain and airborne moisture.

Ejecta consisted of four distinct lithologies: (1) Most abundant (~90%) and widely spread was the light brown massive siltstone blocks, some of which contained abundant accretionary lapilli. (2) Dark grey coarse moderately hard sandstone blocks were of low abundance (~5%). It was cemented with silica to form hard angular blocks. (3) White siltstone blocks were uncommon (~1%) but notable for

their low density and very prominent thin laminar bedding. (4) Dark grey mud (~4%) formed the most widespread unit, which was deposited throughout the eruption so that it occurred underneath and over top of some of the blocky ejecta. A final phase of the eruption was a gentle spattering and then weak overflow of dark grey mud.

In summary, S721 erupted an ejecta volume of about 1200 m³ totalling 1650 tonnes in c. 4 minutes. Launch angles of large ejecta blocks, based upon observed eye witness accounts, were then used to derive eruption velocities based upon calculations of Wilson (1972).

Based upon eye witness accounts, the launch angles of 87° are considered most accurate for the majority of blocky ejecta. Velocities of 10 – 300 m.sec⁻¹ were obtained, although about 100 m.sec⁻¹ is the most common value (Table 3.1) and equates with launch velocities of about 60 – 100 m.sec⁻¹ for a hydrothermal eruption at Taupo (Scott and Cody, 1982). A velocity of 100m.sec⁻¹ equals 360 km.hr⁻¹ and for comparison, the speed of sound in air is 330 m.sec⁻¹ or 1200 km.hr⁻¹. The velocity of blocks in volcanic eruptions is calculated at 285 – 600 m.sec⁻¹ by Shteynberg and Solovyev (1978).

3.6.5 Vegetation Damage

The HE from S721 killed several well established trees and broke down groves of manuka shrubs (Fig. 3.32). The eruption deposit had characteristics of those also seen in volcanic eruptions. Ballistic blocks together with the weight of sticky wet mud smashed branches and tree trunks <0.2 m diameter at 27 m distance from the crater rim. Maple and thuja species ~40 years old and with trunks <0.6 m diameter at 5, 20, 25 and 27 m distance from the crater rim were stripped of most branches and leaves and all died. Manuka shrubs at 35-50 m distance from the

crater and up to 4 m tall with stems <60 mm diameter were all bent over and snapped by the weight of adhering muds. By December 2002, no grasses had sprouted from beneath the mud ejecta deposit and only one maple at ~20 m distance had survived, with all other vegetation killed.

Table 3.2 Volumes, weights and densities of sampled blocks erupted from S721 in Kuirau Park on Friday 26 January 2001, with locations shown in Figure 3.32. These were maximum sized examples for their positions. Note the dense dark grey sandstones were most dense and white siltstone the least dense. Sample 10 is concrete, but badly weathered and corroded to camouflage its initial origin (see text for discussion).

Sample No:	Description:	Dimensions, metres:	Volume, m ³ :	Mass, kg:	Density, kg.m ⁻³ :
1	Silicified SdSt slab	.25 x .77 x .55	.1059	157.2	1484.4
2	Dark coarse SdSt	.38 x .27 x .18	.01847	35.21	1906.3
3	Lt brown Siltstone	.67 x .50 x .27	.09045	123.3	1363.2
4	Lt brown siltstone	.69 x .31 x .28	.05989	82.36	1375.2
5	Bedded white ZtSt	.30 x .32 x .17	.01632	20.59	1261.6
6	Lt brown siltstone	.53 x .51 x .32	.08650	133.9	1547.9
7	Lt brown siltstone	.68 x .57 x .32	.12403	172.0	1387.1
8	Lt brown siltstone	.58 x .30 x .43	.07482	102.9	1375.3
9	Acc.lap. brown ZtSt	.60 x .45 x .28	.07560	113.6	1502.6
10	Grey coarse SdSt	.45 x .09 x .37	.01499	24.25	1617.7
11	Acc.lap. brown ZtSt	.36 x .11 x .25	.00990	13.89	1403.0
12	Acc.lap. brown ZtSt	.43 x .33 x .29	.04115	53.04	1288.9
13	Grey coarse SdSt	.37 x .14 x .15	.00777	13.99	1800.5
14	Bedded Siltstone	.08 x .22 x .25	.00440	6.12	1390.9

Using the volume of 1200 m³ for eruption ejecta materials and assuming an average source depth of 10 m at 112°C with boiling point for depth (BPD) conditions, then the sudden onset of boiling and ultimate cooling to an ambient temperature of about 15°C gives a total energy release of about 114 x 10⁶ Joules. If this had all been released within a few seconds it would equate to an earthquake of about ML 3.

3.7 HAMIORA PLACE, NGAPUNA

At Hamiora Place a street on the east bank of the Puarenga Stream, north of Te Ngae Road (Fig. 1.9) there is an area of boiling ground that straddles both sides of the stream over an area of about 500 m². It is still used for steam cooking by local Maori.

3.7.1 Location and Distribution

A single hydrothermal eruption is known at the hangi cooking area on the east bank of the Puarenga Stream, alongside the northern end of Hamiora Place (U16 965343, Figure 2.7). This eruption occurred on 7 March 1996 and was not witnessed, although people from the nearby marae who were cooking food in the steam boxes alongside, discovered the crater when returning to collect their kai. It appears that the eruption was very short lived, perhaps a matter of minutes only, based upon the times people had been present to attend their food cooking there.

A crater about 15 m diameter with vertical to overhanging walls about 2 m high above the Puarenga Stream waterlevel was created by this eruption (Fig. 2.7,

photograph by WR Esler). Ejecta was thrown to about 5 m radius from the crater edges and formed a low mound about 0.3 m high. From distribution of ejecta it is apparent that the blast was a vertical column, as there was no lateral directional bias on deposit distribution.

Ejecta contained blocks of sulphur cemented rounded pumice gravels, with blocks up to 1.3 m x 0.8 m x 0.65 m in volume (676 litres). Ejecta was thrown to about 5 m radius from the crater edge and when visited on 14 March 1996, water of the Puarenga Stream had infilled the crater, where steady weak gas ebullition was occurring. The crater has been entered in the EBOP RGF geothermal features database as Form F166.

3.7.2 Stratigraphy and Age

The age of this event is precisely known as having occurred on 7 March 1996. It was formed within reworked alluvium of pumiceous sands and gravels that had been remoulded to form a raised stopbank along the stream banks, as part of a flood control measure. The eruption removed a section of the stopbank, which was rebuilt the following year. As a result, all surface evidence of the eruption has now been largely destroyed, although some large (<1 m diameter) blocks of sulphur cemented gravels still lie visible within the stream waters alongside the crater site, which itself is no longer recognisable at all as the stopbank was rebuilt in 1997. Ejecta contained only blocks of these sulphur cemented gravels and a fine dark grey mud of pyritised silica muds and silts.

3.7.3 Lithology

Within the streambed portion of the crater, yellow sulphur cemented sedimentary materials comprised of rounded pumice gravel clasts (<30 mm diameter), sands and dark grey silts and muds were present. None of these blocks were ejected onto the landward side of the crater rim, which infers that the event was a very low energy eruption. Only fine, dark grey muds were ejected from the crater onto the landward eastern rim and these thinned to <10 mm thick at about 5 m distance from the crater rim.

The sulphur cemented blocks contained rounded pumice gravel clasts <30 mm diameter, which were fresh and unweathered, with visible dark ferromagnesian minerals including biotite. It is considered most likely that these were derived from Rotorua Pyroclastics (Kilgour, 2002), which is the only fresh coarse pumice gravel found at shallow levels in Rotorua city.

*A little learning is a dangerous thing
Drink deep and taste not the Pierian Spring
There shallow draughts intoxicate the brain
And drinking largely sobers us again*

- Alexander Pope (An Essay on Criticism)

Chapter 4

PETROGRAPHY AND XRD OF HYDROTHERMAL ERUPTION BRECCIAS

4.1 INTRODUCTION

Eruption breccias produced by three large prehistoric and one modern day HE described in Chapter Three have been studied to identify mineral composition, stratigraphic relationships and other characteristics of each. This was done to try and identify any tephra included in those breccias which could provide some time marker to allow dating the occurrence of each HE and hence to establish some stratigraphic control. Physical and mineralogical studies of these breccias also allows the geothermal conditions preceding each HE to be identified to some extent, including a maximum depth of eruption sources and any subsequent chemical alterations of the eruption breccias. Present day characteristics of eruption breccias are also given here.

The Hamiora Place HE of 7 March 1996 was photographed and visited soon after its formation, although no sampling of ejecta or wall materials was done before the site was reworked during repairs to the Puarenga Stream stopbank. Therefore no XRD or other analyses of the deposit has been done.

Similarly, no thorough investigation of Arikikapakapa Thermal reserve has been done, because ground augering or detailed geological site study would require official permission and much additional work. Arikikapakapa Thermal reserve was mapped in 1989 and all thermal features described. A brief summary of findings has been published (Cody, 1989; 1991). (See also Figure 3.2).

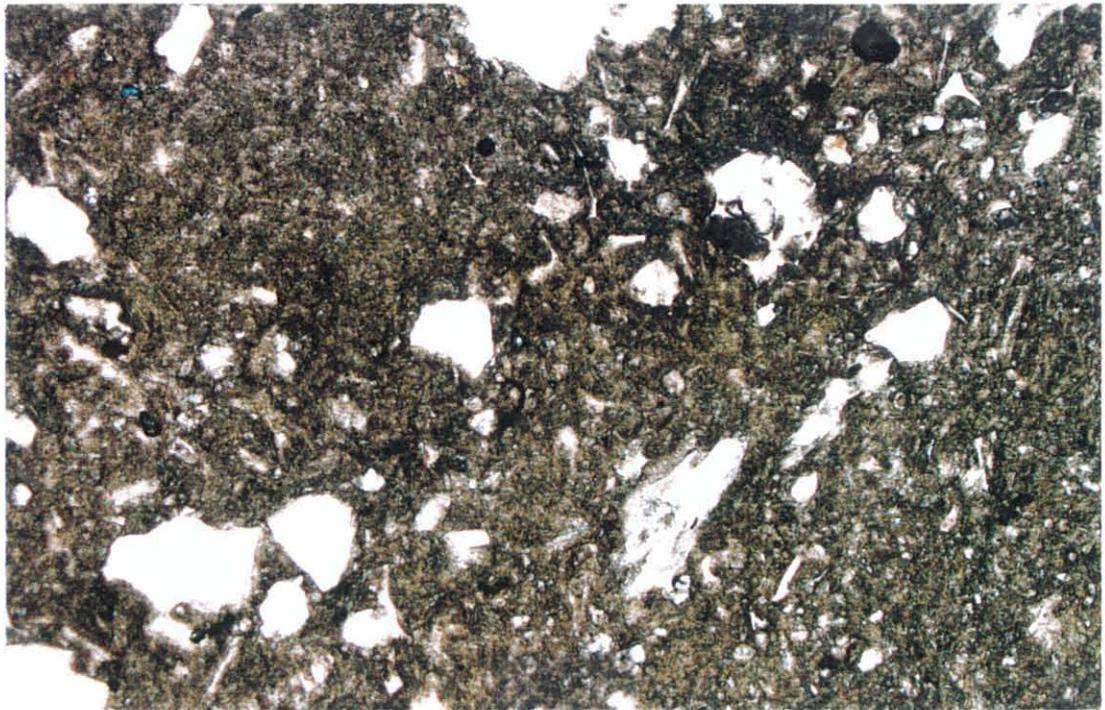


Figure 4.1 Brown isotropic groundmass of glass with lunate and cusped glass shards in HE deposits from Te Puia Hill (sample No. TP-002). Plagioclase and quartz crystals, plane polarised light, x 40.

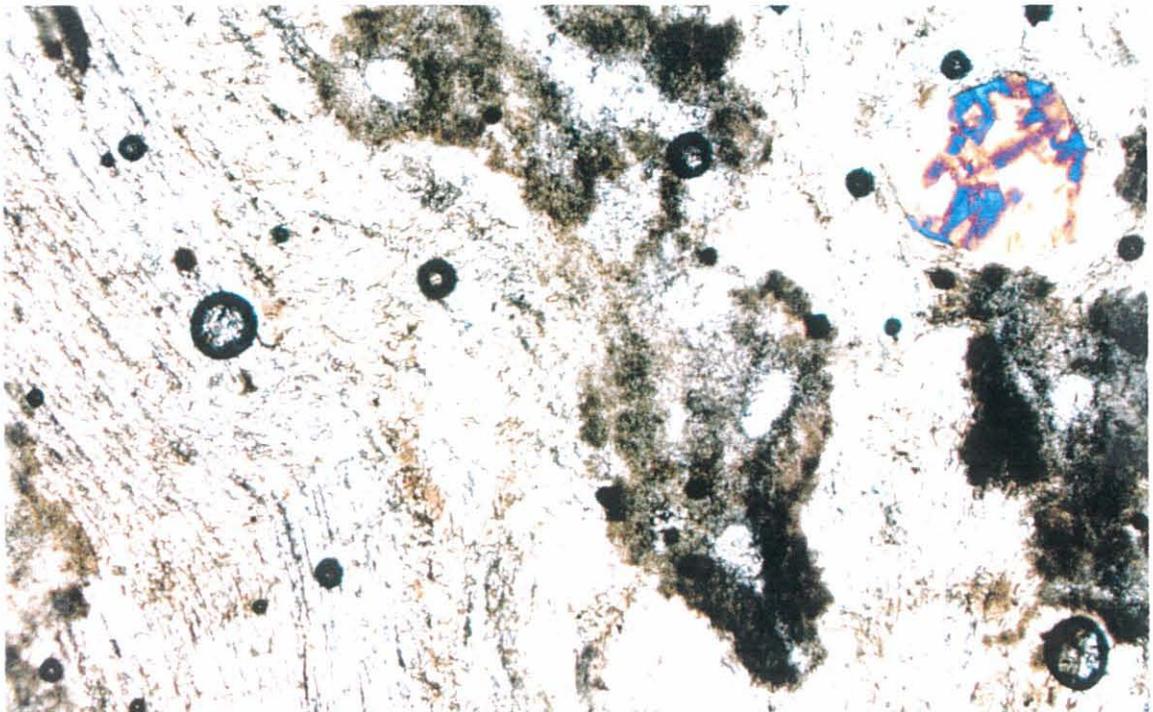


Figure 4.2 Rhyolite clast in HE breccia from Te Puia Hill showing flow banding of amorphous glass groundmass and clays. Quartz crystals replacing devitrified glass. Sample TP-011, crossed polarised light, x 40.

4.2 XRD TECHNIQUES AND EQUIPMENT

Samples were analysed using a Philips XPERT PW 3040/00 and copper K alpha radiation source at 1600 Watts. A scan step size of $0.02^{\circ}2\theta$ per second was used and all data files were stored on computer for later analysis with software library files of mineral patterns. Samples were prepared by dry grinding in agate mortar and pestle, and pressed powder mounts of whole samples in aluminium trays were run over $10-46^{\circ}2\theta$. If any peaks of clay or mica group minerals were present at about 0.257 nanometres (nm), a well mixed water suspension was settled for >24 hours and then pipetted onto a glass slide and air dried prior to scanning for clays and micas over $2-22^{\circ}2\theta$. If any clay group minerals were detected, these samples were subsequently treated with a 10% glycerol solution to expand any swelling clay mineral species and again scanned by XRD.

Glass slides produce strongly enhanced XRD basal reflections from clays and micas, due to strong basal orientation of these sheet like mineral crystals lying flat onto the glass slides. This enhances detection and allows subsequent elimination and confirmation tests to be made, according to well established procedures (Brindley and Brown, 1980). Further tests such as furnace ignition of the clay mounts at 550°C for one hour caused some clay minerals to collapse their crystal spacings by well determined and published amounts. Similarly glycerol soaking caused some clays to swell by well known amounts.

Samples from each of four HE deposits described in Chapter 3 have been analysed. Both clasts and matrix materials were examined and main mineral assemblages identified by XRD. Clay separations were made from thoroughly mixed and separated aqueous suspensions, from which fine turbid upper layers were pipetted off onto glass slides and air dried at room temperature. These thin deposits produced strongly oriented clay mounts, which gave greatly enhanced basal spacing diffractions and therefore very sensitive detection limits for many of

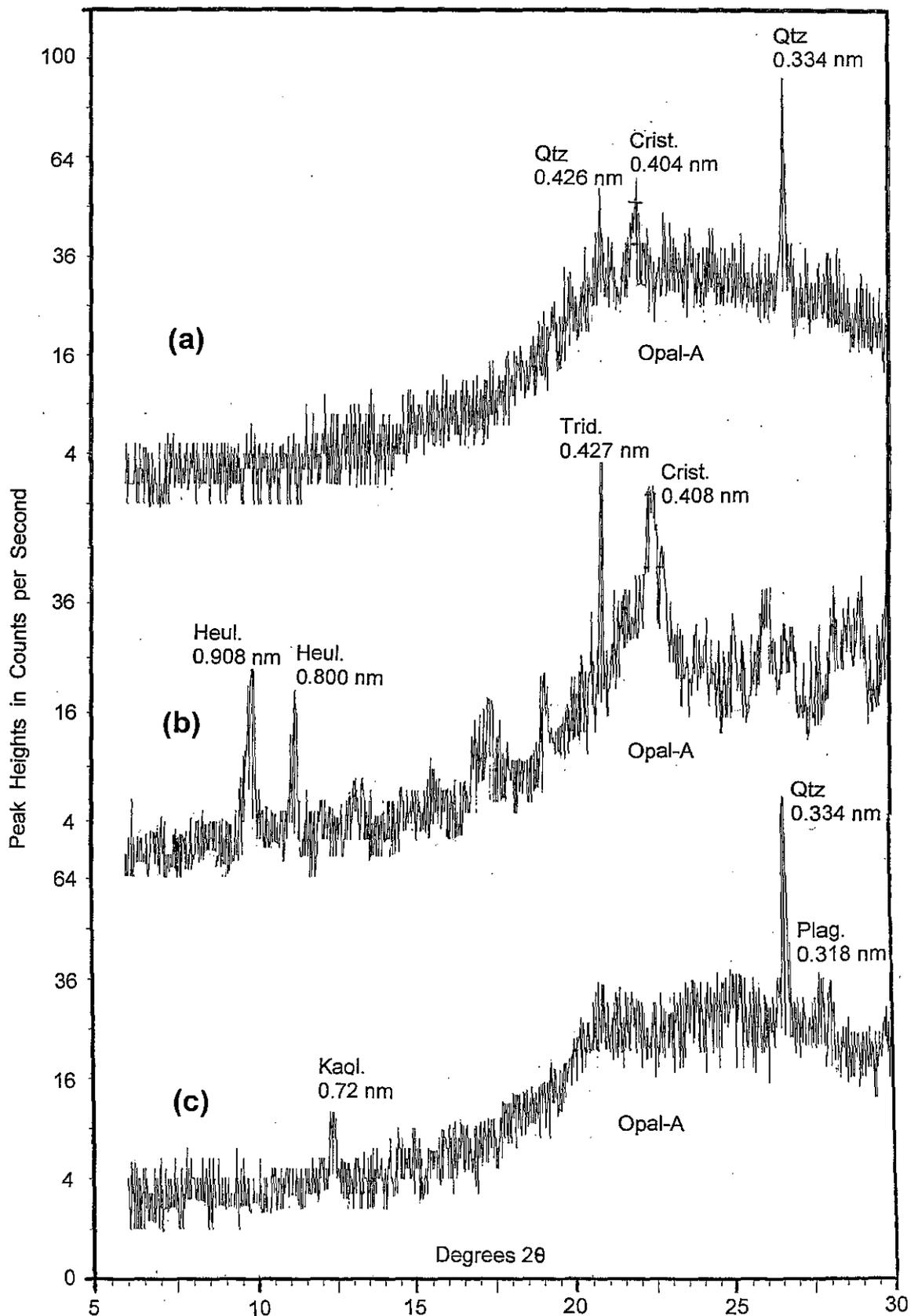


Figure 4.3 XRD scans of clasts from Whangapipiro Bay, F184. (a) = weakly cemented light brown siltstone with mud clasts <10 mm diameter, (b) = pale grey pumice clast 8 mm diameter, (c) = infilled pumice clast 42 mm diameter, light grey with vesicles < 2 mm diameter. Heul = heulandite, Trid = tridymite, Crist = cristobalite, Qtz = quartz, Plag = plagioclase, and Kaol = kaolin. All peak positions are in nanometres, nm.

the clay and mica minerals. Plate smear mounts of clay fractions also allowed very small quantities to be used, instead of needing to extract much larger quantities of clays to fill a tray mount.

In order to confirm the mineral group or individual clay mineral present, bulk sample mounts were firstly run for XRD analysis. Diffraction peaks at spacings of >0.72 nanometers (nm) were then examined in more detail by running an XRD analysis of a glass slide smear mount of the clay fraction separate. Depending upon these findings, further treatments of these thin smear mounts were also made. This involved swelling of the clay minerals by saturation with a 10% ethanol – glycerol mixture, which expanded the basal crystal spacings of some clays and interlayered clay-mica complexes. Furnace firing of smear mounts for one hour at 550°C physically collapsed most clay and mica minerals in well defined amounts that were measured by subsequent XRD analyses. Interpretation of crystal lattice spacing changes following these various treatments is well studied and published (Brindley and Brown, 1980).

4.3 SILICA LATTICE DISORDER

Many samples contained amorphous silica with varying amounts of devitrification due to ageing and crystallisation. Consequently the shape and parameters of the 0.40-0.41 nm peaks was measured according to procedures described by Herdianita, et al. (2000). This procedure characterises the Opal-A and Opal-CT peaks at about 0.4 nm by measuring the half peak height width positions and then recording the total widths. It also gives the ratio of the half peak height widths on each side of the peak maximum height position (Fig. 4.7).

Although this technique has not yet been well quantified, it does define the shape of the main silica species peak at ~0.4 nm. This peak undergoes progressive

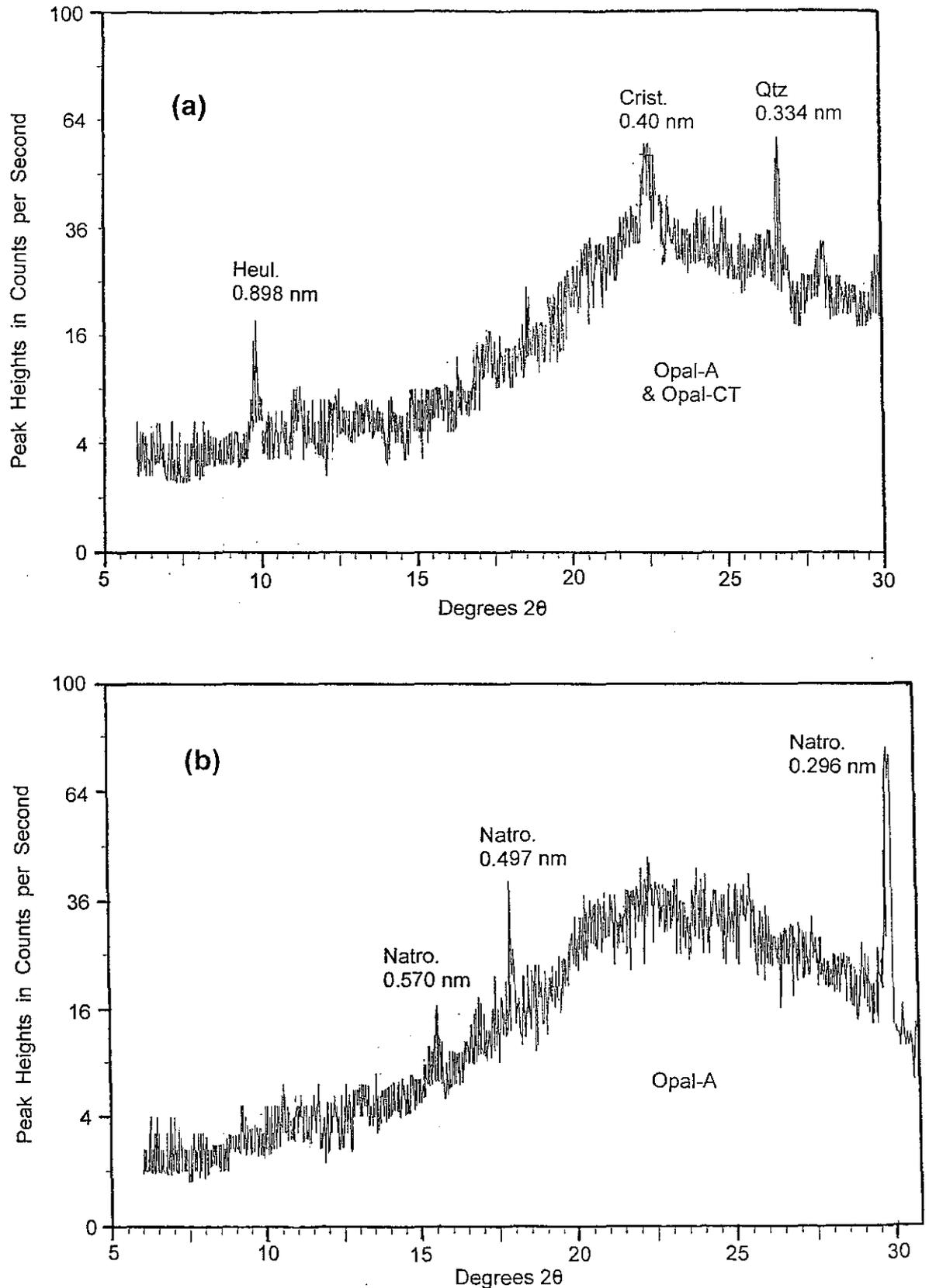


Figure 4.4 XRD scans of clasts from Whangapipiro Bay, F.184. (a) = well bedded dark and light grey banded sandstone, bands <10 mm wide. Moderately cemented angular clast within breccia, and (b) = moderately cemented creamy white angular pumice gravels without any matrix. Overlies breccia outcrops. Heul = heulandite, Crist = cristobalite, Qtz = quartz, Natro = natroalunite. All peak positions are in nanometres, nm.

ordering and increasing symmetry as amorphous silica devitrifies firstly to Opal-A and then Opal-CT, Opal-C and ultimately quartz. Given that conditions are ongoing and similar, then more ordering indicates greater age of the sample. It is useful when comparing samples from within similar geological settings.

4.4 NGAWHA CRATER AND TE PUIA HILL

XRD analyses of samples showed that most materials were comprised largely or solely of amorphous silica species that ranged from Opal-A through to Opal-CT and some minor quartz and feldspars. Materials from here were generally intensely hydrothermally altered, so that no diagnostic rock forming minerals survived. Some minor titanomagnetite still persisted and some inclusions contained iron stained residues of amphibole or pyroxene minerals, which were no longer identifiable by either XRD or microscopic analysis of thin sections. The whole deposit had a brown iron colouring and iron staining of clasts, but no primary and potentially diagnostic ferromagnesian minerals were found in any samples from clasts or matrix.

4.5 WHAKAREWAREWA AND TE PUHUNGA HILLS

Samples from here were invariably uniformly white and without titanomagnetite, ferromagnesian minerals, clays or micas and with only sparse quartz crystals, indicating intensely altered materials due to prolonged hot acid attack. XRD of nearly all samples showed only amorphous silica (Opal-A) and no feldspars or other rock forming minerals. Amphiboles, micas and pyroxenes were all absent and no diagnostic minerals relating to studied tephra or volcanoclastic materials was recognised. However, thin section petrography showed minor plagioclase and quartz, some as products of devitrified glass (Figs. 4.1, 4.2).

Table 4.1 XRD results of whole sample powder tray mounts for the Whangapipiro Bay site breccias. MdSt = mudstone; ZtSt = siltstone; SdSt = sandstone. Waikato University catalogue numbers for these are given in Appendix 1.

Sample Number:	Brief Description:	XRD Results:
F184.1a.001	Silicified clast of Sandstone (SdSt)	Opal-CT>>quartz, heulandite >plagioclase (trace)
F184.1a.002	Cemented off white Siltstone	Opal-CT>>quartz, cristobalite
F184.1a.003	Banded silicified SdSt/ZtSt	Opal-A>>gypsum>smectite
F184.1a.004	ZtSt with MdSt clasts	Opal-A>>quartz>Opal-CT
F184.1a.005	Pumice gravel clast	Opal-A>heulandite, Opal-CT, tridymite and clay?
F184.1a.006	Infilled pumice gravel clast	Opal-A>plagioclase
F184.1a.007	Strongly cemented SdSt	Opal-A
F184.1a.008	Pumice clast 120 mm dia.	Opal-A>>quartz>kaolin, plag.
F184.1c.001	Off white pumice gravels	Opal-A>natroalunite
F184.1c.002	Dense white infilled pumice	Opal-A>>natroalunite
F184.2.001	Creamy soft Mudstone clast	Opal-A>>Opal-CT, quartz>> clay? (smectite?)
F184a	sandy boulder matrix	Opal-A>quartz, tridymite> Opal-CT, plagioclase

Alteration products such as zeolites, alunite or natroalunite were not found. It is considered that these hills are comprised of breccias that have undergone prolonged hot acidic weathering conditions here and consequently any diagnostic

minerals once present in any tephra derived materials have been completely destroyed.

Table 4.2 Characterisation of the relative devitrification of amorphous silica by shape and position of the ~0.4 nm silica peaks (Herdianita, et al., 2000).

Sample No:	Half Peak Height at ~0.4 nm:			Symmetry Ratio, ($I_a - I$) ÷ ($I - I_b$):
	$2\theta_{\max}^{\circ}$:	$2\theta_{\min}^{\circ}$:	Δnm :	
F184.1a.001	.400	.388	.012	1.00
F184.1a.002	.415	.395	.020	0.54
F184.1a.004	.410	.400	.010	0.25
F184.1a.005	.400	.389	.011	0.57
F184.2.001	.417	.396	.021	0.75
S721-2	.414	.400	.014	0.56
S721-5	.413	.399	.014	1.33
S721-5	.419	.406	.013	1.17
S721-7a	.415	.404	.011	0.83
S721-7a	.419	.399	.020	0.82
S721-7b	.415	.399	.016	1.00
S721-7b	.420	.404	.016	1.29
TP.001	.411	.402	.009	1.25
TP.004	.413	.400	.013	1.17

Table 4.3 XRD of clay sized fractions mounted on glass slides. These were run over $2-22^{\circ}2\theta$ at $0.02^{\circ}\theta.\text{min}^{-1}$. Basal reflections around 1.4, 1.0, 0.71 and 0.4 nm were searched for as indicating possible clay or mica materials.

Sample No:	XRD Result (Clay Mounts):
F184.1a.001	No clays; abundant Opal-A; trace zeolite (0.912 nm)
F184.1a.002	No clays; abundant Opal-A
F184.1a.003	No clays; abundant Opal-A
F184a matrix	Kaolin (trace)
F184.1a.004	No clays; abundant Opal-A
F184.1a.005	No clays; abundant Opal-A; trace zeolite (0.907 m)
F184.1a.006	No clays; abundant Opal-A
F184.1a.007	No clays
F184.1c.001	No clays
F184.2.002	No clays
F184.2.003	No clays
F184.2.004	No clays
F184.3.001	No clays

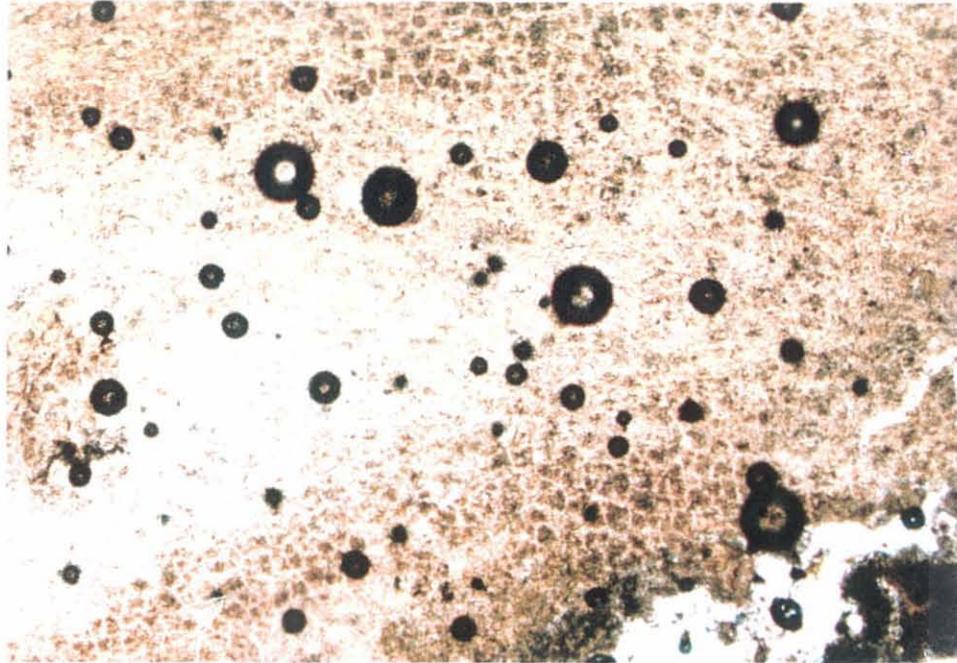


Figure 4.5 Soft mudstone clast, sample No. F184.2.001. Isotropic glass and clay (montmorillonite) groundmass showing polygonal dehydration cracks. Plane polarised light, x 40.

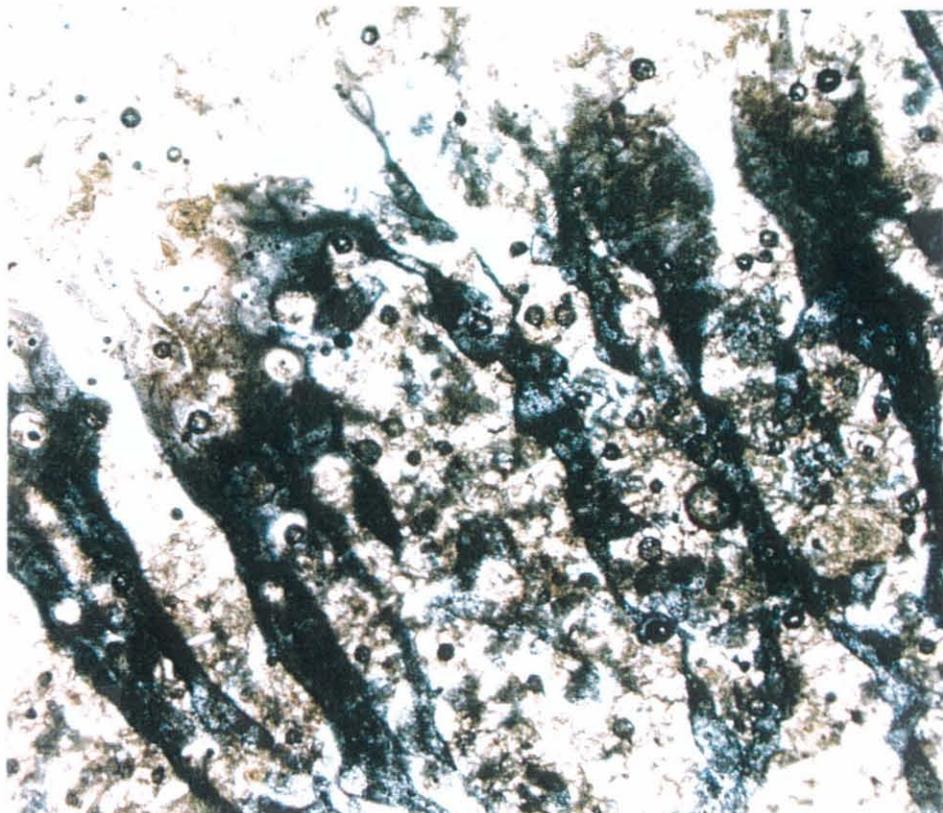


Figure 4.6 Isotropic glass groundmass with internal bacterial growths. Sample No. F184.2.001, plane polarised light, x 40.

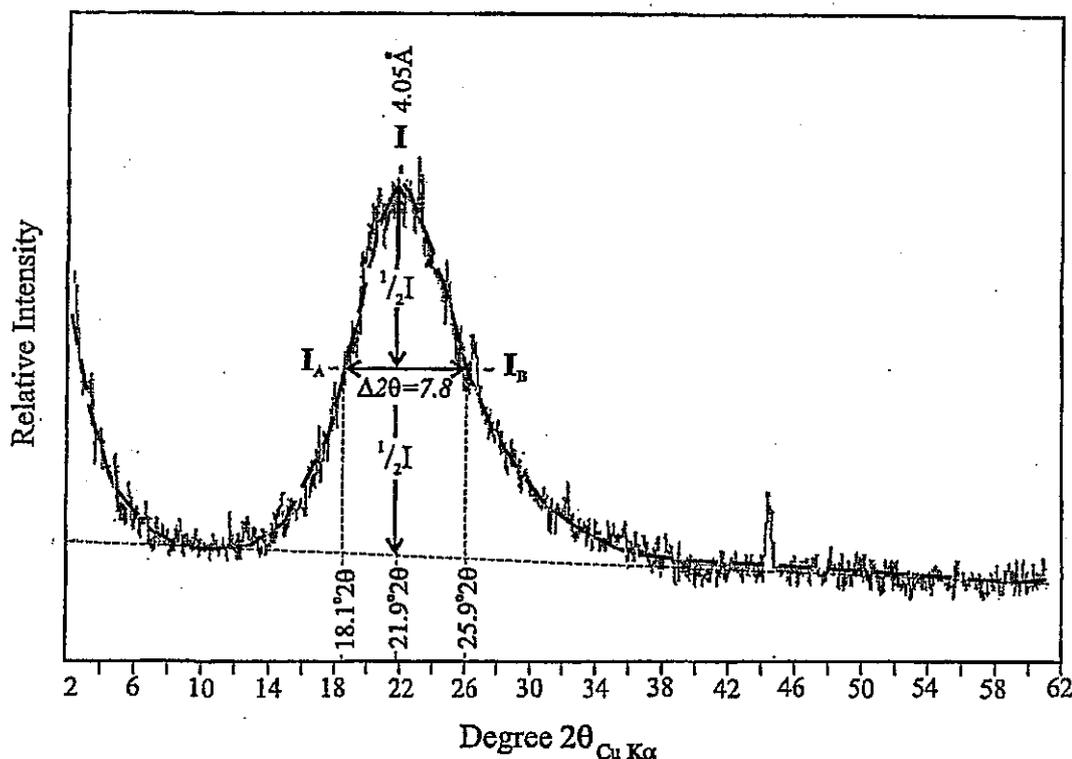


Figure 4.7 Determination of silica order-disorder using the ~ 0.4 nm diffraction line of opaline silica sinters, taken from Herdianita, et al., (2000). The curve is firstly smoothed and a curve and baseline fitted manually. Maximum intensity and then the half peak height intensity are determined.

4.6 WHANGAPIIRO (CRATER) BAY

XRD of samples from here (Table 4.1) showed that generally most rock forming minerals had undergone intense decomposition by prolonged acid alteration conditions (Fig. 4.3). Feldspars have been decomposed to alunite, natroalunite or kaolin, with zeolite (heulandite) (Fig. 4.3b, 4.4) being present as a minor component in a few samples that had been isolated from ongoing attack due to being concealed within raised breccia outcrops that were removed and largely isolated from the underlying hot acidic conditions.

Opaline silica species were largely of Opal-A, with their ~ 0.40 nm peaks being characterised by height and width ratios according to Hirdianita, et al., (2000),

(Fig. 4.7 and Table 4.2). Clay separations were prepared and analysed by XRD (Table 4.3). Polygonal dehydration shrinkage cracking of relic smectite clays were visible in some thin sections (Fig. 4.5), and bacterial or algal growths were present in some clasts (Fig. 4.6).

Nearly all samples contained abundant opaline silica species which were largely of Opal-A, some without development of any ~ 0.4 nm peaks at all. Thin sections showed abundant amorphous silica as both a dark groundmass and as glass shards. Natroalunite was not recognised in thin section and may have been concealed by the mass of dark brown silica, as it was found by XRD.

4.7 OURU, OHINEMUTU

Table 4.4 XRD analyses of whole powder sample mounts in aluminium trays. Scanned over $8-46^{\circ}2\Theta$ at $0.02^{\circ}\Theta.\text{min}^{-1}$.

Sample No:	Sample Description:	XRD Result:
O.008a	Silicified siltstone	Opal-A
O.008b	Silica sinter deposit	Opal-A
O.009	Grey silicified sandstone	Opal-A
O.012	Silicified sinter clast	Opal-A
O.013	Ignimbrite clast	Quartz>>Opal-A>kaolin and halloysite?

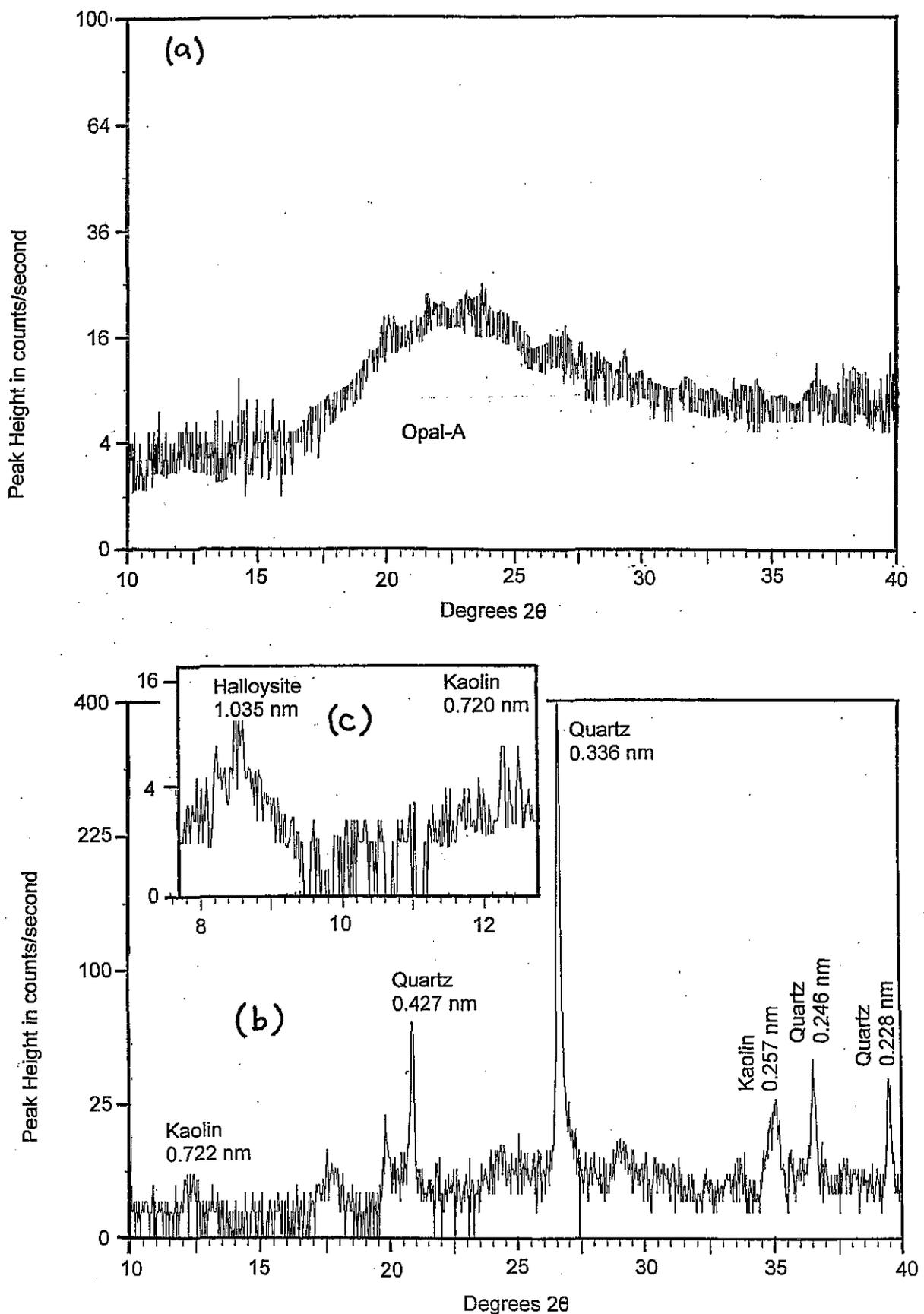


Figure 4.8 XRD patterns for Ouru samples, Ohinemutu. (a) = Sample No. O.012 whole mount, (b) = Sample No. O.013 whole mount, and (c) = Sample No. O.013 clay mount. All peak heights are in counts.sec⁻¹. Sample O.012 is pure Opal-A, O.013 is of quartz>>kaolin>hydrated halloysite?



Figure 4.9 Accretionary lapilli showing fine grained isotropic glass groundmass with clays and dehydration cracks. External matrix has crystals to ~450 microns. Sample No. O.001, Ouru, Ohinemutu. Plane polarised light, x 40.

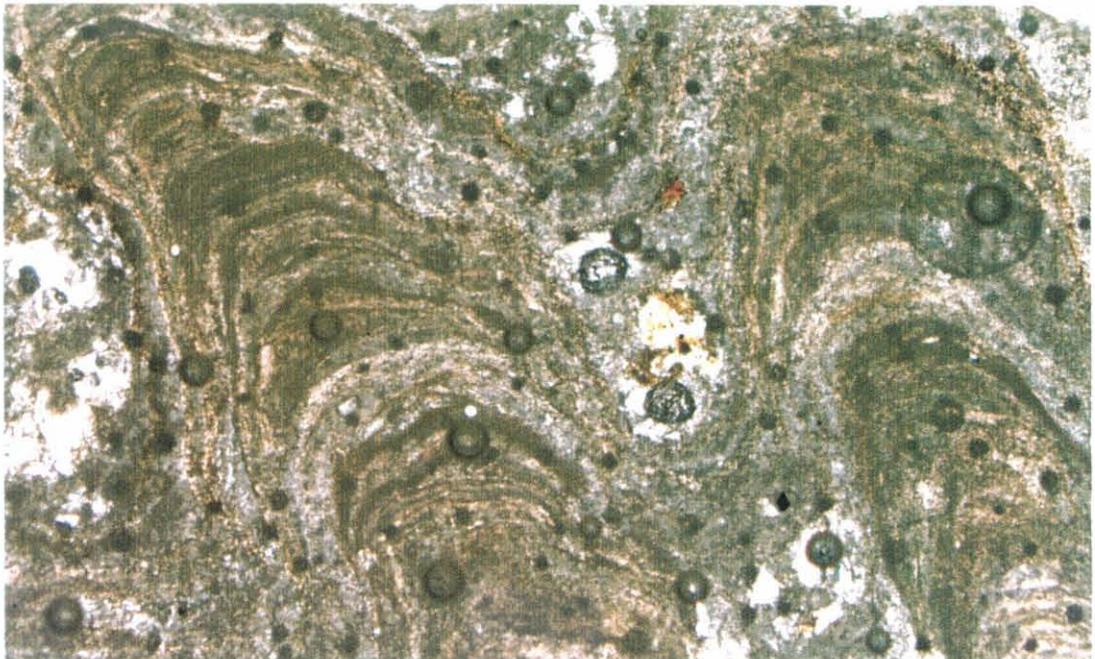


Figure 4.10 Isotropic glass and clay groundmass with spicular algal sinter growths. Sample No. O.009, Ouru, Ohinemutu. Plane polarised light, x 40.

XRD analysis (Table 4.4, 4.5) showed some samples contained kaolin, hydrated halloysite and a zeolite (heulandite). Clay mounts confirmed kaolin and hydrated halloysite in some samples, but most were of abundant amorphous opaline silica (Opal-A) species and minor quartz only (Fig. 4.8). Thin section petrography showed an abundant glassy groundmass, occasionally with spicular algal sinters (Fig. 4.9, 4.10).

Table 4.5 XRD results of clay sized fraction separations onto glass slides.

Sample Number:	Description of Sample:	XRD Results:
O.008b	Silica sinter deposit	No clays or micas
O.009	Dark grey silicified sandstone	No clays or micas
O.012	Silicified sinter clast	Kaolin (trace) and halloysite
O.013	Ignimbrite clast	Kaolin and halloysite

4.8 S721, KUIRAU PARK

XRD analyses of samples from the 26 January 2001 HE had abundant zeolite (heulandite), Opal-A, montmorillonite (Fig. 4.11, 4.12) and an interlayered complex of illite and montmorillonite. Minor plagioclase feldspar, pyrite, gypsum, sulphur and traces of kaolin were also found (Fig. 4.13). XRD results are given in Table 4.6.

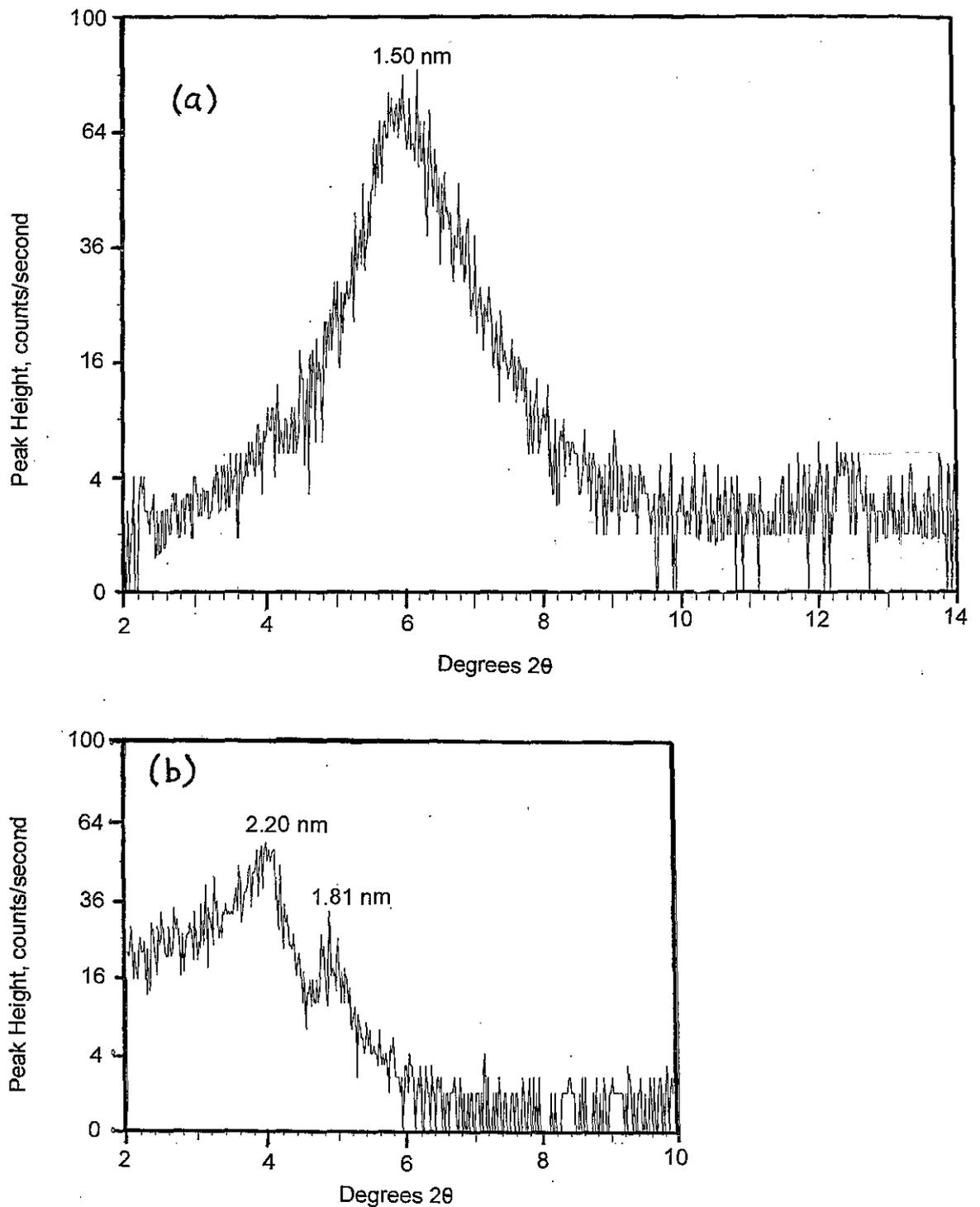


Figure 4.11 XRD traces of clay mounts of sample S721-c, Kuirau Park eruption of 26 January 2001. Sample is of bedded white siltstone. (a) = Clay mount air dried onto glass slide, and (b) = same sample treated with 10% glycerol solution. Expansion of peak at ~1.50 nm to 2.20 and 1.81 nm shows an interlayered montmorillonite-illite clay complex. Peak heights are in counts.sec⁻¹.

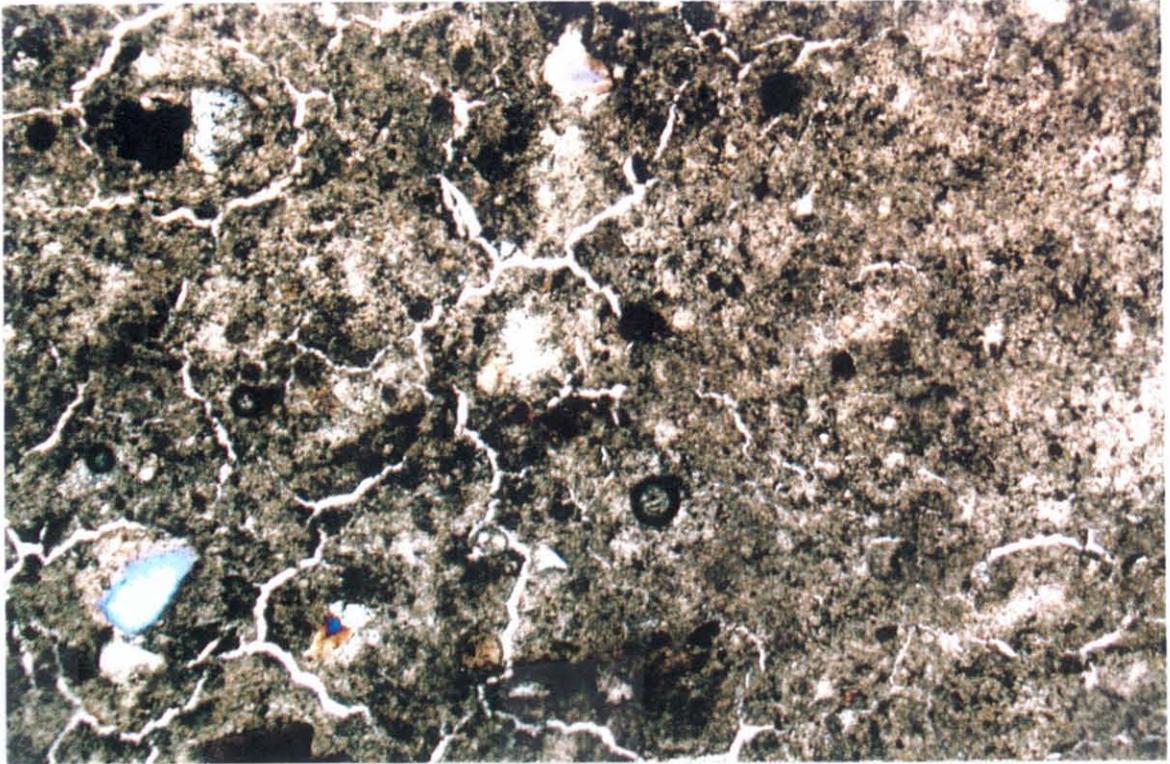


Figure 4.12 Brown isotropic groundmass of glass and montmorillonite clay showing dehydration cracking. Sparse quartz and plagioclase crystals. Sample No. S721-2, crossed polarised light, x 40.

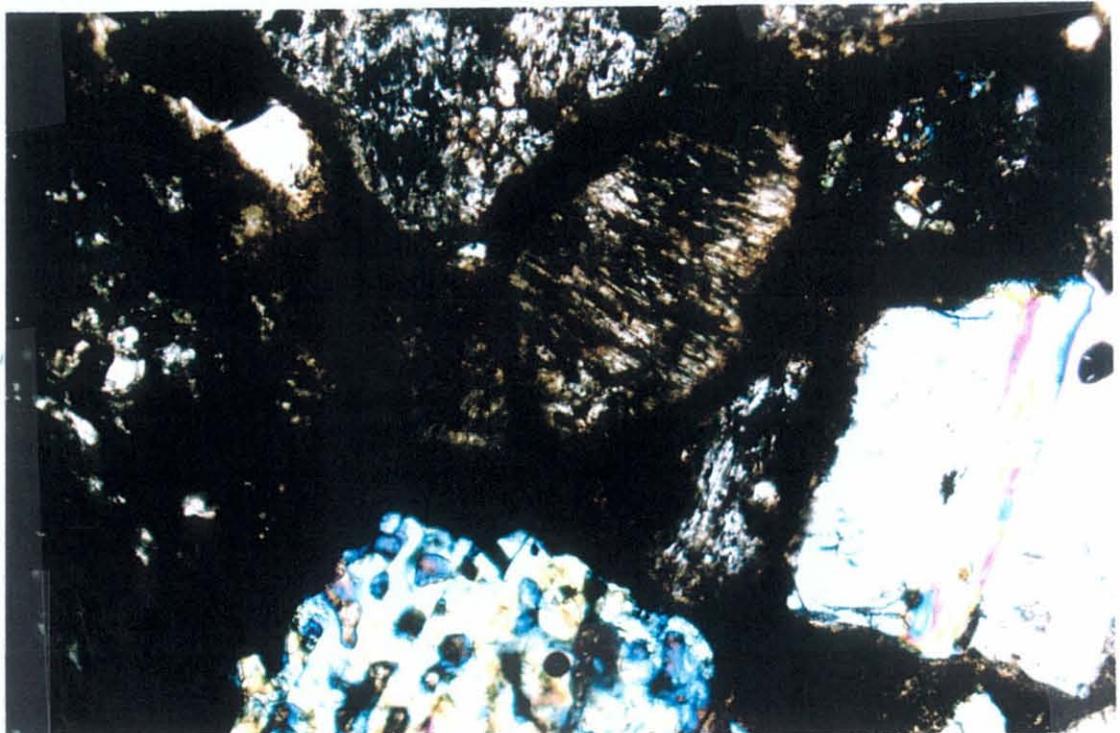
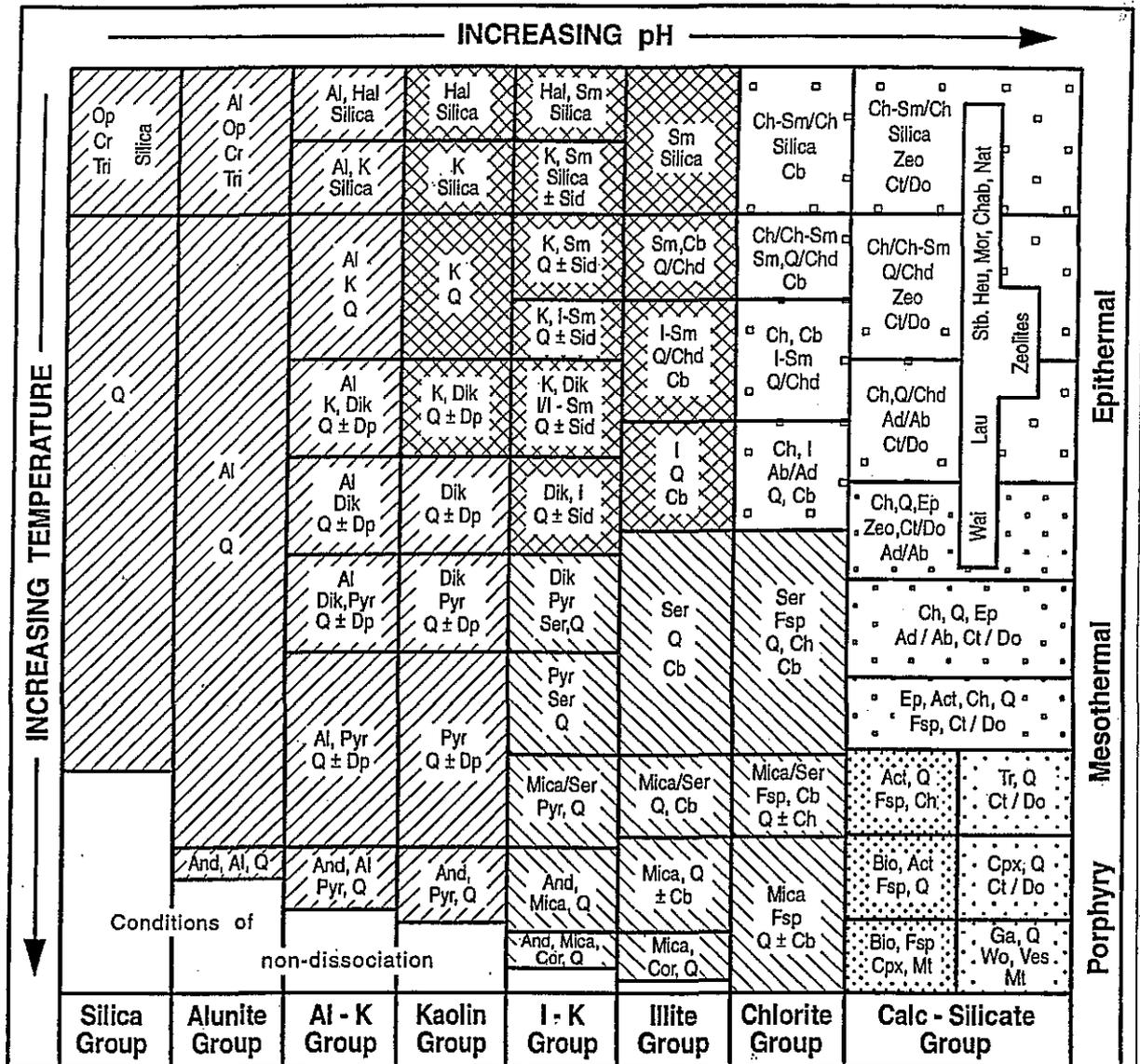


Figure 4.13 Pumice breccia with isotropic glass groundmass, zeolite (heulandite) and montmorillonite clay. Crystals of quartz, plagioclase, titanomagnetite and biotite. Sample No. S721-9, crossed polarised light, x 40.



Mineral Abbreviations :

Ab - albite; Act - actinolite; Ad - adularia; Al - alunite; And - andalusite; Bio - biotite; Cb - carbonate (Ca, Mg, Mn, Fe); Ch - chlorite; Chab - chabazite; Chd - chalcedony; Ch-Sm - chlorite-smectite; Cor - corundum; Cpx - clinopyroxene; Cr - cristobalite; Ct - calcite; Do - dolomite; Dik - dickite; Dp - diaspore; Ep - epidote; Fsp - feldspar; Ga - garnet; Hal - halloysite; Heu - heulandite; I - illite; I-Sm - illite-smectite; K - kaolinite; Lau - laumontite; Mt - magnetite; Mor - mordenite; Nat - natrolite; Op - opaline silica; Pyr - pyrophyllite; Q - quartz; Ser - sericite; Sid - siderite; Sm - smectite; Stb - stilbite; Tr - tremolite; Tri - tridymite; Ves - vesuvianite; Wai - wairakite; Wo - wollastonite; Zeo - zeolite

- | | | |
|----------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|
|  Potassic |  Propylitic |  Outer / Sub Propylitic |
|  Skarn |  Argillic |  Advanced Argillic |
|  Phyllic | | |

Figure 4.14 Common alteration minerals found in geothermal systems. (After Corbett and Leach, 1998).

Table 4.6 XRD results for whole samples mounted into aluminium trays. Mont. = montmorillonite, qtz = quartz, zeol = zeolite, heul = heulandite, accret = accretionary lapilli. Symbol >> = much more than, and > = more than.

Sample No:	Description:	XRD Results:
S721-2	White siltstone	Opal-CT >> mont, qtz > kaolin
S721-3	Mud coating on S721-2	Opal, pyrite, kaolin (no sulphur detected)
S721-4	Dark grey sandstone	Opal-A>>qtz, feldspar>mont, heulandite
S721-5	Siltstone accret. lapilli	Opal-CT >> quartz, montmorillonite
S721-5a	Clear crystal in siltstone	Feldspar (~plagioclase)
S721-6	White salt on siltstone	Gypsum
S721-7a	Grey vein in siltstone	Opal-C>> qtz, pyrite>> mont, heulandite

4.9 DISCUSSION

The presence of natroalunite and opaline silica as major components in matrices and clasts of HE materials at Whangapipiro Bay confirm the prolonged duration of acidic conditions (Fig. 4.14). Other sites also contain abundant opaline silica, but with zeolite (heulandite) and smectitic clay (montmorillonite), indicating neutral to alkaline fluid conditions.

Therefore the alteration mineralogy indicates two distinct suites of pH conditions have been present to allow formation of smectites and zeolites, and also alunites and natroalunites. It is postulated that alkaline fluid outflows once occurred here but were subsequently replaced by steam and gas upflows to produce strongly acidic conditions. This change could occur with falling aquifer pressures so that geothermal fluids no longer discharged at this site and acid gases were produced instead.

A man is to be cheated into passion, but to be reasoned into truth

- John Dryden

Chapter 5:

PROCESSES AND CONTROLS ON HYDROTHERMAL ERUPTIONS

5.1 INTRODUCTION

Hydrothermal eruptions rapidly expend stored energy as the hot water flashes to boiling point with the abrupt fall in confining pressures. This process either opens a new vent or enlarges a previously existing vent, which then allows steady dissipation of any upflow of hot waters and gases (Fig. 5.1). Consequently an equilibrium is quickly reached whereby the opened vent allows ready escape of steam, gases and water at a rate equal to upflow from deeper in the geothermal system. The result is that no further fragmentation and ejection of wall rocks is likely after the initial violent eruption process has ceased. Rarely, the vent may become blocked by collapse of wall rock, so that some subsequent HEs may occur from the vent until it remains permanently open, in which state no overpressuring or elevation of temperatures above boiling point for depth (BPD) conditions can occur (Fig. 5.2).

In geothermal systems, underlying hot waters are often at temperatures above that of surface pressure of water, or very close to BPD conditions. Should some disruption or interference allow the confining pressures to suddenly fall down to boiling point, sudden and violent onset of boiling may produce hydrothermal eruptions, which rupture through to the land surface. In New Zealand, the Taupo Volcanic Zone (TVZ) has many examples of these, such as surface ejecta deposits or large hydrothermal eruption craters.

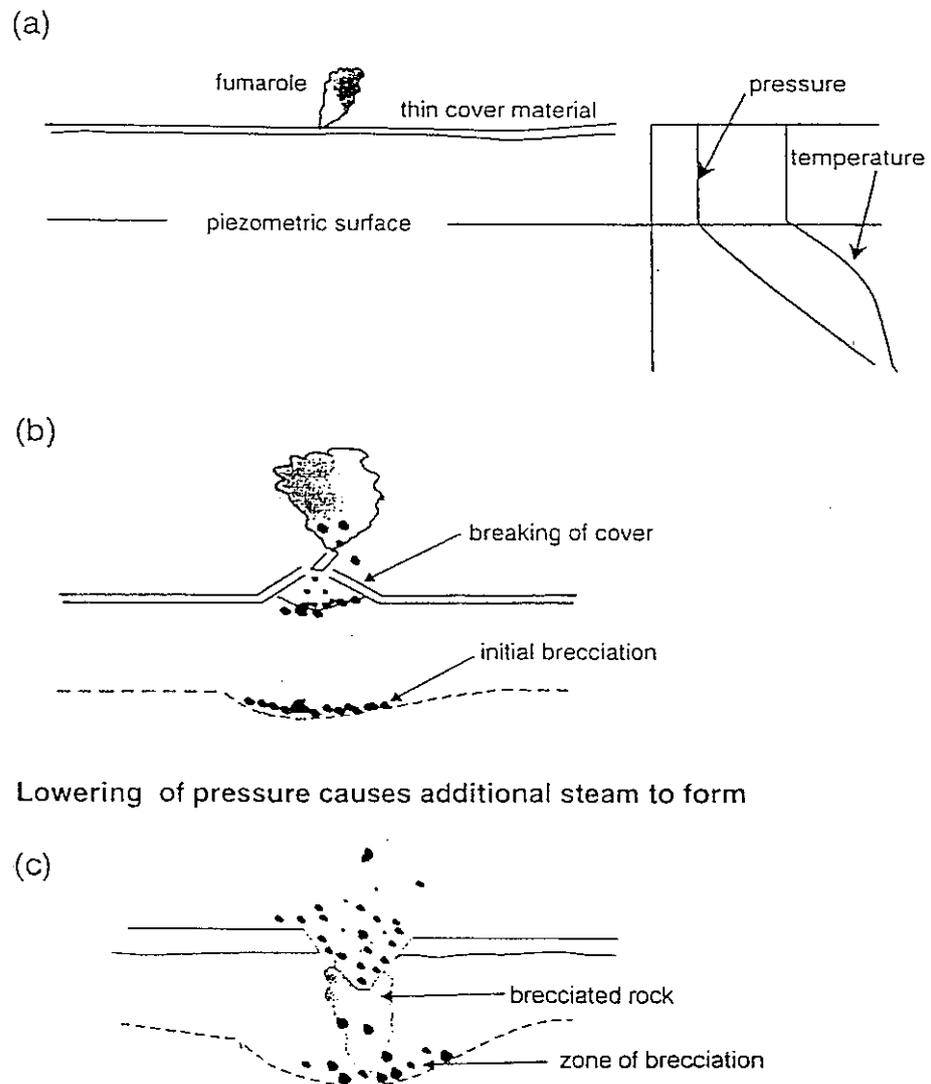
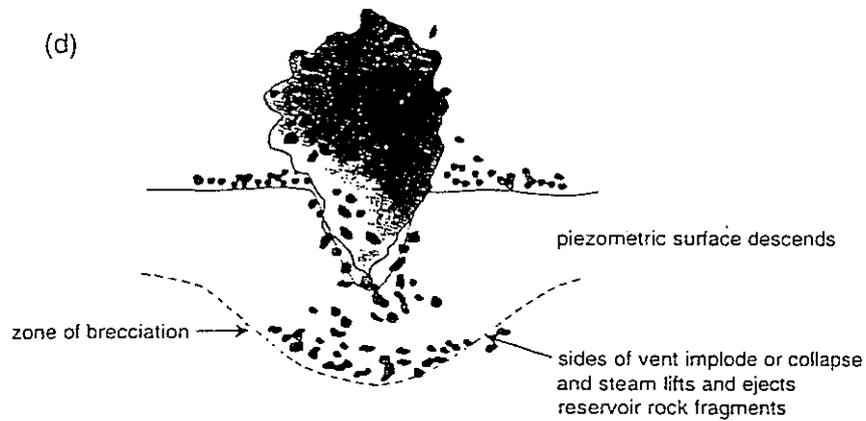
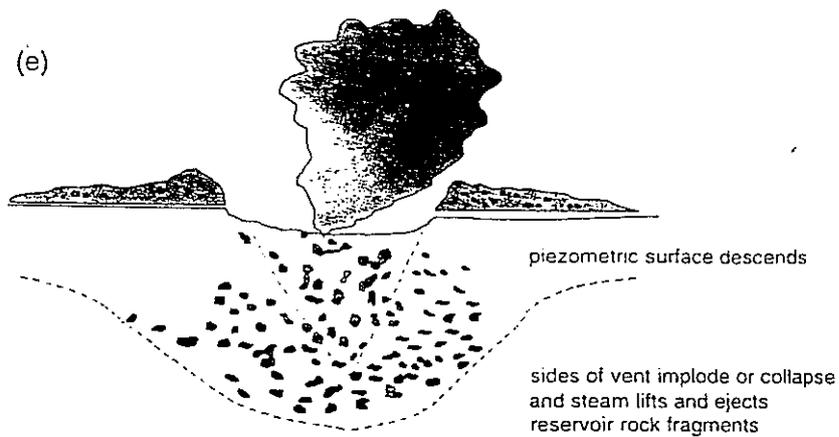


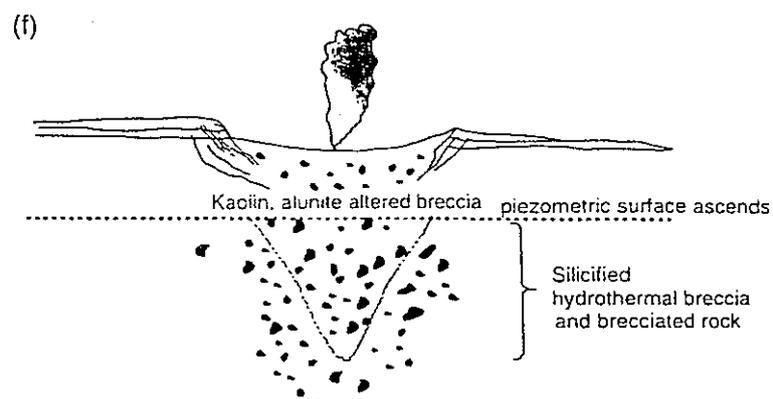
Figure 5.1 The development and progressive course of a hydrothermal eruption (a to f), showing postulated changes in its water-level (piezometric surface) in a hot water geothermal field with a steam cover. Brecciation of the host rocks occurs where the water turns to steam. The steam provides the energy to lift rocks and ejecta out of the vent. Finally the piezometric surface is restored and hydrothermal alteration of the ground causes sealing. Craters can be from 2-5 m up to >100 metres diameter. (From Browne and Lawless, 2001).



Eruption ceases when steam supply is insufficient to brecciate and lift rock fragments



Eruption ceases when steam supply is insufficient to brecciate and lift rock fragments



Hydrothermal system is restored to its former hydrology; piezometric surface ascends and hydrothermal alteration restarts. Sides of crater have slumped

(Figure 5.1, continued)

Almost every geothermal field in the world today has at some stage of its history undergone at least a few hydrothermal eruptions. These have recently been classified by Browne and Lawless (2001).

5.2 BOILING POINT FOR DEPTH (BPD) EFFECTS

Most geothermal systems contain water that is heated well above ambient ground heating rates, which for areas of the Earth outside of geothermal fields is typically at a rate of $30^{\circ}\text{C.km}^{-1}$. When hot water reaches boiling point and suddenly flashes from water to steam, a volume expansion of about 1000 times occurs at surface pressures.

In near surface ground conditions (i.e., about 5-50 metres depth), this sudden onset of boiling and rapid change of volume cannot always be contained by lithostatic loading, particularly if overburden is comprised of unconsolidated loose materials such as tephra or sediments.

When ground rupture occurs, then sudden pressure release creates violent boiling conditions, which propagate into surrounding ground as the vent wall fragments and opens until all stored energy is ultimately released (Fig. 5.3, 5.4). Because of this, HES tend to form craters that taper inwards with depth until boiling no longer occurs and fragmentation of ground then terminates also.

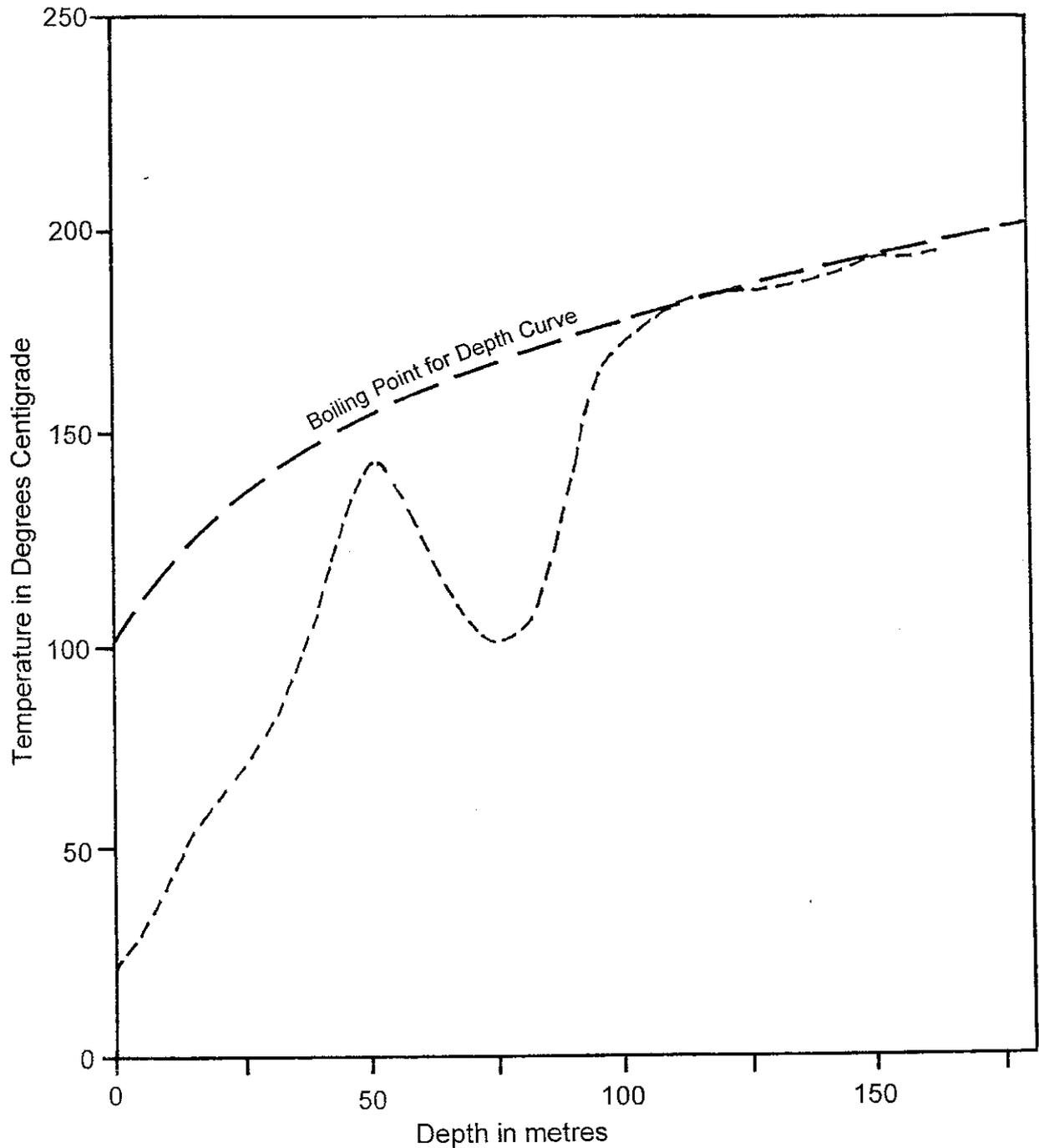


Figure 5.2 Temperature profile down monitor well M.16 with curve of Boiling Point for Depth (BPD) conditions shown. Note how conditions approach near to BPD at 50-55 metres and from 100 metres to hole bottom. This profile was measured on 2nd February 2000. (Data from Environment Bay of Plenty).

5.3 LITHOSTATIC AND HYDROSTATIC LOADING EFFECTS

Hydrothermal eruptions can occur whenever the confining pressure of lithostatic loading is in some way released or exceeded, so that boiling can then occur (Fig. 5.5, 5.6). This can be initiated by localised steam and/or carbon dioxide overpressures developing in hydrothermal fields. Where such conditions are prone to develop, various triggering mechanisms have often been recognised as initiating hydrothermal eruptions and some of these are discussed elsewhere (Lloyd, 1959; Scott and Cody, 1982; Allis, 1984; Hedenquist and Henley, 1985; Browne and Lawless, 2001).

In the late nineteenth and early twentieth century, the level of Lake Rotorua was not controlled by any weir at the Ohau Channel outlet. Consequently the lake level fluctuated seasonally by a metre or more in level as months of low rainfall allowed draining of the lake, and conversely it filled in times of prolonged heavy rainfall. The Puarenga Stream delta area in Sulphur Bay had many large (>50 m high) HES in that period which were observed and recorded.

In this location it is considered that sulphur deposition from ongoing solfatara activity has continually cemented fluvial materials washed in by the Puarenga Stream. This forms a coherent aquaclude that allows over-pressuring of the near surface geothermal system. Temperatures then become elevated above normal coldwater hydrostatic BPD conditions. Ultimately the sulphur cemented aquaclude either ruptures under increased pressures, or it gets broken by tectonic movement or shaking. Rupture then allows a sudden onset of boiling to develop and a hydrothermal eruption ensues until all stored energy in the form of water above BPD is flashed to steam.

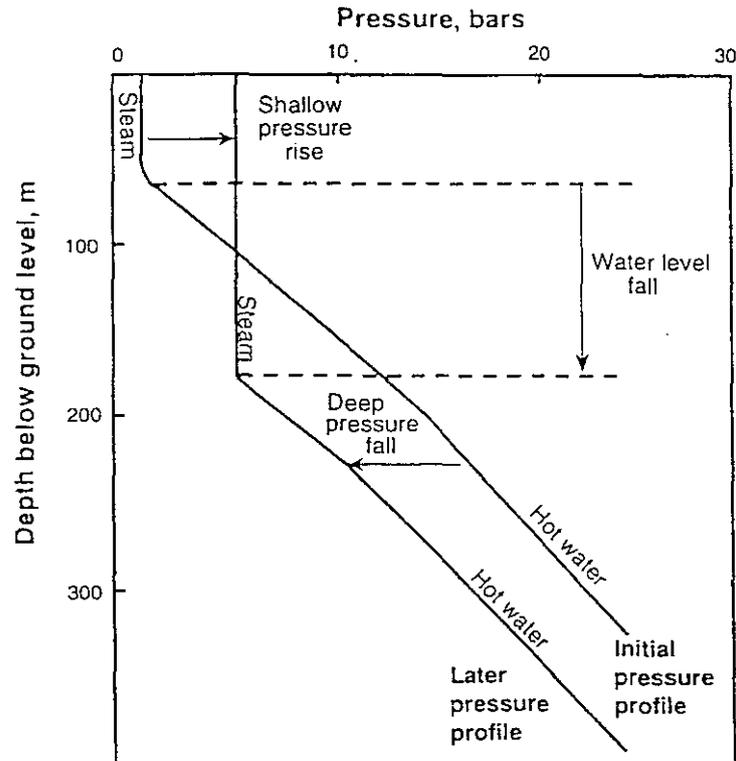


Figure 5.3 Pressure and depth relations in a geothermal system, showing how a decline of water level and a drop of deep pressure can cause shallow pressures to rise due to the formation of a steam zone. (From Browne and Lawless, 2001).

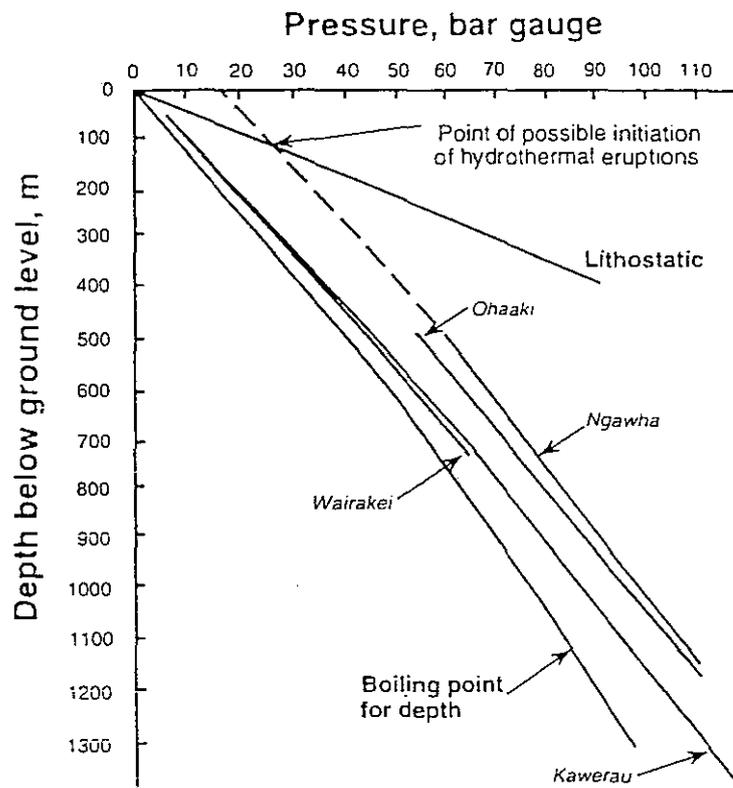


Figure 5.4 Pressure and depth profiles in explored New Zealand geothermal systems. No such deep data is available from Rotorua geothermal system yet. (From Browne and Lawless, 2001).

5.4 TRIGGERING MECHANISMS

5.4.1 Introduction

The larger prehistoric eruptions in the Rotorua Geothermal Field appear to have occurred at times of sudden pronounced changes in the level of Lake Rotorua. Some smaller historical eruptions appear to be associated with locally falling groundwater lakelevels following erosional downcutting of streams, or months of very low rainfall. Lowered groundwater or lakelevels reduce the near surface lithostatic loadings due to groundwater retreat. For example, a fall in groundwater level of one metre over an area of 100 m by 100 m would reduce the lithostatic loading by 10,000 tonnes, or by one tonne.m⁻².

If boiling or very near to BPD conditions were present in the near surface depths (say 1-25 m deep), but isolated from overlying groundwater by a suitable aquiclude, a rapid fall in groundwater level could be sufficient to trigger a hydrothermal eruption (Table 5.1).

Table 5.1: Changes of boiling point for depth (BPD) at 5 m and 25 m depths following fall of groundwaters by 1 m and 5 m, producing pressure reductions of hydrostatic loadings by 10 KPa and 50 KPa respectively.

Depth (metres) from groundlevel:	Boiling Point for Depth (BPD), °C:	BPD with -1 m groundwater fall:	BPD with -5 m groundwater fall:
0	100	100	100
5	105	104	100
25	136	135	130

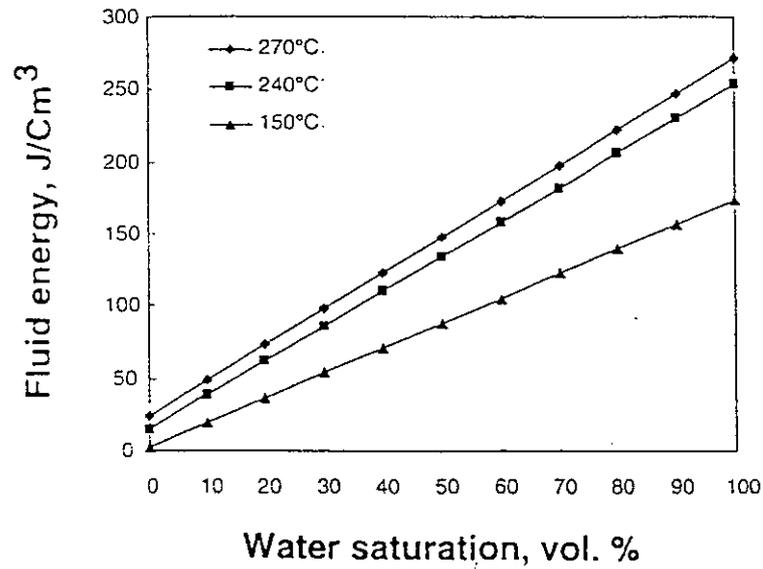


Figure 5.5 Amount of energy in fluid per unit reservoir volume in a geothermal system, at varying degrees of water saturation by volume. (From Browne and Lawless, 2001).

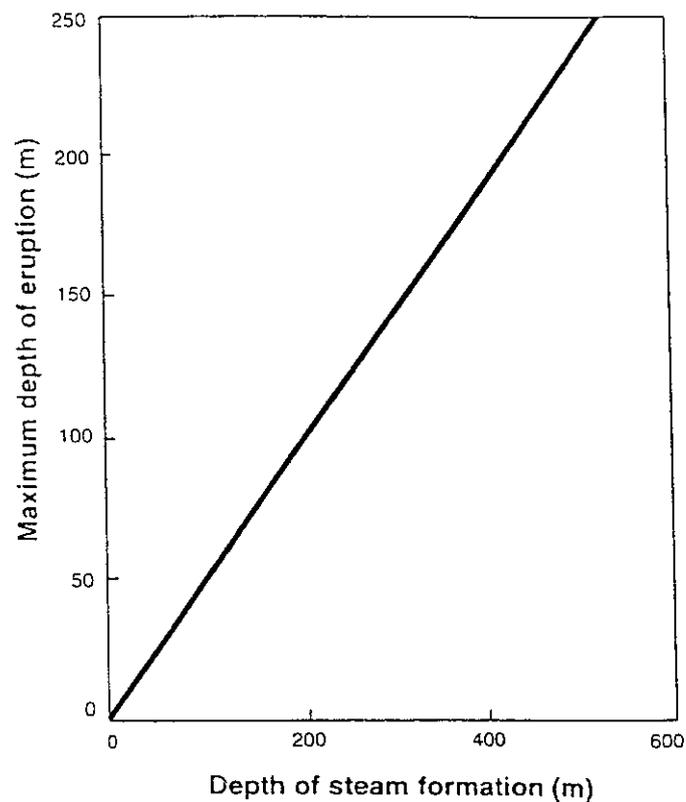


Figure 5.6 Depth of possible eruption focus due to lithostatic unroofing based upon depth of steam generation. (From Browne and Lawless, 2001).

Karapiti Blowholes ("Craters of the Moon") at Wairakei are a good example of hydrothermal eruptions induced by the sudden onset of boiling conditions caused directly by human exploitation of the Wairakei geothermal field. That has led to a pressure reduction of about 2 MPa (20 bars gauge, or 280 psi) in the geothermal aquifer, which continues to date.

5.4.2 Meteorological Changes

It has been recognised that HEs can be initiated by progressive or sudden changes in meteorological conditions, especially abnormal falls and sudden replenishments of groundwater levels due to unusual rainfall patterns (Mongillo and Allis, 1988; Bromley, 2001). Ongoing studies at Wairakei geothermal field have shown how HE events at Karapiti (Craters of the Moon) have been related to episodes of dry weather and lowered groundwater levels, followed by either a sudden high rainfall event or a low air pressure system passing over the central North Island.

In the RGF it has been recognised that periods of unusually high and intense rainfall, at rates of double to treble the monthly average rainfall, have been periods when unusual hot spring activity is most likely (Fig. 5.7; Kissling, 2000). Hot spring and geyser activity has been shown to sometimes respond to varying air pressures, when the spring feeder pressure is weak enough to be responsive to air pressure changes. At Whakarewarewa, Okianga geyser has been found to erupt more frequently during low air pressures (Cody and Simpson, 1985) and at Orakeikorako, Wairiri geyser lengthened its dormancies during periods of increased air pressures (Allis, 1983).

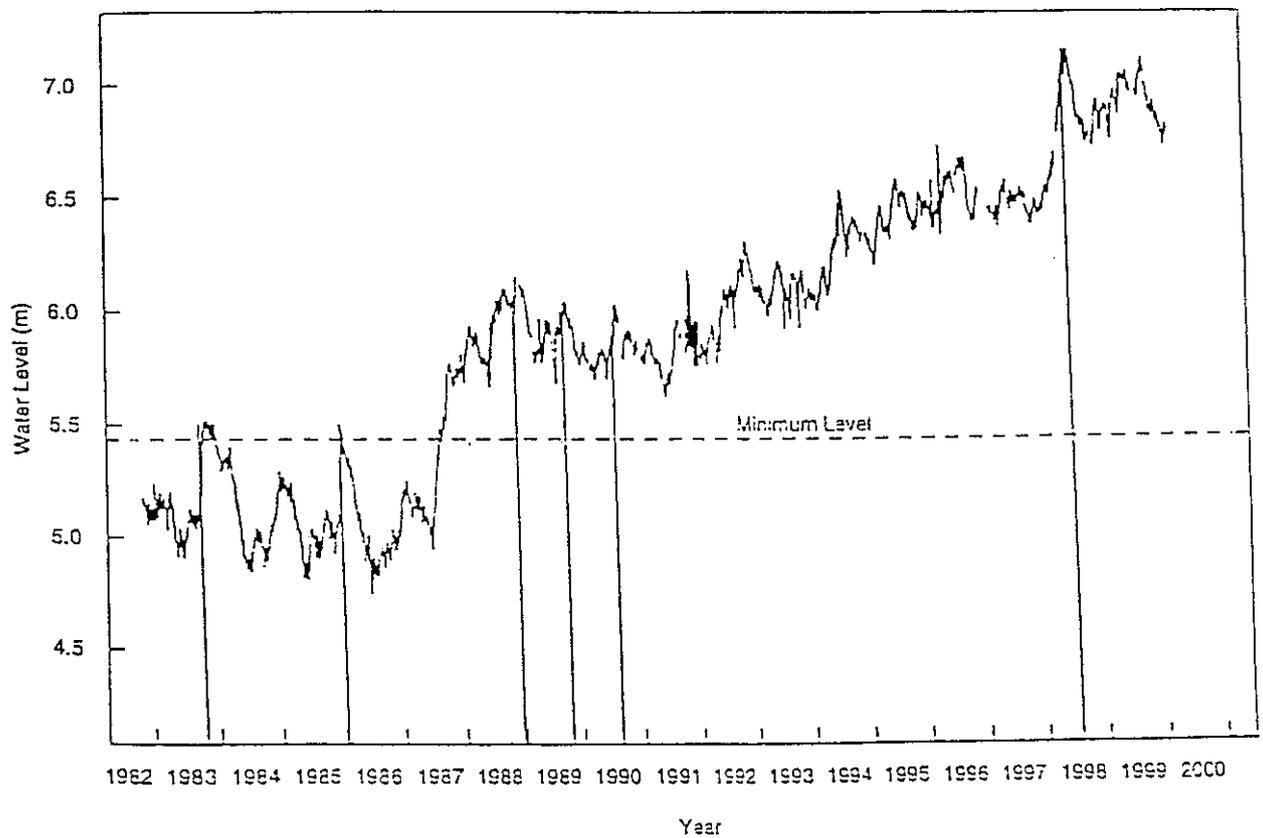


Figure 5.7 Water-level at monitor well M.12 on Pukeroa (Hospital) Hill in the RGF, showing effects of months with heavy rainfall. Barometric pressure effects have been removed. Six indicated months (vertical lines) are the only ones with rainfall greater than 250 millimetres per month since 1979. (From Kissling, 2000).

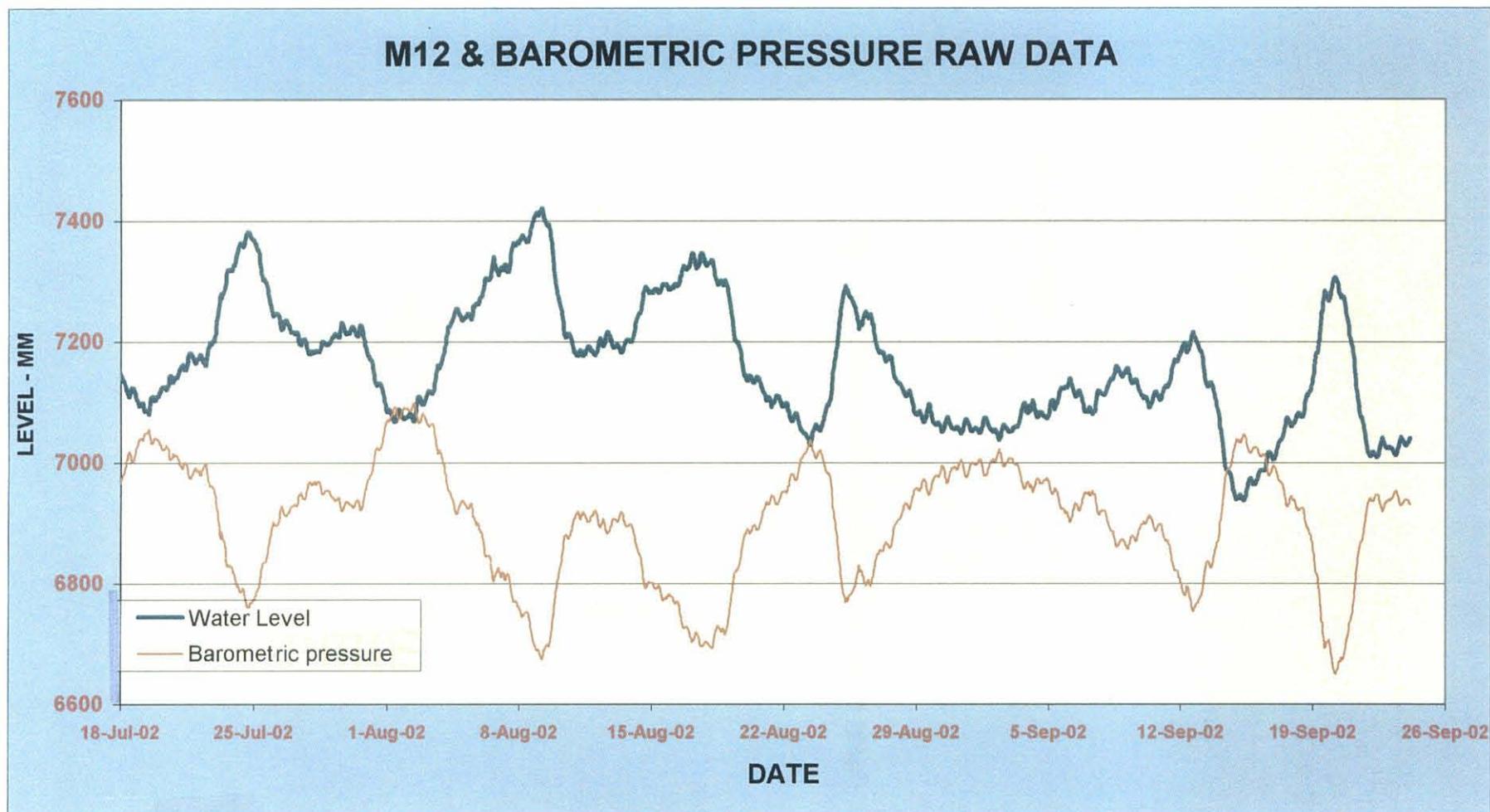


Figure 5.8 Waterlevel recording from monitor well M.12 on Pukeroa (Hospital) Hill. Air pressures for same period are also shown. Waterlevels are in millimetres above a datum origin of 0000 millimetres, which is at 278.563 metres above sealevel, or about 10 metres below ground surface. See also text Section 6.3. (Data courtesy of Environment Bay of Plenty).

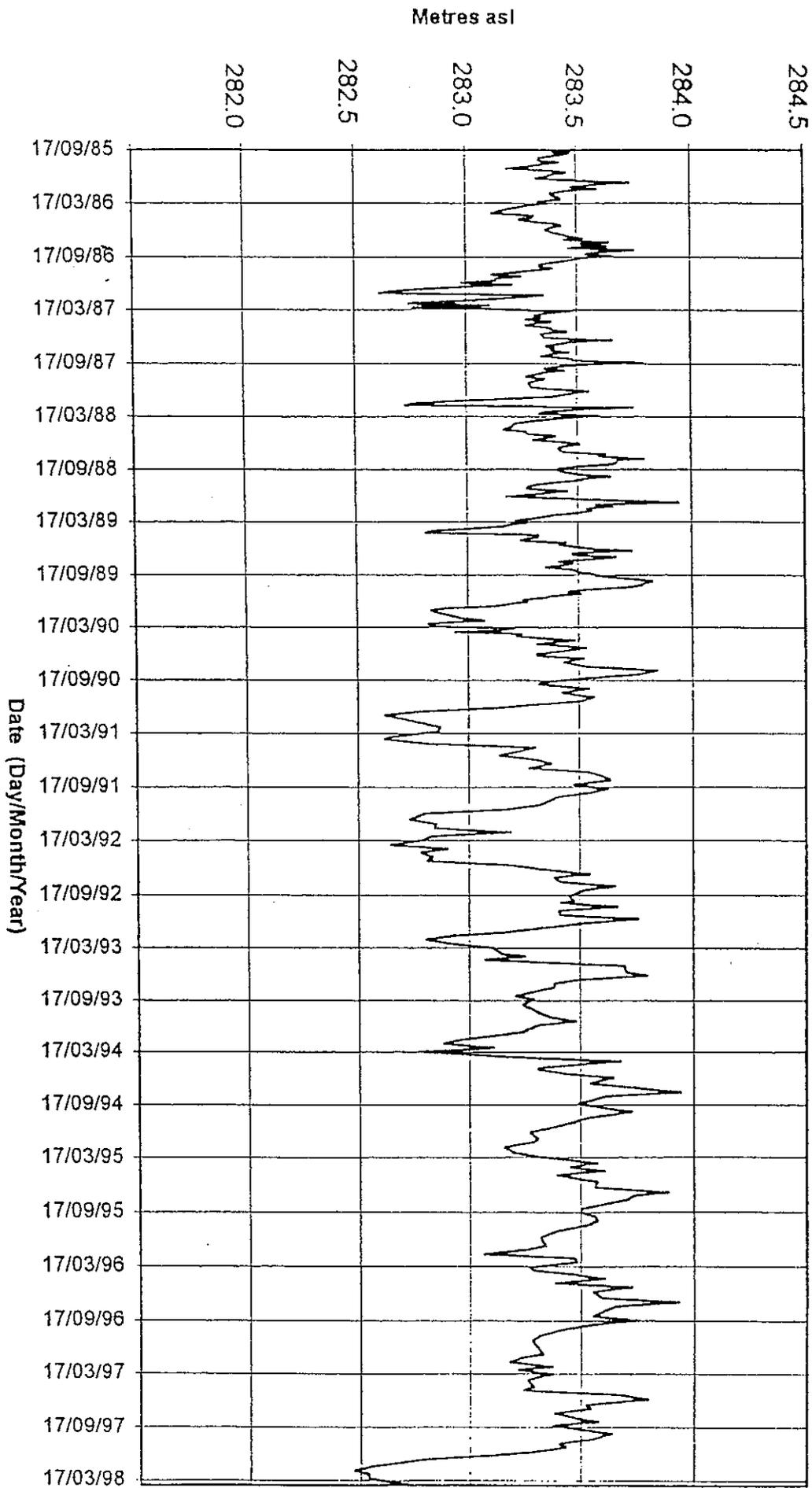


Figure 5.9 Waterlevel records from groundwater monitor well G.2 in Kuirau Park. Levels in metres above sea level.

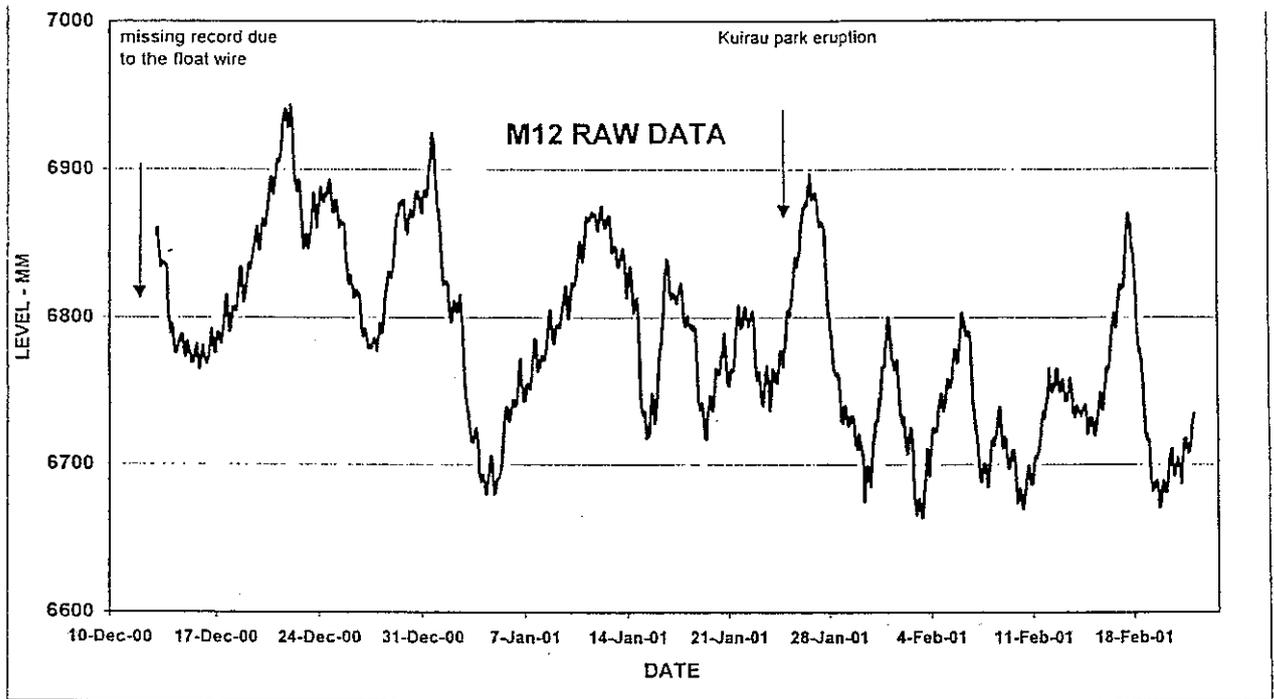


Figure 5.10a Water-level in monitor well M.12 at Pukeroa (Hospital) Hill, uncorrected for atmospheric effects. For period 10 December 2000 until 23 February 2001. (Environment Bay of Plenty).

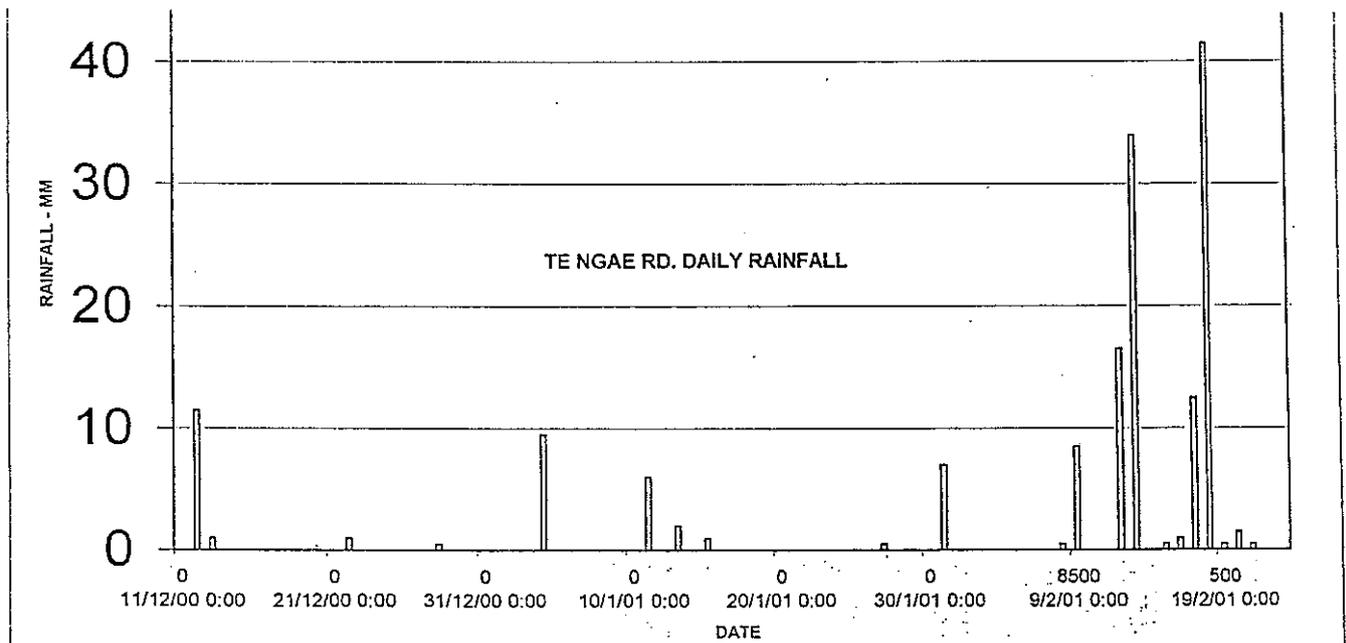


Figure 5.10b Rainfall for period 11 December 2000 until 24 February 2001 recorded at Te Ngae Road, Rotorua. (Environment Bay of Plenty).

Air pressure changes are able to induce HES by allowing the geothermal water column to lift during periods of lowered air pressure (Fig. 5.8). From studies of hot springs and well water levels in Rotorua over many years, it is now well proven that a very high efficiency (80-100%) of correlation exists between air pressure and hydrostatic levels (Kissling, 2000), with areas in the RGF showing precise and ongoing steady levels of correlation (Bradford, 1985). For monitoring and management purposes these short term variations have to be corrected for in order to detect any underlying changes, but in considering the initiation of HES, this change of water level due to air pressure effects is a proven phenomenon in many geothermal areas.

A low pressure cyclonic air pressure system crossing over the North Island of New Zealand can provide sufficient change of air pressure to induce an HE. A sudden change of up to about 50 hectopascals (hPa; about 980 –1030 hPa or 5 kPa) can occur within a few hours. A 5 kPa pressure change in a hot spring area with a 100% efficiency of correlation equates to a surface water level change of 0.5 metres and is consistent with observed levels for many hot springs. This amount of change is sometimes sufficient to act as a trigger for an HE by inducing sudden boiling conditions, with a consequent hydrothermal eruption.

5.4.3 Human Induced Changes

Of particular relevance to the Rotorua Geothermal Field are three possible mechanisms which might induce hydrothermal eruptions as a consequence of human activity and which may have already occurred in historical and modern times. These are:

- 1). Lowering of groundwater tables following accelerated groundwater runoff due to the removal of any vegetation; deliberate drainage of any perched

groundwaters; or reduction of groundwater recharge due to urbanisation processes, such as the collection and piping of rainwater and the paving and sealing of surfaces for roads and parking.

2). Excessive drawoff from the geothermal aquifer, without any comparable reinjection of used fluids. This activity frequently leads to a lowering of aquifer pressures, which in turn may allow boiling to occur beneath the ground surface (Fig. 5.2). Cooling of any underground boiling zones by any use of downhole heat exchangers (DHEs) could also collapse boiling and propagate a low pressure effect.

3). Any change (particularly any lowering) in water levels of Lake Rotorua, as this appears to be a major control upon water levels in the geothermal aquifer of the Rotorua geothermal field.

5.4.4 Groundwater Fluctuations

At Karapiti (“Craters of the Moon”) in the Wairakei geothermal field, HEs occur about annually and have been correlated with periods of sudden rainfall following several months of very low rainfall, so that ground waters have been lowered and increased ground heating can occur (Bromley, 2001). Sudden influx of waters is then flashed to steam through unconsolidated ground materials to produce violent eruptions. In the RGF this mechanism has not been conclusively seen as yet, but may be a possible contributory situation.

Groundwaters in the RGF show marked seasonal fluctuations (Fig. 5.9), with low levels common in summer months. The geothermal aquifer water level recorded in monitor well M.12 by Kuirau Park and rainfalls around the time of the HE of S721 on 26 January 2001 is shown in Fig. 5.10a.

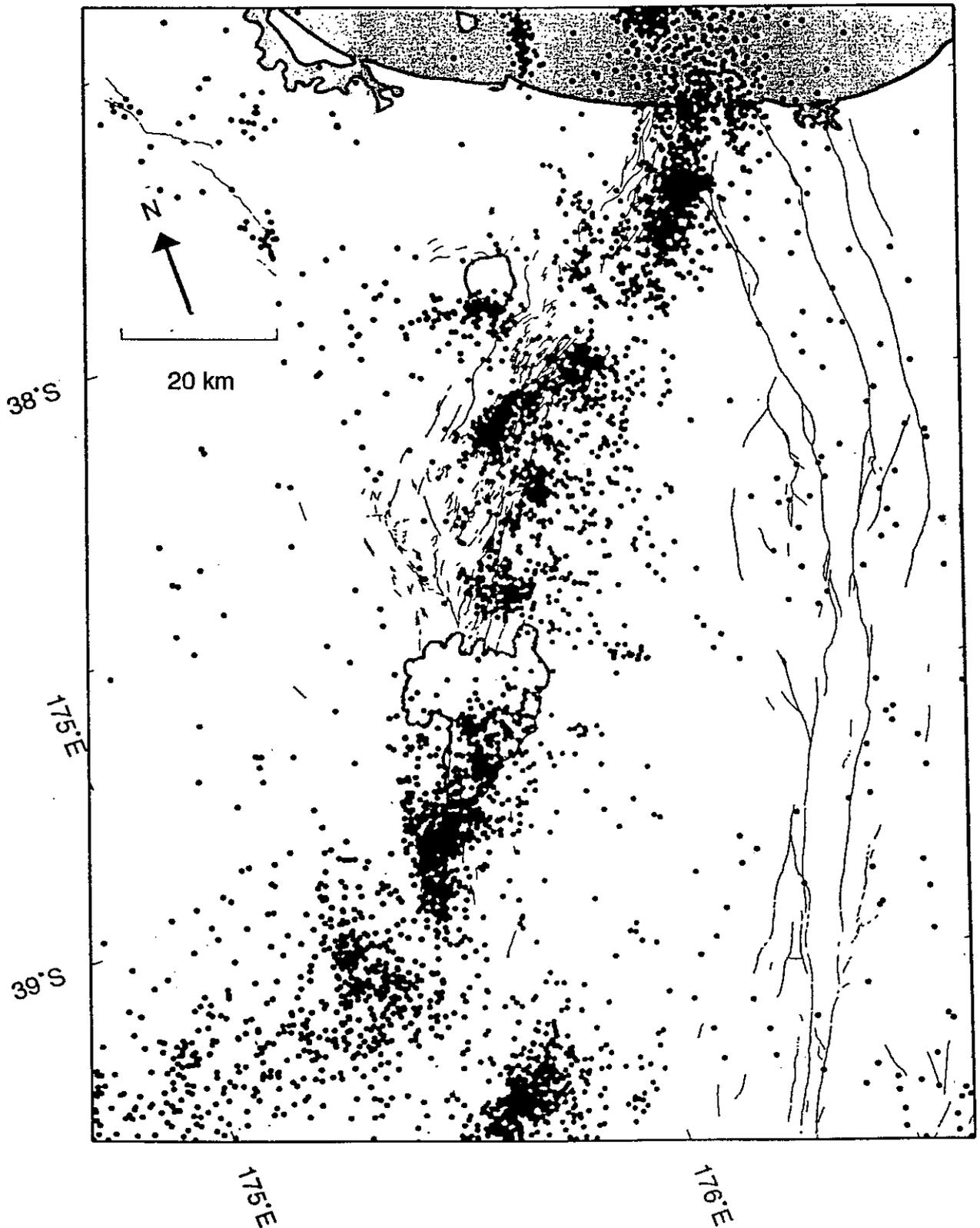


Figure 5.11 Epicentres of shallow earthquakes in the TVZ between 1987-1994. Of these, >80% of all recorded earthquakes had hypocentres <6 km deep and none were >10 km depth. Note how RGF is seismically active, whereas Reporoa caldera and Mount Tarawera are both aseismic. Lakes Taupo and Rotorua are shown for reference. (Data from Bryan, et al, 1999).

5.4.5 Seismicity

It has been recognised in New Zealand and overseas that ground shaking during earthquakes can cause changes to surface activity in geothermal systems. At Whakarewarewa, Geyser Flat has ruptured on several occasions in recent decades immediately following locally centred earthquakes and its rupture on 10 June 1886 created Prince of Wales Feathers geyser, that today is one of the most dependable and frequently active of all Rotorua geysers (Cody and Lumb, 1992). At Orakeikorako, the cessation of Wairiri geyser activity in June 1983 was attributed to earthquake shaking following swarms in the Taupo region, some of which were felt at Orakeikorako (Allis, 1983).

In the Taupo Volcanic Zone, earthquake activity is extensional and this can open fissures, joints and faults to allow diversion of water flow paths or the sudden fall of geothermal aquifer pressures as fluids suddenly migrate into newly opened voids and fissures. Any such leakage towards the ground surface can then lower pressures to a point at which boiling conditions may then develop.

Shallow (<20 km deep) earthquakes recorded in the TVZ during 1987-1994 (Bryan, et al., 1999) are plotted in Fig. 5.11 and illustrate the concentration of these along the TVZ and also the ongoing seismicity in the RGF.

Earthquakes occurring <10 km deep and within 11 km of Pohutu geyser during 1998 are shown in Fig. 5.12. This seismicity may have induced renewed waterlevel rises in the RGF (Fig. 5.7) that began in early 1998 and were followed within weeks and months by eruptions from long dormant hot springs in Tarewa Road.

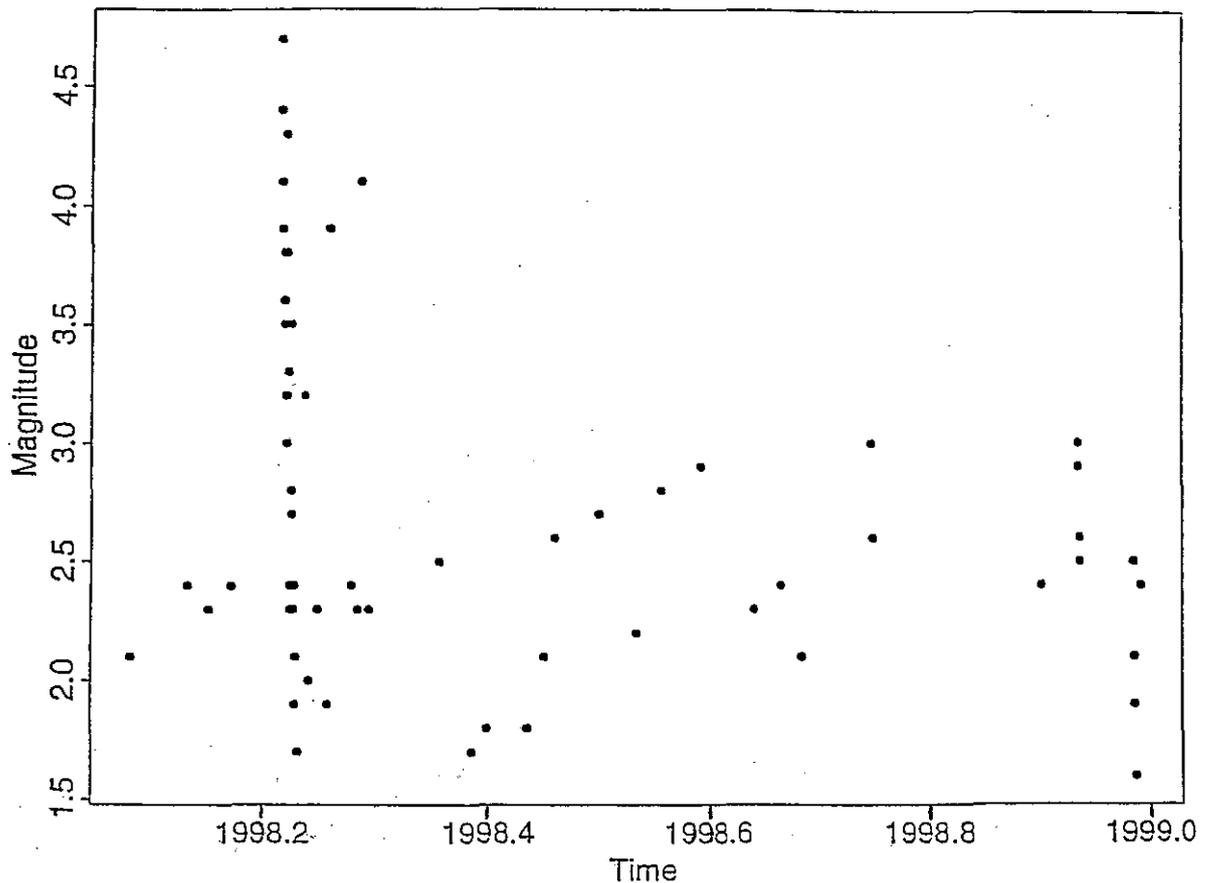


Figure 5.12 Plot showing magnitudes of 73 earthquakes which occurred <10 km deep and within 11 km of Pohutu geyser during 1998 (Bryan, et al., 1999). The swarm on 25 March consisted of 31 earthquakes and was centred 8 km south east of Pohutu geyser (Kissling, 2000).

On Saturday 20th January 2001, swarms of earthquakes were felt in Rotorua city. Most occurred during ~1100 hrs to >1500 hrs NZDT. Strengths were magnitude ML <3.2 and all within <5 km radius of the CBD and <1 km deep (IGNS; Daily Post, Mon. 22nd and Tues. 23rd January 2001). This swarm was strongly felt in Rotorua by virtually everyone (AD Cody Fieldbook -26).

It is postulated that these earthquakes may have caused movement on the Kuirau Fault (Fig. 3.30). Deeper hot waters then either moved upwards, or else boiling began due to pressure drop. Several days later this culminated in the hydrothermal eruption from spring S721, on 26th January 2001.

*If an elderly but distinguished scientist says that something is possible,
He is almost certainly right; but if he says that it is impossible he is
almost certainly wrong*

- Arthur C. Clarke

Chapter 6:

DISCUSSION OF HYDROTHERMAL ERUPTIONS

6.1 INTRODUCTION

Hydrothermal eruptions have occurred in almost every geothermal system in New Zealand, with multiple events in many of these. While these events are infrequent in comparison to human lifespans, it is considered that HEs are a commonly occurring primary vent opening process by which most flowing hot springs are created in geothermal systems, both in New Zealand and overseas.

These may occur anywhere that temperatures near to BPD conditions exist at near to ground surface. Usually some external triggering mechanism is required to initiate onset of the eruption. If all blowouts, ground collapses and pipe ruptures relating to geothermal wells are excluded, then all other hydrothermal eruptions known in historical and modern times can be plotted spatially on maps to indicate areas within Rotorua city which are at high risk for such events.

Some detailed descriptions of HEs that occurred during the 1980s are given by Cody and Simpson (1985). A discussion of HEs in the RGF and their frequencies in the RGF (Fig. 6.1) is also given by Scott and Cody (2000). Looking at these in time, it appears as though an unnaturally high number of hydrothermal eruptions have occurred in the 1960s-1980s period. These appear to correlate well with a period when the RGF underwent a progressive drawdown in pressures and water-levels, prior to 1987 when managed controls on the total withdrawal quantities of fluids and the reinjection of wastes was required.

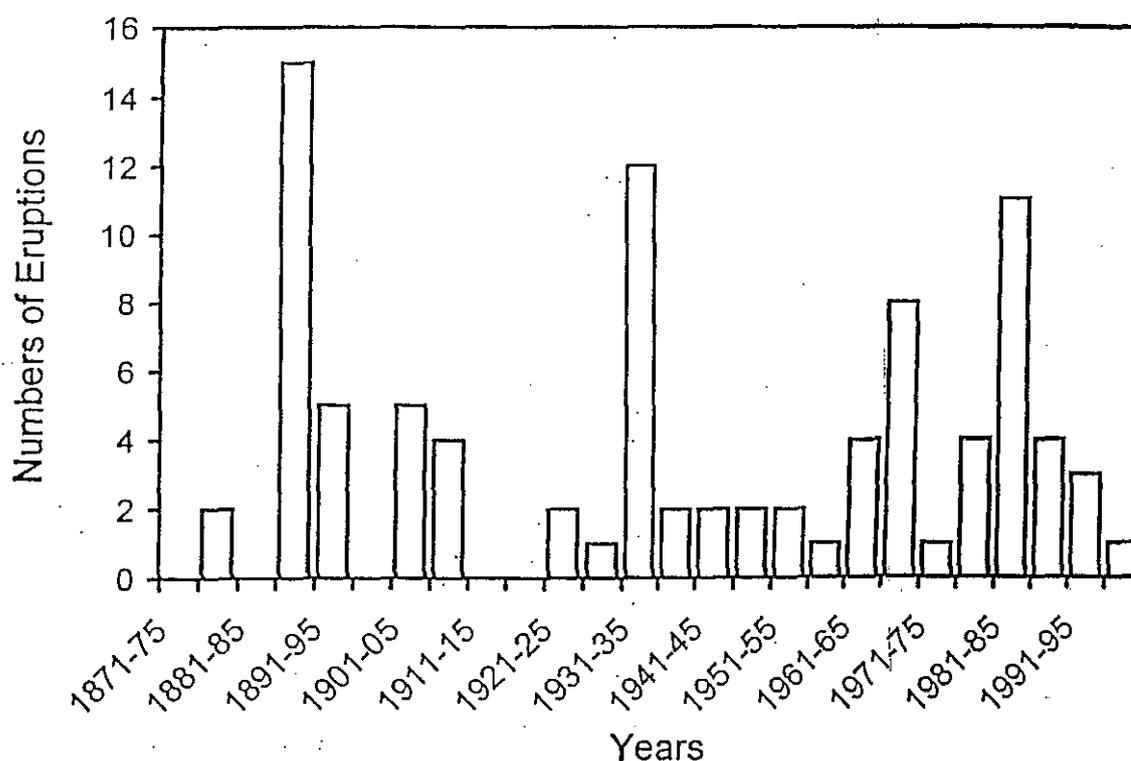


Figure 6.1 Time series plot showing occurrence and frequency of hydrothermal eruptions in the RGF through historical time. (From Scott and Cody, 2000).

The historical record of HEs in the RGF will be incomplete and may provide a biased impression of their frequency. However, the 1960s to 1980s was a period of pressure reduction and water-level drawdown in the RGF, in the order of about 50 KPa or 0.5 bars, equal to 5 m water-level fall. This period was also coincident with an apparently unnaturally high number of hydrothermal eruptions. This is an expected response, as falling geothermal aquifer pressures allow a greater extent of boiling to occur.

Potential hazards posed by HEs in the urban areas of Rotorua city have not been addressed in this study. However, Bromley and Mongillo (1994) give an outline of information significant to an assessment and mitigation of hydrothermal eruptions in any geothermal field. Their key findings require collation of the following information:

- Evidence of any previous hydrothermal eruptions in area to be assessed;
- Any increased steamflow to surface following pressure drawdown in deep geothermal aquifers;
- Presence of vigorous or superheated steam emission, in the location of uncompacted low density ground formations;
- Near surface aquifer temperatures close to boiling point for depth conditions (Figure 6.2);
- Near surface aquacludes; e.g. silica cements, clays, mudstones;
- Fluctuating groundwater levels; e.g. from rainfall variations or draining of lakes;
- Reduction in lithostatic loads by removal of overburden; and
- Shallow gas pockets, kicks or blowouts during any drilling of wells.

(From Bromley and Mongillo, 1994). Any process that causes disturbance to a delicate balance of boiling or nearly boiling shallow aquifers can upset conditions so that sudden eruptive boiling can develop through unconsolidated ground.

6.2 SIGNIFICANCE OF HYDROTHERMAL ERUPTIONS

In any developing or waxing geothermal field where temperatures and pressures are increasing, hydrothermal eruptions may be the single most important or primary mechanism by which new flowing springs and geysers develop surface vents. By a variety of possible mechanisms (e.g. Lloyd, 1959; Allis, 1984; Hedenquist and Henley, 1985; Nelson and Giles, 1985), overpressures are developed in the near surface environment, which upon suitable triggering may lead to sudden eruption through to the ground surface.

Many geothermal fields have evidence showing that hydrothermal eruptions have occurred during their history, although only larger events have left geological evidence. In New Zealand, such occurrences in prehistoric time have been identified at: Whakarewarewa (Lloyd, 1975); Kawerau (Nairn and Wiradiradja, 1980); Waiotapu (Lloyd, 1959; Hedenquist and Henley, 1985); and Orakeikorako (Lloyd, 1972). In the Utuhina Valley, at least two eruption breccias were discovered by the author, although they have not yet been described. They are considered to be older than 13.5 ka but younger than 26.5 ka.

Likewise, at least two other previously unrecognised and undocumented HE breccias are present in Rotorua city, one at Ohinemutu (adjoining Howard Morrison's property) and the other (possibly two?) at Sulphur Bay, where they form the conspicuous embayments from Sulphur and Rocky Points westward to the Bath House and Polynesian Pools. This western shoreline exposes eruption breccias that overlie muds derived from erosion and subsequent lacustrine deposition of the 26.5 ka Oruanui Formation, with 13.5 ka Rotorua Pyroclastics on top.

In historical and recent times, hydrothermal eruptions have been observed in Rotorua at Ngapuna, in the vicinity of the Puarenga Stream mouth (Allen, 1894;

Jaggard, 1932); as well as at Tauhara (Scott and Cody, 1982); Wairakei (Allis, 1984); and at Waimangu (Morgan, 1917; Lloyd and Keam, 1974). It seems probable that many other much smaller eruptions have occurred in most New Zealand geothermal fields in prehistorical times, but have not left evidence recognisable today.

At Whakarewarewa, Lloyd (1975) considers that terraces cut into the older lake terrace are the result of a high stand of Lake Rotorua. However, the water cut terrace may also have been created by a meandering of the Puarenga Stream prior to it downcutting its bed as deep as the present day, and not only by a high stand of Lake Rotorua, so the lake need not be involved.

Fluvial gravels and sands containing reworked Rotorua Pyroclastics pumice gravels are deposited on this intermediate terrace, indicating it has been crossed by the Puarenga Stream after deposition of the HE breccia. It is conjectured here that the stream also persisted about that level after the breccia deposition. This HE breccia is also one of at least two separate deposits. One occurred before Rotoiti Pyroclastics and the second, from Ngawha Crater, is >13.5 ka but <26.5 ka in age.

Varying intensity of geothermal alteration and devitrification of silica glass shards and cements, together with varying thicknesses of HE breccias all suggest that more than one single HE event has been preserved at Whakarewarewa. The HE origins of Te Puhunga and Whakarewarewa Hills predated Rotoiti Pyroclastics 65 ka BP and the second, from Ngawha Crater, postdates 26.5 ka BP.

6.3 PREDICTIONS OF FUTURE FREQUENCIES OF HYDROTHERMAL ERUPTIONS

Based upon historical records of HE occurrences and the frequency of these events in the RGF to date, some indication of the future frequency of such HEs is deduced. Even quite small perturbations to the geothermal system have produced spectacular HEs in historical and modern times. Therefore any changes to the RGF that varies upflow pathways or flowrates of geothermal fluids to the surface are likely to initiate further HEs.

Earthquakes which produce ground shaking of MM VI and above in the RGF are probable precursors to an HE occurring in areas where temperature profiles into the ground are already close to or at BPD conditions. Although some faults are mapped and others inferred to exist within the RGF, others may be present that are yet to be discovered. Fault movements in the RGF and the TVZ as a whole are extensional normal faults (Rowland and Sibson, 2001), which open scarps and allow new or rejuvenated upflows of hot fluids. This is probably what happened on 26 January 2001 as a result of an earthquake swarm centred within the RGF on 20 January 2001 (GNS records).

Resumption of volcanism anywhere in the TVZ and especially in the Okataina or Rotorua volcanic centres will most likely initiate HE events in the RGF. It also appears probable that human induced pressure disturbances in the RGF have directly led to HEs in the past, for example the drawdown of geothermal aquifer pressure during the twentieth century up until the 1980s by about 0.5 bars pressure (Mahon, 1985) coincides closely with an increased frequency of small but damaging HE events.

Meteorological extremes of rainfall, either as an excess or a lack of, may alter groundwater levels and hence change hydrostatic loading on the geothermal aquifer beneath. This type of fluctuation is considered to be the primary cause of HEs at Karapiti (Craters of the Moon) at Wairakei (Bromley, 2001).

Using the historical record of HE event frequency (Fig. 6.1; Scott and Cody, 2000) an average return time of about one event per year is typical in the RGF. These have been confined to the areas of known BPD conditions close to or at the surface, (see Map 1, Map Pocket, where surface geothermal activity is shown).

Kuirau Park has an ongoing history of HE events, with deposits of prehistorical HEs found there also. The concentration of HE deposits at Kuirau Park coincides with an area of geothermal upflows and a land surface close to ground water levels. Two faults are postulated to cross Kuirau Park and both of these are associated with widespread silica sinters and flowing hot springs. Geology and temperatures here are shown in Figure 6.2, with spring sites shown in Map 3.

6.4 SPATIAL AND TEMPORAL TRENDS

HEs occur almost exclusively at Ohinemutu and Kuirau Park in the northwest; the delta of the Puarenga Stream; the western and southern shorelines of Sulphur Bay; and in Whakarewarewa and Arikikapakapa, all of which have had many HEs in prehistorical and modern times. Surface evidence such as breccias or raised mounds of ground surrounding pools and depressions occur throughout the RGF, although these deposits are most likely to under represent all such eruption events in the RGF.

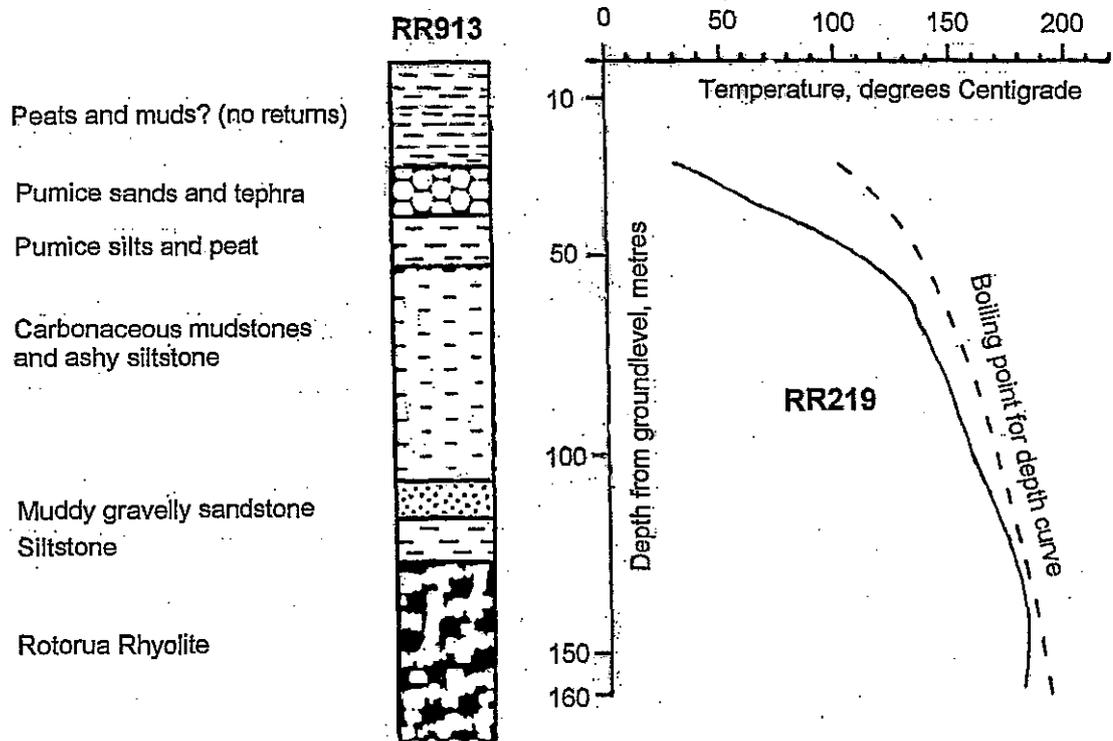


Figure 6.2 Geology from well RR913 and temperature profile in well RR219 (run T2034). Both wells are close to a feeder fault. See Map 3, Map Pocket, for well locations. (From Wood, 1992).

6.5 AGES OF PREHISTORICAL BRECCIAS

In the RGF, several breccias of prehistorical age are preserved to the present day. At Ngawha Crater in Whakarewarewa, Lloyd (1975) assigned an age to this breccia of Rotoiti Pyroclastics (65 ka) because the breccia had been laid upon a terrace later cut by what he described as a high stand of Lake Rotorua. However, this breccia is intensely thermally altered and is present on the north side of the Puarenga Stream only as an iron stained pug of mottled red, purple and ochre brown colouration. It is considered here to be sourced from the breccias of Te Puhunga and Whakarewarewa Hills and not from Ngawha Crater, which has a much less weathered and decomposed breccia. Lloyd did not recognise two distinct HE breccias at Whakarewarewa and assigned all breccias preserved there to a single event and source.

6.6 PRESERVATION OF BRECCIAS

Knowledge of HE events in the RGF is presently known largely from historical records and a very few preserved breccia deposits. The near surface ground materials in the RGF are lake silts and muds, intercalated with airfall tephra and occasional lakeshore and stream sands and gravels. Therefore the materials through which HEs develop is generally unconsolidated and easily excavated by the sudden onset of boiling conditions during an HE. Only rarely have these erupted materials been silicified prior to eruption and emplacement as surface breccias, yet it is only by cementation that these breccias can resist erosion and surface weathering effects. Generally breccias of unconsolidated materials rapidly weather and disperse to become incorporated into soil or acid ground development, so that they can no longer be positively identified as an HE breccia deposit.

Urbanisation and various human activities and processes have also severely modified and destroyed some HE breccias that had been preserved by silicification prior to their eruption. At Ohinemutu, boulders of silicified breccia up to about 1 m diameter have been removed and lost as recently as the early 1990s.

In Kuirau Park, the breccia deposit from the 26 January 2001 eruption of spring S721 has been preserved by the Rotorua District Council, with a fence excluding access to general visitors. However, this deposit is undergoing rapid slaking and exfoliation of its clasts, so that it is unlikely to leave any identifiable deposit for preservation in the geological record. Instead it will become incorporated into the acidic and leached soils as a thin layer several centimetres thick of a white to pale grey silt of silica, indistinguishable from a water deposited silt. Its HE origin will not be recognisable after a few years and so its mode of formation will not be recognised by study of its remains.

In nature there are no rewards or punishments; there are consequences

- Horace Annesley-Vachell (The Face of Clay)

Chapter 7:

CONCLUSIONS

This study was made with three main aims: (1) to record all hydrothermal eruption sites in the RGF, (2) to identify the ages of HE breccias and correlate these, if possible, with local volcanism or changes of water-level in Lake Rotorua, and (3) to identify possible triggers of HEs.

These aims may offer useful information and knowledge to statutory authorities and emergency services which may assist them in the mitigation or avoidance of the consequences of future HEs. This chapter summarises findings and briefly discusses conclusions with respect to these aims.

7.1 AIM ONE - RECORD ALL HE SITES IN RGF

A thorough review of much historical material has been made and compiled into the summary given in Appendices 4, 5 and 6. Every published issue of New Zealand Herald and Bay of Plenty Times have been searched, as well as all known issues of Rotorua newspapers. Many early books, travel guides and diaries, etc., have also been examined and information about geothermal events in Rotorua have been obtained from many museums throughout New Zealand. Some early accounts of geothermal phenomena are of insufficient detail or description to precisely identify any particular spring or feature, although in many instances this can be done.

7.2 AIM TWO - IDENTIFY AGES OF HE BRECCIAS AND CORRELATE WITH LOCAL VOLCANISM AND LAKELEVELS

The few preserved HE breccias of prehistoric origins have been studied to identify ages and possible relationships to volcanism and waterlevel changes in Lake Rotorua. At Ohinemutu, the silicified breccia at Ouru is underlain by subaerial pumice gravels of the Rotorua Pyroclastics which are dated at 13.5 ka. Lake silts overlie the breccia and were deposited during a high stand of Lake Rotorua at about 290 m asl, which correlates with the Rotoma eruptive episodes of Okataina volcanic centre at 9.5 ka.

Because silica sinters were later deposited over the breccia and preserved it, the presence of a flowing alkaline hot spring at an elevation above that of the breccia is confirmed as once having occurred near there. The HE is therefore considered to have occurred during the high stand of Lake Rotorua soon after 9.5 ka and cannot predate 13.5 ka.

The HE breccia at Whangapipiro (Crater) Bay predates the 13.5 ka Rotorua Pyroclastics pumice airfall, which overlies the breccia. Here too, a hot flowing alkaline spring close by has laid down silica sinters over the pumice gravels and breccia. To lift the elevation of a hot spring requires a rise of neighbouring cold groundwaters to buoyantly lift the fluids. Therefore the hot spring was formed after deposition of the breccia and the Rotorua Pyroclastics tephra. This elevation of the hot spring is considered to have occurred after the Rotoma eruptive episode of 9.5 ka.

The silt underlying the breccia has affinities that are inferred to be of a lacustrine mud derived by erosional reworking of Oruanui Formation pyroclastics (26.5 ka) erupted out of Taupo. The HE breccia at Whangapipiro Bay is therefore deduced

as being post 26.5 ka and pre 13.5 ka in age and it may have incorporated older breccias from the same site.

The HE breccias at Whakarewarewa are considered to represent at least two episodes of HEs there, with a wide time interval between so that thorough and intense weathering and alteration of most diagnostic rock forming minerals has occurred to the older unit. Accretionary lapilli are incorporated into breccias at Ouru, Kuirau Park and Whakarewarewa yet nowhere do these have internal grain sizes or diameters at all similar to those of the Rotoitit Pyroclastics (65 ka) deposited upstream in the Puarenga Valley. Instead they are visually closely similar to those of the widespread Oruanui Formation pyroclastics that outcrop in Arikikapakapa and in shallow excavations throughout Rotorua city.

7.3 AIM THREE - IDENTIFY POSSIBLE TRIGGERING MECHANISMS

The HE at Ouru of c. 9.5 ka is considered to have been initiated by the hydraulic lifting of geothermal fluids associated with the elevation and high stand of the surrounding cold lake waters following the Rotoma eruptive episode. At Whangapiro (Crater) Bay, the triggering mechanism is not clearly recognised. However, because the HE breccia is directly overlying Oruanui Formation silts, it may be associated with falling levels of Lake Rotorua and hence a depressuring of the geothermal aquifer so that boiling conditions may have been induced.

At Whakarewarewa, the Ngawha Crater beccia is considered to be post 26.5 ka and pre 13.5 ka in age due to the presence of underlying Oruanui Formation and overlying Rotorua Pyroclastics. Falling levels of Lake Rotorua are considered to have reduced geothermal aquifer pressures and induced boiling conditions, which could not be contained by poorly consolidated shallow ground.

The earlier breccia unit may have been associated with lake-level changes about the time of Rotoiti Pyroclastics eruption at 65 ka.

From modern day observations and study it is known that geothermal waterlevels respond to short term air pressure and groundwater changes. Some observed HEs in RGF and at Wairakei appear to have been triggered by a sudden fall of air pressure accompanying the rapid passage of cyclonic weather systems across the North Island of New Zealand. Hot springs and geothermal waters are often buoyantly lifted by high groundwaters following increased or intense rainfall episodes.

Surrounding ground then becomes heated with outflow and percolation of the hot waters and where heating occurs to within a few degrees of boiling point, the sudden onset of a low air pressure system can induce boiling conditions. If the ground is only weakly consolidated, a hydrothermal eruption can then occur. Similarly, in times of prolonged rainfall deficit and falling groundwaters, high steam upflows can heat ground close to boiling point. Any subsequent rainfall episode then provides an influx of groundwater that is suddenly flashed to steam.

7.4 FUTURE RESEARCH

More detailed study of existing hydrothermal eruption breccias could define the ages of these deposits more precisely and therefore allow possible correlation to other local events that might be associated with triggering mechanisms.

Trace element analyses of glass shards within breccias may allow parent materials to be identified, or at least sourced to either the Okataina or Taupo volcanic centres, which in turn would allow likely identification of those tephras and pyroclastics.

The Whakarewarewa breccias are intensely altered and at least two suites are recognised, the Ngawha Crater breccia overlying the older and more intensely altered Te Puhunga-Whakarewarewa Hill breccias. Further and more detailed description and study of these may offer new insights to their ages and origins.

Rates and degree of devitrification in volcanoclastic glass shards and hot spring sinters may also provide better constraints on ageing of these deposits.

Nature is often hidden; sometimes overcome; seldom extinguished

- Francis Bacon (Essays)

Chapter 8:

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*Discovery consists of seeing what everybody else has seen and
thinking what nobody else has thought*

– Albert Szent-Gyorgyi (in I.J. Good – The Scientist Speculates)

APPENDIX I:

**Field and Waikato University Sample
Numbers and Locations**

The following table lists field sample numbers used in this thesis. Samples that have been assigned a Waikato number are retained by the Department of Earth Sciences, University of Waikato. Grid references (GR) relate to the NZMS 260 Sheet U16 Rotorua. XRD = X-ray diffraction analyses, wh = whole sample tray mount and cl = clay separation onto glass slide. PTS = polished thin section.

Field No	Waikato No	XRD	Thin Section	Comments
Kuirau Park				GR U16 946361
S721-1	W020801	wh + cl	√	Bedded white siltstone
S721-2	W020802	wh + cl	√	White siltstone
S721-3		wh	√ + pts	Grey mud on S721-4
S721-4	W020803	wh + cl	√	Coarse sandstone
S721-5	W020804	wh + cl	√	Siltstone + accretionary lapilli
S721-6		wh		White salt on siltstone
S721-7a	W020807	wh		Sulphides in siltstone
S721-7b	W020807	wh	√	White salt on siltstone
S721-8	W020805	wh	√ + pts	Spongy sinter
S721-9	W020806	wh + cl	√	Pumice breccia
Te Puia Hill				GR U16 954324
TP001	W020808	wh + cl	√	Creamy dense siltstone clast
TP002	W020809	wh + cl	√	Accretionary lapilli siltstone
TP003	W020810	wh + cl	√	Rhyolite gravel clast
TP004	W020811	wh + cl		Soft light brown siltstone
TP005	W020812			Silicified mottled sandstone
TP006	W020813	wh + cl	√	Silicified banded sandstone
TP007	W020814	wh + cl		Brown ignimbrite clast
TP008	W020815	wh	√	Dense grey veins in siltstone
TP009	W020816	wh	√	Hard silicified sinter clast
TP010	W020817	wh	√	Ignimbrite clast
TP011	W020818		√	Rhyolite clast
TP012	W020819		√	Silicified rhyolite clast
TP013	W020820		√	Dark silicified sandstone

Field No:	Waikato No:	XRD:	Thin Section	Comment:
Ouru, Ohinemutu				GR U16 948364
O.001	W020821		√	Accretionary lapilli siltstone
O.002	W020822		√	Light brown sandstone
O.003	W020823	wh		Silicified white clast
O.004	W020824	wh + cl	√	Mottled porous sandstone
O.005	W020825	wh + cl	√	Light brown sandstone
O.006	W020826	wh		Cemented pumice gravel
O.007	W020827	wh		White infilled pumice clast
O.008a	W020828	wh	√	Bedded light brown siltstone
O.008b	W020829	wh + cl	√	Sinter layer on siltstone
O.009	W020830	wh + cl	√	Dark grey sinter band
O.010	W020831		√	Grey rhyolite and pumices
O.011	W020832		√	Dense bedded sandstone
O.012	W020833	wh + cl	√	Porous sinter clast
O.013	W020834	wh + cl	√	Ignimbrite clast
Sulphur Bay, F184:				GR U16 958355
1a.001	W020835	wh + cl		Silicified sandstone clast
1a.002	W020836	wh + cl		Silicified white siltstone
1a.003	W020837	wh + cl		Banded sand-siltstone
1a.004	W020838	wh + cl	√	Sandstone with mud clasts
1a.005	W020839	wh + cl		Pumice sandstone clast
1a.006	W020840	wh + cl	√	Infilled pumice clast
1a.007	W020841	wh + cl	√	Silicified sandstone clast
1a.008	W020842		√	Large pumice clast
F184.1a	W020843	wh + cl		Large silicified grey clast
F184.1c	W020844	wh + cl	√	Pumice gravel conglomerate
2.001	W020845		√	Mudstone clast and matrix
2.002		wh + cl	√	Soft light brown mudstone
2.003	W020846	wh + cl	√	Sandstone clast
2.004		wh + cl		Firm light brown siltstone
3.001		wh + cl		Soft thixotropic mud
F184.1a	W020847			Clasts and matrix

I like terra firma – the more firma, the less terra

- George Kaufman

APPENDIX II:

Hydrothermal Eruption Inventory Numbers

All sites and geothermal features known to have had HEs are listed in numerical order by areas. Only identified features and sites are included, many others are omitted because of only vague descriptions of locality. For further details of each refer to the EBOP-RDC geothermal inventory. Fields of data recorded for each entry are as shown in the example form, Appendix 3. Locations are shown on Map 1 (Map Pocket) and also Figures 1.6 – 1.12, Chapter One.

Form Number:	Spring Number:	Name or Comments:
(a) Kuirau Park		
129	624	Soda Spring
135	615	1966 Crater
146	657	Parekaumoana
149	649	Tarewa
150	653	Tarewa Group
155	646	Parekohoru Group
156	646.1	Parekohoru Group
157	644	(Pool beside RR1039)
207	1303	
235	614	1966 Crater
239	618	east of Lobster Pool
256	632	
273	646.2	Rotoiatuhi
275	646.4	Rotoiatuhi Group
279	652	Tarewa Group
309	683	
311	684	
313	685	
344	715	Mayor's Mouth
448	1305	
1460	653.1	Tarewa Group
1461	726	

350

721

Form Number:	Spring Number:	Name or Comments:
(b) Ohinemutu		
192	1226	Great Waikite Geyser
193	1227	Porahi
194	1260	Waihunuhunukuri
197	1252	Rangihaupapa
199	1209	Waikite Group North
200	1207	Waikite Group South
211	1295	Canoe Line
369	1205	
370	1206	(below bamboo)
375?	1214	
376	1216	
390	1232	Ruapeka Bay
391	1234	Muruika Point
404	1247	
425	1273	Omarukaipua
448	1305	Hale's property
547	1314	Kahukura area

Form Number:	Spring Number:	Name or Comments:
(c) Sulphur Bay		
167		Ngapuna Haangi, 7/03/96
169		Stopbank Spring
183		Rachel (Whangapipiro)
184		Whangapipiro (Crater Bay)
502	1359	Sulphur Bay, midway
503	1360	offshore Motutara Point
514	1371	off Puarenga stream mouth
515	1372	Puarenga mouth, 1998
519	1376	Ngapuna geyser? 1973
1489		Rocky Point, March 1931
1504		Puarenga delta, 18/05/92
1505		Puarenga delta, March 2001
1506		Puarenga delta, west side

Form Number:	Spring Number:	Name or Comments:
(d) Arikikapakapa		
14	2142	large crater, now infilled
16	2032	Te Oka-a-Ngahihi
17	2033	Te Oka-a-Tunohopu
21	2051	Te Wai-a-Taiapua
23	2041	Te Turi-a-Taeatu
24	2042	Te Roto-a-Panuiomarama
30	2050	Te Roto-a-Pakiura
35	2100	Ngakuru-a-Paeahi
36	2090	Ngakuru-a-Paeahi
531	2021	alongside Awarua
548	2052	alongside Parekawa
571	2092	Tangatarua area
577	2099	beside Tangatarua
578	2101	part of Tangatarua
594	2119	near old bath (Jack's Bath)
595	2120	near old bath (Jack's Bath)
596	2121	"Old Bath" on 1925 map

Form Number:	Spring Number:	Name or Comment:
(e) Whakarewarewa		
5	262	Ngamokaiakoko
64	172	Blue Lake, Bluey
71	213	Ngawha Crater area
78	93	
81	283	Korotiotio
82	284	Parekohoru
89		Takou
90	337	Roto-a-Tamaheke
94	435	
100	952	THC Blowout, 17/12/84
101	488	Okianga
102	426	FRI pathway
105	333	Te Wai-o-te Nihotahi
119	290	Whakamanu geyser
656	228	Pohaturoa area
657	227	Pohaturoa area
658	226	Pohaturoa area
680	96	
681	97	
684	328	Rahopeke
685	460	
940	305	
1019	399	
1222	755	
1223	756	
1026	406	
1232	765	
1305	838	

APPENDIX 3:

INVENTORY OF GEOTHERMAL FEATURES		Form Number	481
Field Name	Rotorua Geothermal Field	English Name	
Spring No	1338	Maori Name	
RDC Ref			
LOCATION			
Street Number	2A	Street Name	RANOLF ST
Area Name	Pukeroa Hill	Grid Ref Northing	6335942
Map Series	NZMS 260	Grid Ref Easting	2794716
Map Sheet	U16 Rotorua	Elevation	286 (m asl)
Land Status	Reserve B		
DESCRIPTION OF FEATURE			
Physical Description	Rockpile over hot hole 1.5 dia.; Steaming		
Acid Spring	<input type="checkbox"/>	Mud Pool	<input type="checkbox"/>
Turbid Pool	<input type="checkbox"/>	Fumarole	<input type="checkbox"/>
Steaming Warm Ground	<input checked="" type="checkbox"/>	Alkaline Spring	<input type="checkbox"/>
Collapse Crater	<input checked="" type="checkbox"/>	Mud Cone	<input type="checkbox"/>
Geyser	<input type="checkbox"/>	Other Feature	
ATTRIBUTES OF FEATURE			
Water Analysis	<input type="checkbox"/>	Flowrate	<input type="checkbox"/> Measurement <input type="text"/> (LPS)
Gas Analysis	<input type="checkbox"/>	Mineral Analysis	<input type="checkbox"/>
Isotope Analysis	<input type="checkbox"/>	Temperature	<input type="checkbox"/> Measurement <input type="text"/>
Eruption Records	<input type="checkbox"/>	Radius	<input type="text"/>
		Other Attributes	
USES OF FEATURE			
Scientific	<input type="checkbox"/>	Cultural Swimming	<input type="checkbox"/>
Culture Cooking	<input type="checkbox"/>	Cultural Bleaching Flax	<input type="checkbox"/>
Recreational	<input type="checkbox"/>	Tourism	<input type="checkbox"/>
Exploration Wells	<input type="checkbox"/>	Production Wells	<input type="checkbox"/>
Water Drawoff	<input type="checkbox"/>	Energy Production	<input type="checkbox"/>
Mining	<input type="checkbox"/>	Other Uses	
THREATS TO FEATURE			
ADDITIONAL COMMENTS			
In central lawn, east side of Ranolf Street.			
REFERENCES			
Add Reference Detail		<input type="text"/>	
AD Cody (pers. obs.)			
Compiler By	A Cody & H Robertson	Date Compile	02/02/00

RGF GEOTHERMAL INVENTORY FORM

This is an example of the information that is captured with these forms. Any single field can be searched for and sorted to produce a new table.

*Discovery consists of seeing what everybody else has seen and
thinking what nobody else has thought*

– Albert Szent-Gyorgyi (in I.J. Good – The Scientist Speculates)

APPENDIX 4:

Diary of Known Hydrothermal Eruptions

The following list of hydrothermal eruptions (HEs) are given in chronological order, together with references to sources of information. Where exact locations have been identified, the Environment Bay of Plenty (EBOP) RGF database Form Number is given (e.g. F205). The earlier (pre-1991) New Zealand Geological Survey database spring number is also given where known, as much early published information quoted these identifying numbers (e.g. S529). Grid references are also given for known locations of features as a GR number (e.g. GR 2794640 mE, GR 6335895 mN; or 946359). All these features are on NZMS 260 Sheet U16 Rotorua.

The following events are those that have occurred as natural occurrences without any direct failure of man-made structures such as well casings or pipelines. Full references for these entries are given in References. Events are listed in chronological order and locations are shown on Map One and in Figures 1.6-1.12 for those which can be identified to a precise feature or site.

Information in this appendix was collated for this thesis and has never been previously either published or disseminated in any way. It is solely of hydrothermal eruptions in the Rotorua Geothermal Field (RGF) and excludes other geothermal events and phenomena described by various historical accounts, which have also been collated as part of a computer based geothermal history listed subsequently here as Appendices Five and Six.

Dates are listed as the year only, if no precise date is known. Otherwise dates are of six digits in the sequence of year, month and day, e.g. 990226 is 26 February 1999. The date of 26 February 1899 is also shown as simply 990226, but its position relative to entries before and after it will identify which century is

referred to. Nearly all natural geothermal features in the RGF have been collated into a geothermal GIS inventory held by EBOP and RDC. Features all have a Form Number (e.g. F 1520) and may also have a Spring Number (e.g. S 601). Therefore descriptions of unnamed features may refer to these solely by either the form or spring number.

1875: Kuirau Lake (S601) erupted 10-15 m high during a high waterlevel period. This lake often surged and fell markedly during 1870-1885 (Harris, 1878).

March 1877: In Lake Rotorua near Ohinemutu, a late night eruption threw mud and debris to 10 m high and roused most of the residents. It subsided almost immediately and only the crater could be found next day (Bay of Plenty Times, 3 March 1877).

c.1877: A mud hydrothermal eruption occurred at Arikikapakapa. Mud was thrown about 12m high but after a short time it disappeared and has not appeared since (pp.218-219 in Senior, 1880).

May 1879: At Okomutu, on the east bank of the Utuhina Stream in Ohinemutu, an eruption threw mud and stones about 10m high. No previous thermal activity of this nature had been known at this site (N.Z. Herald, 16 May 1879). F425? S1273? Omarukaipua area. GR 6336623mN?, 2794539mE?

1880: At Arikikapakapa a fountain of boiling black unsavoury mud had but a short time before added itself to the strange sights of the district (p.219 in Senior, 1880).

9 May 1886: In Lake Rotorua an eruption about 30m high occurred. (Evening News, 10 May 1886; East Coast Business Advocate, 10 May 1886).

20 May 1886: At Ohinemutu an eruption suddenly occurred (Waikato Times, 29 May 1886).

10 June 1886: At Ohinemutu several hydrothermal eruptions took place during the Mount Tarawera eruption around the north end of Pukeroa Hill and Lake Road (Leys, 1886; Keam, 1988).

15? July 1886: Hydrothermal eruptions described in N.Z. Herald, ~15 July 1886.

September 1890: On Little Point (Muruika) in Ohinemutu a brief eruption occurred, with material thrown 12-15 m high (N.Z. Herald, 5 September 1890). F391? S1234? GR 6336648 mN? 2794879 mE?

April 1891: In Ohinemutu a hydrothermal eruption occurred during the night in a back garden; it also erupted during the following day. (N.Z. Herald, Saturday 18 April 1891).

June 1891: Opposite the Palace Hotel in Ohinemutu, eruptions took place in a pool at the northeast end of Ohinemutu Village. (N.Z. Herald, 5 June 1891). A hydrothermal eruption also occurred near the Utuhina Bridge on the afternoon of Thursday 4 June; this erupted to about 4.5 m (15') high (N.Z. Herald, Saturday 6 June 1891). F387? S1229? GR 6336514 mN?, 2794906 mE?

27 March 1894: At Ngapuna an eruption 7-10 m high broke out. (Allen, 1894). F519, S1376, 6335100 mN, 2796600 mE.

16 April 1894: A large eruption occurred at the mouth of the Puarenga Stream. Mud and water were thrown about 100m high for about two minutes then it ceased activity, leaving a crater some 20m diameter with mud up to 1.5m deep around its edges. The ground for a radius of 40-60m was cracked and subsided towards the crater (Malfroy, 1894; Allen, 1894). F519, S1376, 6335100 mN, 2796600 mE. The beginning of 1894 was excessively wet and this swamped some springs but on the lakeshore near Ngapuna Village, several small hydrothermal eruptions occurred prior to the large one of 16 April (Malfroy, 1894).

June 1895: The same site at the mouth of the Puarenga Stream that erupted in April 1894 again erupted for about two weeks, throwing muddy debris to 30m high (Hot Lakes Chronicle, 26 June & 3 July 1895). F519, S1376, 6335100 mN, 2796600 mE.

October 1895: The Ngapuna geyser gave a single eruption to about 60 m high (Hot Lakes Chronicle, 9 October 1895). F519, S1376, 6335100 mN, 2796600 mE.

January 1896: In the Tarewa Road springs (S649-652) one of them erupted 10m high and its discharge matched that of Kuirau Lake (S601) at about 4,000,000 litres per day (N.Z. Herald, 9 January 1896). F149, S649, GR 6336170 mN, 2794300 mE.

April 1896: A new geyser formed near the lakeshore west of the Utuhina Stream, on the property of Mrs Ratema and close to Mr Yates' residence. Eruptions 10-15m high lasting about three minutes occurred regularly at 15 minute intervals. A canoe was used to ferry visitors across the Utuhina Stream and many people visited the geyser (N.Z. Herald, 6 April 1896; Hot Lakes Chronicle, Wednesday 15 April 1896; p.19 *in* Stafford, Steele and Boyd, 1980). F207, S1303, GR 6336840 mN, 2794545 mE.

March 1897: The Ngapuna geyser erupted frequently to about 15m high for about one month and appeared to have become an annual event (N.Z. Herald, 26 March 1897 and 12 April 1897). F519, S1376, 6335100 mN, 2796600 mE.

Early 1901: Kuirau Park had a small hydrothermal eruption (N.Z. Herald, 12 May 1902). F129? S624? GR 6335895 mN, 2794640 mE.

010324: On Sunday 24 March an eruption occurred some 800 m beyond the Postmaster Bath, near the Puarenga Stream mouth. Mud was thrown some 30 m high and the lake was considerably disturbed. This Ngapuna geyser last erupted four years ago after very wet weather, but used to erupt every year (N.Z. Herald, 26 March and 27 March 1901).

020214: The large geyser at the mouth of the Puarenga Stream erupted to about 30 m high on Friday afternoon, sending up mud, stones and water. This feature came into action about once a year and was last active in March 1901 (N.Z. Herald, Mon. 17 February 1902). F519, S1376, 6335100 mN, 2796600 mE.

020509: In Kuirau Park a minor hydrothermal eruption occurred at a site which had also erupted a year earlier; see entry for early 1901. (N.Z. Herald, 12 May 1902). F129? S624? GR 6335895 mN, 2794649 mE.

020916: This afternoon of Tuesday 16 September an eruption broke out near the Spout Baths in Whakarewarewa during a thunderstorm. It was accompanied by underground rumblings and shot mud and stones to about 7 m high (N.Z. Herald, Tuesday 16 September 1902).

040410: On the evening of Sunday 10 April a large mud hole broke out on the margin of Lake Rotorua, near the end of Queen's Drive. Boiling mud was ejected about 2m high and a hole about 4m diameter formed where previously the ground presented its normal appearance, without any sign of thermal activity (N.Z. Herald, Monday 11 April 1904).

040420: In Arikikapakapa a blowout threw ejecta ~30 m high (N.Z. Herald, 23 April 1904).

050904: At Ohinemutu a hydrothermal eruption 20 m high occurred (N.Z. Herald, 6 September 1905).

060228: The Ngapuna geyser usually played frequently 2-3 m high, but recently gave a shot 30 m high (N.Z. Herald, 1 March 1906). F519, S1376, 6335100 mN, 2796600 mE.

060321: An eruption 15 m high took place in Kuirau Park. (N.Z. Herald, 22 March 1906).

061104: On Sunday 4 November two eruptions occurred from Whakamanu Geyser (S290) at Whakarewarewa, near the bridge into the Village and near Guide Bella's house. Loud reports accompanied the eruptions, which threw mud, water and stones up to 100m high. The eruptions lasted about twenty minutes and covered surrounding whares with mud and threw stones a considerable

distance (N.Z. Herald, Monday 5 November 1906).

080120: In the afternoon of Monday 20 January, a mud geyser in Arikikapakapa erupted mud about 20 m high for about half an hour (N.Z. Geological Survey File U.16/466 General).

080302: Today the mud geyser just below the caretaker's house in Whakarewarewa erupted for 23 minutes, throwing mud 10-15 m high. This was the mudpool Ngamokaiakoko (S262), then known as "The Devil's Reception" (N.Z. Geological Survey File U.16/466 General). This caretaker's House was on the present day site of the regal Geyserland Hotel, on the northwestern bank above Ngamokaiakoko. Early photographs exist which show this house, which was present until c.1930s.

080310: The mud geyser below the caretaker's house at Whakarewarewa was active again today, ejecting mud to 7m high for ten minutes. This feature was Ngamokaiakoko (S262), also then known as "The Devil's Reception" (N.Z. Geological Survey File U.16/466 General).

250616: A hydrothermal eruption occurred at Ohinemutu, damaging some property. (Weekly News, 25 June 1925).

251004: An eruption occurred at Ohinemutu, by the Lake Hotel (Weekly News, 15 October 1925). This same site erupted again in December 1960 (see later entry). F194 Waihunuhunukuri, S1260 GR 6336500 mN, 2794743 mE.

November 1927: An eruption at Ohinemutu threw debris to 30 m high (N.Z. Herald, 18 November 1932).

March 1931: At Rocky Point in Sulphur Bay an eruption occurred. A clear acid spring with a light green tinge; changed to a turbid pool following a blowout (p.91 in Grange, 1937).

310617: Another eruption at Ngapuna, up to 30 m high. This was the Ngapuna Geyser, in the delta of the Puarenga Stream mouth. It last erupted on 28 February 1906 (N.Z. Herald, 20 June 1931). F519, S1376, 6335100 mN, 2796600 mE.

311010: Following the heavy rain on Wednesday night a small geyser broke out on the edge of the hot pool (S352) in front of the Spout Baths. This made S352 muddy, which also disturbed and muddied the water supply into the inlet for the Tourist Department's baths (Rotorua Morning Post, 10 October 1931). May be S351?

320118: About 100m offshore from the mouth of the Puarenga Stream a huge eruption occurred at c.1945 hrs, throwing muddy debris 60-120 m high. (Rotorua Morning Post, 19 and 21 January 1932; Jaggar, 1932). F514, S1371, 6335215 mN, 2796548 mE.

320618: An eruption occurred at Ohinemutu, in Haukotuku Street. This was a double eruption, the larger event threw debris about 10 m high and took in a fence and power pole; a crater 8m by 6m area resulted. The smaller vent threw material to 30 m high (Rotorua Morning Post, 20 June 1932; N.Z. Herald, 7 July 1932). A discussion about filling in this hole appeared in the Rotorua Morning Post, 13 July 1933. F457, S1314 Kahukura, GR 6336590 mN, 2794657 mE.

320724: A minor blowout occurred on the Ngapuna side of the lakeshore. Rumbblings were heard, with pillars of mud and steam rising to a great height from the lake edge. It only played for a few seconds then died away completely (Rotorua Morning Post, 25 July 1932). This eruption and site was also referred to as "Ngapuhi Geyser" (p.91 in Grange,1937). F515, S1372, 6335150 mN, 2796600 mE. Vicinity of Ngapuna geyser, for which this one has been misnamed?

321116: An eruption at Ohinemutu interrupted tea when a kettle was blown out of a hot pool used for cooking. Debris was thrown up to 10 m high from two holes in a garden amongst houses; these pools supplied water for three baths. Practically no ejecta and no damage resulted to gardens or adjoining baths. Now only two holes about 0.3 m diameter remain, with muddy boiling water in the bottom (Rotorua Morning Post, 17 November 1932; N.Z. Herald, 18 November 1932). F197, Rangihauapa, S1252, GR 6336467 mN, 2794800 mE.

321220: On Tuesday 20 December an eruption occurred in Arikikapakapa; this was not witnessed but mud was found about 20 m up in some trees and later another eruption from the same site was seen. Large quantities of mud were ejected, with eruptions occurring every 80 minutes; crowds of spectators were attracted to it. This feature was active over the next few years and was characterised by loud detonations; later referred to by name "Messine's Mud Geyser". (Rotorua Morning Post, Thursday 22 December 1932).

3301: A fumerole recurred in Haupapa Street near the Government Gardens, where a breakout occurred several years ago but was filled in. (Rotorua Morning Post, Tuesday 3 January 1933).

3302: Messine's Mud Geyser in Arikikapakapa was again active over the past few days, with eruptions up to 3 m high occurring every five minutes. Two neighbouring pools were also very active. The frogpond on the other side was also very active and ground all around quivered when Messines erupted. The path in was obstructed by fallen trees. (Rotorua Morning Post, Tuesday 21 February 1933).

330331: A new mud geyser formed near the Model Pa at Whakarewarewa. This was past the entrance and on the right hand side (ie. in Arikikapakapa). Eruptions up to 3 m high occurred every five minutes, from a rather small hole surrounded by fern and scrub. (Rotorua Morning Post, Saturday 1 April 1933).

3305: A mud geyser recurred on the Rotorua golf course at Arikikapakapa. (Rotorua Morning Post, Tuesday 9 May 1933).

3307: A new mud hole broke out in the past week near the curio shop in Ohinemutu and for a week now has boiled furiously. At first it splashed mud a few metres distance but by 25 July it was surrounded by stones; other new steam jets in the vicinity indicated further outbursts seemed likely? (Rotorua Morning Post, Tuesday 25 July 1933). F193? S1227? Porahi? GR 6336515mN, 2794867 mE.

3310: A small blowout occurred on the Arikikapakapa golf course. Hot ground had killed all the grass; a vent pipe was put in and this steamed strongly. It was situated in a gully by the seventeenth fairway (Rotorua Morning Post, Monday 30 October 1933).

331214: An eruption broke out on the Ohinemutu lakeshore, opposite the Lake House Hotel bath (Waihunuhunukuri, S1260). It erupted several times; two eruptions were about 10 m high, then it subsided into a boiling mud pool on the shore. (Rotorua Morning Post, Friday 15 December 1933). F194, S1260 Waihunuhunukuri, GR 6336500 mN, 2794743 mE.

3402: An hydrothermal eruption took place at Ngapuna. (N.Z. Herald, 7 February 1934). F515, S1372, 6335150 mN, 2796600 mE. Through time several HEs at this site have occurred and most have been assigned to the Ngapuna Geyser. However, it is likely the actual vent in each HE may have varied slightly in position.

3403: On a small island at rear of the Ward Baths a geyser has been playing intermittently for the past two weeks. Usually it played 1-1.5 m high but occasionally sent up shots very high, in the nature of a blowout. (Rotorua Morning Post, 2 March 1934).

340812: On Sunday 12 August a blowout occurred in the centre of the road around Motutara golf course, about 50 metres from the seventh tee. On Monday 13 August this was found by workmen, who noticed a strong new steam column; they found a hole 2 m long by 0.3-1 m wide and although no longer erupting it was still violently bubbling. The road was deviated around the hole (Rotorua Morning Post, Tuesday 14 August 1934).

341020: A hydrothermal eruption occurred at Whakarewarewa, in the frogpond below the Caretaker's house. People were awakened early Saturday morning when the building was rocked for several minutes by the activity. Mud was erupted about 5 m high and several more eruptions occurred throughout the day, although these later ones were only about 2 m high. (Rotorua Morning Post, Monday 22 October 1934). (Frogpond or Ngamokaiakoko, F5, S262).

3605: A minor blowout occurred near one of the pathways in Kuirau Park. Lake Rotorua waterlevel had been falling recently but pools in Kuirau Park were still at high waterlevels and the frogpond was much hotter and more active (Rotorua Morning Post, Tuesday 26 May 1936).

3703: The geyser just offshore near the lakefront at Ohinemutu was playing vigorously and frequently. People lined up on the shore to watch the 10-15 m high eruptions. Pohutu Geyser (S75) was dormant over Easter, so this geyser at Ohinemutu provided an alternative attraction. (Rotorua Morning Post, Tuesday 30 March 1937 and Friday 2 April 1937). F390, S1232? GR 6336640 mN, 2794851 mE.

3712: Close to the Hinemaru Street boundary of the Government Gardens, a small boiling vent was very active and yesterday played 3-5 m high. (Rotorua Morning Post, Wednesday 15 December 1937).

3801: The Mud Geyser (Whakamanu Geyser, S290) at the left of the Whakarewarewa entrance bridge was in action again, the first time for several weeks; it was active for several hours and threw mud 1-2 m high. (Rotorua Morning Post, Wednesday 19 January 1938). F119, S290, GR 6332733 mN, 2795482 mE.

380622: On Wednesday morning 22 June an eruption occurred in Kuirau Park, near the Alum Pool and beside the main footpath leading from the park entrance to Lake Road. Mud was thrown to 40 m away and part of the footpath was blown away. A crater about 3 m diameter was still boiling violently on Thursday, when workmen sounded it to about 4.5 m deep below waterlevel. Several other pools normally calm in Kuirau Park had also begun boiling in the past few days (Rotorua Morning Post, Friday 24 June 1938). F239? S618? GR 6336017 mN, 2794594 mE.

3807: Several blowouts occurred on the northern shores of Roto-a-Tamaheke, after the lakelevel was suddenly dropped about 150 mm by the villagers interfering with the western dam. "Fortunately the waterlevel was restored in a few hours" (N.Z. Geological Survey File U.16/466 General). F1050, S436, GR 6332708 mN, 2795700 mE. Also F94, S435, GR 6332712 mN, 2795700 mE.

3810: During Labour weekend the waterlevel of Roto-a-Tamaheke was again interfered with by the villagers, who broke down the dam and robbed the Spoutbath of its gravity-fed cooling waters. This sudden change in lakelevel was attributed to causing two very nasty blowouts on the northeast shore of Roto-a-Tamaheke some hours later, with the result that the lake suddenly found an underground outlet and lowered considerably. Bags of stones and cement were used to try and..."repair this leakage and seemed to be satisfactory, although not without considerable difficulty..." (N.Z. Geological Survey File U.16/466 General).

410522: Early in the morning of 22 May a hydrothermal eruption occurred in a vacant section beside guide Georgina's house in Tryon Street. Loud rumbling sounds accompanied continual earth tremors and at daybreak a muddy geyser was seen erupting 15 m high; a crater about 2 m deep and 3 m diameter had formed and mud was thickly deposited to about 20 m radius from the vent. Eruptions continued for about two hours. This eruption occurred from an old hole but there was no knowledge of any previous activity here before. A big gum tree near the eruption centre had mud to its top. (Rotorua Morning Post, Friday 23 May 1941).

450316: A mud geyser erupted on Friday afternoon, 16 March, about 200 m northwest from the Puarenga Stream footbridge near Ngapuna. Mud was thrown about 60 m high and the following day a crater about 15 m diameter remained, full of steaming muddy water. Large deposits of mud remained to a radius of 15 m from the crater edge and a witness said it appeared reminiscent of a miniature Waimangu geyser (Rotorua Morning Post, Monday 19 March 1945). A sketch of this was made by Mrs Spenser, wife of the Rev. F. Spenser, when it erupted in 1894 (Allen, 1894).

480505: A blowout occurred on the afternoon of Wednesday 5 May 1948, on the shore of Lake Rotorua near the Postmaster Bath entrance. It geysered hot mud and water 5-7 m high for several hours, then subsided during the night into a boiling mud pool. (Rotorua Morning Post, Thursday 6 May 1948).

510809: A geyser started gushing at 1300 hrs in a private garden in Tarewa Road, heralded by loud rumblings for several hours this morning. This was at Peter Maranui's place, opposite Mr. G.H. Humphries. Mud, water and rocks were erupted to 15 m high and the eruption was only 8 m from Maranui's house, which was covered in mud. By 1430 hrs it had calmed down and only a small boiling spring remained. A large area was covered in mud and rubble, with ejecta blocks up to 0.3 m diameter. F146? S657? Waiariki Parekaumoana, GR 6336232 mN, 2794277 mE.

Mr. Maranui had been digging a hole nearby to make a mineral bath which he was going to supply by draining a nearby hot spring. Mr Humphries said such outbreaks were common in this area and a few similar ones had occurred in the last 1-2 years. He sounded today's hole to 2 m depth without reaching bottom. (Rotorua Morning Post, Thursday 9 August 1951).

1959: Northeast of Geyser Flat beside the Puarenga Stream, S175 had an eruption which was witnessed by Guide Rangi (N.Z. Geological Survey File U.16/466 Spring Survey 1969).

601228: A minor hydrothermal eruption took place at McGuire's place in Ohinemutu, by the Lake Hotel. This was after 74 hams had been cooked in a spring there. The last eruption from this site was in October 1925. (Auckland

Star, 29 December 1960; Daily Post, Tuesday 10 January and Thursday 26 January 1961). F194 Waihunuhunukuri, S1260, GR 6336500 mN, 2794743 mE.

c. 1960: A geyser erupted in the lake at Sulphur Bay, shooting to about 35 m high. (Daily Post, Tuesday 2 June 1964).

610126: An eruption occurred at McGuire's place, near the Lake Hotel bath house in Ohinemutu. The first few eruptions threw mud to 30 m high, but these rapidly subsided to 3 m high eruptions (N.Z.Herald, Friday 27 January 1961; Daily Post, Thursday 26 January 1961 and Friday 27 January 1961). F194, Waihunuhunukuri, S1260, GR 6336500 mN, 2794743 mE.

6103: On the north end of the sinter sheets along west side of Roto-a-Tamaheke, S399 had an eruption. Sinter blocks and debris were scattered around, mainly to the northwest (N.Z. Geological Survey File U.16/466 Spring Survey 1969). F1019, S399, GR 6332642 mN, 2795592 mE.

631031: On the lakeshore property of Mr and Mrs Martin, east of Whittaker Road, a large eruption blew out a crater of about 15 m diameter. By 8 November it was erupting to about 70 m high and had ejected about 400 m³ of material; part of Martin's garage was destroyed by the eruptions. Rotorua Well-drillers vented the crater with pipes before filling it with boulders; bore RR211 about 20 m away was grouted out at the same time, although there was no evidence that it was involved with this eruption (G. Brown, pers. comm.). A high heatflow still occurred here in 1985, when the crater was catalogued as S1305 (Daily Post, Thursday 31 October 1963; N.Z. Geological Survey File U.16/466 and U.16/448; N.Z. Herald, 1 November 1963; Annabell, 1977; Healy, 1963). F448, S1305, GR 6336890 mN, 2794570 mE.

640105: Another eruption broke out at Martin's property in Whittaker Road. (Auckland Star, 6 January 1964). F448, S1305, GR 6336890 mN, 2794570 mE.

640531: A hydrothermal eruption formed a crater behind the Sportsdrome in the Government Gardens today. Muddy debris was ejected to about 18 m high in several spurts directed to the north-northeast. Two distinct vents were formed, which later in the day had water levels about 1.8 m below ground level and 99°C violently boiling mud (E.F. Lloyd, Diary). This site was still a large open pool of bubbling muddy water in 1987. (N.Z. Herald, Tuesday 2 June 1964 and Wednesday 3 June 1964; Daily Post Monday 1 June 1964 and Tuesday 2 June 1964).

640828: Today Rachel Spring (Whangapipiro) began overflowing at about 1.5 litres/second, with muddy water. This overflow had ceased by 9 September but recommenced on 15 September 1964 with a roaring, seething ebullition head about 0.6m high and a cycling waterlevel fluctuation (Daily Post, Tuesday 15 September 1964). (Rachel spring, F183).

650729: Black foamy clumps of sulphur suddenly appeared along the southern shore of lake Rotorua, covering a wide area. The material looks like dirty greasy soapsuds but is mainly sulphur. RDC asked Jim Healy (Govt Volcanologist) to investigate; Healy suspected a hydrothermal eruption had occurred. This material appeared in the lake on Tuesday and Wednesday, but had disappeared by Saturday 31 July. (Daily Post, Thursday 29 July 1965)

In the past fortnight and a series of small local earthquakes has occurred and at the Ward Baths the water has gone black during this time also. The bath superintendent (Mr F.W. Jones) said he had never seen anything like this in the past 35 years. DSIR Wairakei was also asked to help (NZGS File U16/466 General; NZ Herald, Friday 30 and Saturday 31 July 1965).

660711: On Monday 11 July 1966 a mudpool nearby Rachel (Whangapiro) Spring erupted, but by Thursday 14 July it had shown no further signs of activity. The eruption was thought to have been connected with the Rachel Spring (N.Z. Herald, Thursday 14 July 1966).

660815: Today (Monday) Rachel (Whangapiro) Spring erupted violently at c.0100 hrs. Five eruptions occurred between 0100-0300 hrs, each producing a thunderous roar. These were witnessed by Mr. C.K. Holden, a resident at nearby Gardenholm Old Folks Home. He said the first eruption awakened him and he saw a column of steam rising about 60 m high. (Rachel spring, F183).

These eruptions burst a hole through the concrete surrounds of Rachel Spring, threw a large quantity of water over nearby lawns and washed soil away from flowerbeds. Workmen roped off about 0.4 hectares around Rachel Spring area later in the day. By mid-morning the ground around Rachel was still shaking and the spring was steaming violently. E.F. Lloyd measured 102°C at 0.6m depth and 105°C at 6m depth in Rachel Spring this same day (Daily Post, Monday 15 August 1966).

660815: Rachel Spring had several violent eruptions, ejecting muddy water over surrounding gardens. In October 1966 an outlet ditch was dug, and in November 1966 a permanent covered outlet was begun ???; by then Rachel was still boiling powerfully with strong overflow (Daily Post, Monday 15 August 1966; Daily Post, Friday 21 October 1966; Daily Post, Thursday 3 November 1966; NZGS File U16/466 General vol.2).

660822: S615 in Kuirau Park erupted violently just before 1200hrs today. It burst through near the Lobster Pool (S613, also known as Papatangi) and blasted a crater several metres wide as well as ejecting a vertical column of muddy water about 50m high [ADC has photo]. F135, S615, GR 6336048mN, 2794578mE.

Subsequent eruptions occurred at c. five minute intervals and a large crowd gathered on Ranolf Street to watch. These later events formed two further eruption craters (S614 and S615/1) a few metres from the first and a flow of hot, thick mud spread out over surrounding lawns. Ejected material totalled an estimated 80 tonnes (Daily Post, Monday 22 August 1966 and Tuesday 22 November 1966; Healy 1966).

A colour photograph of one of these eruptions was supplied by an anonymous person to the Public Relations Office, who passed it on to the N.Z. Geological Survey. This photograph shows streetlamps and trees that provide excellent reference points, which identify S615 as the site. EF (Ted) Lloyd (retired District Geologist, NZGS) also personally showed ADC the exact crater in November 2001.

660822: An eruption in Kuirau Park today from S614 and S615, just southwest from Lobster Pool or Papatangi (S613). Lasted up to about five minutes with mud and some rocks being thrown out (Healy, 1966).

660916: In Kuirau Park an eruption about 15m high occurred today (Friday), on the edge of S613 (Lobster pool, or Papatangi), a large hot pool. It formed an enlargement of S615 and also the nearby S614. This eruption continued geysering frequently until at least Tuesday 20 September 1966, when it was seen erupting to about 10 m high. This event was close to S615, which was formed by eruptions on 22 August 1966 (Daily Post, Tuesday 20 September 1966; Healy 1966). F235, S614, GR 6336058 mN, 2794586 mE.

670302: Today (Thursday) a submarine hydrothermal eruption occurred in Lake Rotorua, about 200m offshore northwest of Muruika Point in Ohinemutu. In the morning Mr H. Whitfield, helicopter pilot, saw a dirty yellowish patch of about 6m diameter with a strong upwelling like a fountain. By noon the discoloured water had spread across to Kawaha Point. (Daily Post, Thursday 2 March 1967).

1968: Ngungukai (S327), in front of the Wahiao Meeting House at Whakarewarewa Village, erupted violently and covered surrounding houses with mud. No accurate date is known, but it was some years before 1969. (N.Z. Geological Survey File U.16/466 Spring Survey 1969). F121, S327 Ngungukai, GR 6332696 mN, 2795477 mE.

681009: At Whakarewarewa Village, S305 (about 10m northeast from the Oil Baths) erupted violently, ejecting mud and blocks up to 45m away. (Daily Post, 9 October 1968; N.Z. Geological Survey File U.16/466 Whakarewarewa Survey). F940, S305, GR 6332725mN, 2795377mE.

6812: On the mudflats to the east side of Roto-a-Tamaheke, nearest to Forest Research Institute (FRI) workshops, S406 had a small eruption and deposited a thick mound of mud around its vent. (N.Z. Geological Survey File U.16/466 Spring Survey 1969). F1026, S406, GR 6332677mN, 2795744mE.

730227: A big eruption occurred at the mouth of the Puarenga Stream, forming a crater 15m diameter and ejecting muddy debris to a radius of 15 m out from the edge of the crater (EF Lloyd, Fieldbook; EF Lloyd_Photo).

1977: An eruption occurred at Whakarewarewa in the Rahopeke Arm adjacent to S329. A mud volcano about 1m high grew rapidly to nearly the full width of the Te Kokonga (S328) channel leading to the Downbath. Muddy outflow into the Puarenga Stream aroused public attention (Mr. Arthur Baulcomb, pers. comm). F684, S328 Rahopeke, GR 6332697 mN, 2795538 mE.

1978: A blowout suddenly formed near the intersection of Ariariterangi and Tunohopu Streets, along the sewerage line route. (I.G. Donaldson, pers.comm.).

790104: A new chloride spring (S529) broke out about 25m east of Papakura Geyser (S28). On 18 January mud about 0.05m thick surrounded the newly formed spring, suggesting mud was ejected before the spring developed. At this time it was cyclicly boiling with ebullition up to 0.3m high; boiling lasted about 15 seconds and the period was about eight minutes. Initially it was pH 8.3, 516ppm chloride and 72 ppm sulphate, but by 6 June 1980 it was 33°C, pH 2.9, 315ppm chloride and 525 ppm sulphate (Glover, 1985; Lloyd, Fieldbook 1979).

810807: An eruption suddenly occurred at Sulphur Point, near Government Gardens. Mud was thrown to 10m high (Daily Post, 8 August 1981).

811109: In Kuirau Park, S715 began erupting muddy columns 6-8 m high every hour, and continued for three weeks. A lot of debris was thrown out of an old sinter-lined vent, which was named "Mayor's mouth" because of all the trash that issued fourth F344, S715, GR 6336115mN, 2794301mE (AD Cody, Fieldbook-1).

811117: On Tuesday 17 November, Martha Mihinui's driveway at Whakarewarewa Village suddenly erupted 1-2 m high and left a crater 2 m diameter and 2 m deep containing 90°C muddy water. This vent was catalogued as S765, although about 20 years ago it was a dormant crater that was filled in to provide vehicular access (Te Autiti Wikirihi, pers. comm.; AD Cody, Fieldbook-1). F1232, S765, GR 6332703 mN, 2795516 mE.

820914: Korotiotio (S283/1) erupted violently several times, removing sinter banks and debris. Eruptions to 7 m high threw ejecta to about 10 m radius although these subsided within a few hours (A.D. Cody, Fieldbook-2). F81, S283 Korotiotio, GR 6332686 mN, 2795377 mE.

821013: Korotiotio (S283/1) again erupted violently, this time removing all sinter embankments that used to separate the two pools at the southern end. A big muddy outflow had occurred from S287 (about 15m north of S283), during the night. Mud and ejecta surrounded S283 to a radius of about 10m (A.D. Cody, Fieldbook-2).

821105: S426 erupted several times to 0.5 m high, accompanied by strong outflow surges. The waterlevel was lowered 0.3 m today to divert outflow while a V-notch weir was installed, and this work induced the eruptions (A.D. Cody, Fieldbook-3). F102, S426, GR 6332746 mN, 2795707 mE.

830903: On Saturday 3 September, Martha Mihinui's driveway hole (S765) again erupted 1-2 m high for 3-4 hours, accompanied at the same time by a strong and muddy upwelling below the Downbath. (Te Autiti Wikirihi, pers. comm. to A.D. Cody). F1232, S765, GR 6332703 mN, 2795516 mE.

Another blowout formed on the FRI pathway this same morning, just east of G10 waterlevel hole; this was numbered S725. It was not witnessed in eruption but a mudflow along the footpath and mud splattered in manuka trees remained as evidence (A.D.Cody, Fieldbook-4). F1222, S755, GR 6332774mN, 2795722mE.

840109: On the alluvial flats north of and below S426 (northeast of Roto-a-Tamaheke) an eruption occurred within the past few days. It formed a black bubbling muddy pool that killed a manuka bush and spread black silt to a radius of about 2m. This pool erupted again during Easter, a few days prior to 26 April 1984; catalogued as S755 (A.D. Cody, Fieldbook-6).

840225: A blowout occurred on the FRI path by Roto-a-Tamaheke, about 10m west of S426; it was catalogued as S723 (A.D. Cody, Fieldbook-6; Daily Post, 27 February 1984; van der Werff, 1984). F1190, S723, GR 6332737 mN, 2795696 mE.

840424: Nearby S426 at Roto-a-Tamaheke, another eruption occurred during Easter and formed S756; close to S755, which formed in January 1984. (A.D. Cody, Fieldbook-6). F1223, S756, GR 6332809 mN, 2795691 mE.

840915: On the western shore of Roto-a-Tamaheke, S369 went very muddy this weekend and began overflowing into S365. Usually S369 has been clear and cold at 30°C, but this weekend it was 53°C, very muddy and appeared to have had an eruption in it, although no ejecta was present (A.D. Cody, Fieldbook-8).

841023: An eruption occurred at Hakaraia's place in Ariariterangi Street today. A hole about 1m diameter formed and splashed muddy water to about 2m radius. It was 96.5°C, pH 5.8 and 103 ppm chloride. An old drum set into ground and a concrete vent pipe put here when road was sealed suggests thermal activity was present here in the past (A.D. Cody, Fieldbook-8). F421, S1268, GR 6336619 mN, 2794646 mE.

850513: On Monday 13 May, Te Wai-o-Te Nihotahi (S333), at Kuru Waaka's place in Whakarewarewa Village, erupted this evening. Muddy water was thrown

3-5 m high in numerous spurts and about 3 m³ of garden was lahared over the surrounding lawn and bach roof. Activity subsided overnight, with the assistance of a coldwater inflow from a garden hose (A.D. Cody, Fieldbook-9; N.Z. Geological Survey File U16/466). F105, S333, Wai-o-Te Nihotahi, GR 6332730 mN, 2795538 mE.

851217: Ian Johnstone, a pilot with Helicopter Line, reported an eruption crater that had not been present on 16 December. This site was about 100m west of the mouth of the Puarenga Stream on Sulphur Flats; it was inspected on 17 December by A.D. Cody and B.M. Simpson, at which time it was a gently bubbling pool about 5m diameter and 83°C, with black muddy ejecta uniformly surrounding the crater to about 5m radius from the edges. X-ray Diffraction (XRD) analysis of the black surface froth on the pool (XRD No.3269) showed orthorhombic sulphur, natroalunite, pyrite and traces of kaolin (A.D. Cody, Fieldbook-10; N.Z. Geological Survey File U.16/466 Eruptions).

851222: Frank Emerali, Maori Arts and Crafts Institute (MACI), rang on Monday 23 December to inform N.Z. Geological Survey of a small blowout that had occurred on the bank of Ngamokaiakoko (S262), on the weekend of 21-22 December 1985. By 1500hrs on Monday 23 December when inspected by C.P. Wood and A.D. Cody, a small hole about 0.3 m diameter and 2 m deep was found at the southwestern side of S262, up on the level of the walkway. Mud had been thrown to a radius of about 2 m and had splashed over the safety railing, but this mud was by then all cold and the vent only weakly steaming. Ruku (MACI) said only very small steaming cracks had been at this site prior to the blowout (A.D. Cody, Fieldbook-10).

860412: On Saturday 12 April a large muddy upwelling occurred in Lake Rotorua, about 400 m northeast off Motutara Point. This muddy circle of water was also ringed in foam (N.Z. Geological Survey File U.16/466).

8606: About this time an eruption occurred on east bank of Puarenga Stream, forming a crater about 4 m diameter with one metre high vertical banks and resulting in a new strongly boiling alkaline spring with outflow of ~0.5 litres.second⁻¹, pH 7.2, 2020 ppm chloride 101°C on 6 August 1986. Site was buried when Puarenga Stream was realigned and its stopbanks rebuilt up by RDC in c. 1984 (A.D. Cody, Fieldbook-11). F169, S---, Stopbank Spring, GR 6334859 mN, 2796552 mE.

8802: During inspection of Ohinemutu with Mike Mongilo (IGNS) I found a new eruption crater on the lakeshore. (ADC Fieldbook). Blowout was witnessed by 'Eich' Mitchell son in law of Hamuera ("Sam") Mitchell, who said it threw mud and rubble over ~30 m radius and to ~10 m high, with numerous eruptions occurring over an hour or so (pers. comm. to ADC). Site ~5m south from lake edge, directly north from Tunohopu Meeting House.

880607: A blowout occurred on the pathside at Roto-a-Tamaheke nearby S426 and S430. Found on Tuesday 7 June c.1200 hrs and thought to have occurred on Monday 6 June. Mud deposited over scrub and along pathway (A.D. Cody, Fieldbook-15).

890714: On Friday 14 early a.m. a hydrothermal eruption occurred in Kuirau Park at Soda Spring (S624) and its neighbouring S623. Soda Spring became very muddy grey on Friday, with thick mud deposits all around inside stone wall. By Sunday 16 July the waterlevel had fallen 310 mm below its previous normal flowing level, and 170 mm below overflow level; it no longer filled the RDC Footbath from Sunday. To the immediate north S623 had two centres of firm steady ebullition and was also very muddy. Neither spring had ejecta above waterlevel but both had suddenly become very muddy. Prior to this date S623 had been a cool calm pond with floating ferns and algae present (A.D. Cody, Fieldbook-17). F129, S624 Soda Spring, GR 6335895 mN, 2794640 mE.

960307: Eruption on east bank of Puarenga Stream, blew out circular crater 15m diameter. Not witnessed but only lasted a few minutes, as local people from marae were cooking in steam hangi pits ~10-15m north from crater. (WR Esler, photographs; ADC Fieldbook). At hangi cooking area to west from end Hamiora Place. Ejecta contained blocks of sulphur cemented rounded pumice gravels, with blocks up to 1.3 m x 0.8 m x 0.65 m volume. Ejecta thrown to ~5 m radius from edge of crater and when visited on 14 March 1996 by ADC, water of Puarenga Stream filled crater, where steady weak gas ebullition was occurring. F167, GR 6334345 mN, 2796467 mE.

980508: S657 (F146) began boiling overflows and S657/1 erupted 5-10m high many times. In July 1998 both springs and also F279 at No.20 all erupted many times, opening up craters and flooding muddy debris and waters around area. Note that all the Tarewa Group springs filled up and began boiling overflows in March 1998, immediately after an ML 4.9 earthquake 20km southeast of Rotorua.

990920: Eruption witnessed by Mike West (pers. comm. on 4/9/00). Policeman, off duty often sits out on walkway rest seats and watches, reads, etc. Eruption seen between 12 noon and before 3pm on Monday 20 September 1999. Scared flocks of birds; columns of black muddy water shot up suddenly 3-5 m high repeatedly and steam clouds produced. Only lasted a minute or less.

000119: Tarewa Road, S652 erupted, destroyed a fence and formed a crater ~5m dia.

000124-26: Tarewa Road, S649 had at least six eruptions 7-10m high, flooding mud and debris over surrounding land.

000821: On lakeshore, crater ~8 m diameter about the site of Ngapuna geyser of the 1900s. Another crater formed by eruption sometime in week or two before 4 September 2000. On east bank of Puarenga Stream delta ~50 m south from lakeshore and ~10 m east from bank of stream. Crater has rim of rounded pumice gravel ejecta ~2-3 m wide from rim and <100 mm deep. Has already been modified by rainfall but crater filled with black turbid water which has steady gas ebullition (ADC Fieldbook-25).

010126: In Kuirau Park, pool S721 suddenly erupted violently at about 1600 hrs on a Friday afternoon. About 1200 m³ of material was erupted within about 4-5 minutes, with blocks up to ~1 m diameter being thrown about 70 m distance. A fine aerosol of muds was dispersed downwind up to ~1.5 km to east as far as Queen Elizabeth Hospital (Daily Post, 27/01/01; Slako, 2002). F350, S721, GR 6336100 mN, 2794521 mE.

0212: In early December 2002, an hydrothermal eruption occurred at No. 18 Tarewa Road. Pool S656 blew up and flowed across road and killed all grasses, plus a pile of muddy rubble on west side of pool to ~2 m distance. Another flow of hot waters went east into Kuirau Park and killed a swathe of lawns ~5 m wide and ~20 m long. (ADC Fieldbook No. 29).

*If an elderly but distinguished scientist says that something is possible,
He is almost certainly right; but if he says that it is impossible he is
almost certainly wrong*

- Arthur C. Clarke

APPENDIX V:

Diary of Known Ground Collapses

These are known collapse events, as opposed to those caused by over pressures leading to hydrothermal eruptions. References are given in Chapter Eight and these often give detailed descriptions of each occurrence. All entries are in chronological order. They are given here because some accounts or recollections of these events may incorrectly describe them as HEs.

>1961 <1979: A collapse crater (S2017) formed in Arikikapaka Golf Course, near its northern boundary with Sophia Street. This feature is absent from 1945 aerial photographs. However, subsequent photographs show that it may have begun development by March 1961, but had enlarged greatly by early 1979 to near its 1989 dimensions of about 7 m deep and 10 m by 5 m area (NZ Aerial Mapping Rotorua Sheet 5 of 8 May 1945; NZAM Rotorua Photograph No.2754 of 26 March 1961; and NZAM Photograph R.21 for RDC).

750808: At the Landmark property at the southern end of Fenton Street, a big collapse crater suddenly formed. In June 1975 the reinjection well was blocked and steaming up outside its casing, and in July 1975 both the production and reinjection wells were grouted out with nine tonnes of cement. The collapse on 8 August 1975 rapidly enlarged to about 8 m diameter and 6-7 m deep (NZGS File U16/448).

810415: An extensive subsidence suddenly occurred during the night of Wednesday 15 April, in the Rotorua Hospital grounds at the corner of Arawa and Ranolf Street. Further collapse occurred in northeast corner during the following few days. It was circular, of ~30 m diameter; RDC staff fenced it off by 18 April 1981. In 1989 this site was still gently and steadily steaming, with dead vegetation inside the entire collapse area (Daily Post, Saturday 18 April 1981).

830605: On Sunday 5 June a collapse hole suddenly formed in the Whakarewarewa Village, on the south side of the driveway near the Downbath (Hirere Bath). This hole was ~4 m diameter and ~2 m deep and was catalogued as S766 (N.Z. Herald, Tuesday 7 June 1983).

880208: The front lawn of Brandley, 32 Sophia Street, suddenly collapsed into a crater of ~5 m diameter and ~10 m deep. This occurred two days after MacLeod's well at 30 Sophia Street erupted mud and ejecta through its uncapped wellhead. Brandley's lawn began thumping and steaming prior to its

collapse (NZGS File U16/468; Dominion Sunday Times, Sunday 7 February 1988; NZ Herald, Monday 8 February 1988; Daily Post, Monday 8 February

1988; NZ Herald, Tuesday 9 February 1988; Daily Post, Tuesday 9 February 1988).

890106: In Arikikapakapa, Hoketoru (S2028) suddenly collapsed and formed a crater about 4 m deep into gaseous bubbling mud. Surface opening of ~0.7 m diameter, widening to ~3 m diameter at its bottom. Weakly steaming but strong hydrogen sulphide odour. Heavy rains had fallen during the preceding days and a cold lake had developed in this doline, but which then drained abruptly (ADC Fieldbook-16; Daily Post, Thursday 9 February 1989).

890119: In front of Wahiao Meeting House in Whakarewarewa Village, a collapse occurred along the western stone wall, by the crater of S325, S326. A truck had parked here and the ground subsided beneath it.

890312: Today a collapse occurred in carpark at Whakarewarewa Village, in front of Wahiao Meeting House. This was along the northern side, close by to Ngungukai (S327). A hole ~0.5 m diameter at the surface opened to ~2.5 m diameter at ~2 m depth. Scalding steam gently issued out. (ADC Fieldbook-16).

890313: During the weekend of 11/12 March a collapse occurred in the street corner of Hinemaru and Whakauae Streets. A hole ~0.7 m diameter belled out to ~2 m diameter at ~1.5 m depth. Infilled on Monday 13 March by RDC and Pool Bros. A similar collapse occurred here in late November 1988 (Daily Post, Tuesday 29 November 1988; ADC Fieldbook-16).

890331: On Friday 31 March 1989 the Hinemaru Street again collapsed, near the corner with Whakauae Street. This hole was ~0.7 m diameter at the surface and belled out to ~2.5 m diameter at ~1.5 m depth (ADC Fieldbook-16).

890903: At Whakarewarewa, in the carpark in front of Wahiao Meeting House, a collapse crater suddenly formed on Sunday 3 September. Initially a small fissure in the bitumen sealing was seen strongly steaming, with a conspicuous depression of ~1 m diameter surrounding it. This collapsed soon after to form a crater ~1.5 m diameter and ~3 m deep to vigorously boiling muddy water. On Tuesday 5 September RDC staff filled in the hole and left a pile of boulders on top (Daily Post, Monday 4 September 1989).

990705: On Sunday 5th July, a collapse crater formed in north side driveway alongside FRI hostels. Monday morning it was dug open to expose a crater ~4 m deep to warm water, and ~10 m diameter. (Daily Post, Tuesday 7 July 1999; ADC Fieldbooks 24, 28).

010803: At Whakarewarewa Village, on Friday 3rd August at ~1600 hrs, a large collapse hole suddenly formed in roadway ~20m west of Catholic church. Crater was actually an extension of the large mud pool known as Te Waro-a-Ngawai with Wharerewa on its northern bank. The hole in road was ~7 m x ~5 m area and ~4 m deep. (ADC Fieldbook-27).

020629: Hole on north side of FRI hostel again subsided and opened up. See entry of 5th July 1999, when it first formed. (RDC staff, pers. comm.).

*A little learning is a dangerous thing
Drink deep and taste not the Pierian Spring
There shallow draughts intoxicate the brain
And drinking largely sobers us again*

- Alexander Pope (An Essay on Criticism)

APPENDIX VI:

Diary of Known Well Blowouts and Ruptured Piping

This is a list of all eruption events which are known to have been caused by either geothermal wells or associated pipe works failing, with consequent violent blowouts. Events are listed in chronological order, with references to sources of information. These may occasionally be recalled as having been HEs, although they are known to be directly attributable to broken well casings or associated pipes.

1926?: Well RR36 erupted during hand-drilling; geyser action and the formation of a crater about 5 m diameter and 2-3 m deep resulted (Modriniak, 1945). This site is at Utuhina Lodge, where the original eruption crater still existed in 1996 as an alkaline flowing hot spring of about 5 m diameter. (Old casing was still visible in 2002).

On Monday 31 October 1988 this pool suddenly commenced powerful oscillating boiling 0.1-1.0 m high, with greatly increased outflow. A few days later in early November the pool suddenly went calm and muddy, but with strong boiling then occurring from underneath its eastern bank; it continued so until at least 24 February 1989).

570121: Jaffe's building in Eruera Street erupted, presently site of Gould's camera shop. A new building had been erected over an old ungrouted open bore (RR154) and about one month later on 21 January 1957 it erupted, breaking up a concrete floor and fountaining 4 m high through the street footpath. It flowed at about 3 litres.sec⁻¹ for several days (Daily Post, 3 May 1960; N.Z. Geological Survey File U.16/448). On Friday 18 January 1957 hot water had been coming out of the cold water taps (Mr Gould, pers. comm. 1984; Rotorua Post, Tues 22 & Wed 23 January 1957).

Nov. 1962: A collapse crater about 7 m deep and 7 m diameter formed suddenly at 42 Sophia Street, then Galloway's property. Bore RR369 was drilled in late 1958 and soon after, by October 1958, trees and vegetation around the bore died and the ground became hot (N.Z. Geological Survey File U.16/448).

September 1966: A new geyser seen erupting frequently 12-15 m high in Kuirau Park was actually due to geothermal effluent from the nearby King George V Hospital being piped under Ranolf Street and into a hot pool (Daily Post, Tuesday 27 September 1966).

July 1975: Geothermal well RR727 in Scott Street gave a lot of trouble during its drilling by Carpenter. The hole collapsed and had to be re-drilled, with a slotted liner inserted. Soon afterwards it erupted, throwing muddy ejecta over all the surrounding buildings. This well never produced properly and was later grouted out. Correspondence regarding analysis of ejecta is on N.Z. Geological Survey File U.16/425 (Mr Pilcher of Pilcher Engineering Limited; pers. comm.).

750808: At the Landmark property at the southern end of Fenton Street, a big collapse crater formed suddenly. In the early 1960s a bore (RR66?) here blew out during drilling and about five tonnes of grout were used to seal it; another bore was then drilled. Further collapse craters occurred here in 1967 and 1973, although the 1973 event resulted from a bulldozer that broke through the ground. A hole 0.9 m diameter and 6-7 m deep occurred and blasted steam for some time.

The crater formed on 8 August 1975 was suspected of being due to the leaking casing of the high pressure bore; this crater rapidly enlarged to about 8 m diameter and 6-7 m deep to water. In June 1975 the reinjection bore was already long blocked, but steam was coming up through the ground. Both the production and reinjection bores were grouted out with nine tonnes of cement in July 1975 (NZ Geological Survey File U.16/448).

780529: On Monday 29 May at 36 Seddon Street, bore RR259 (drilled in April 1955) was found to be leaking into the subsurface; all vegetation was dead within a radius of about 10 m around the bore. A strong smell of hydrogen sulphide and the presence of evaporite salts on the ground were conspicuous (N.Z. Geological Survey File U.16/448).

810509: At the property of C. Baskin, 38 Sala Street, a soakwell erupted early on Saturday morning. For about two hours, muddy water was erupted with loud roaring noises. A crater about 6m deep and 1m diameter was formed where the soakwell had been. RDC Geothermal Inspector (Joe Smith) said this was the fourth such eruption in the past year, two of which had caused injuries resulting in Hospital admissions (Daily Post, Tuesday 12 May 1981; p.1 photograph and article).

841217: Behind Geyser Tavern on the banks of the Puarenga Stream an eruption suddenly occurred, forming a crater about 10m diameter and removing about 100 cubic metres of ground in less than one hour. This crater was catalogued as S952 and flowed at 3 litres per second at 90°C, pH 8.5 and 1000 ppm chloride. It was later proven by dye tracing to be connected with a failed casing in nearby well RR527 (Cody, 1985).

850206: An eruption occurred in the N.Z. Railways (NZR) yard in the early hours of the morning, due south of the NZR Travel Centre. Police contacted B.J. Scott and together with A.D. Cody visited the site at about 0730 hrs NZDT. Very muddy water was geysering 1-1.5 m high every few seconds, with a steady outflow of about 0.5 litres.second⁻¹. We found out that Carter's bore (RR719) supplied the NZR Travel Centre by a 150 mm diameter pipe buried about 3 m deep, and that it had burst about 2-3 weeks ago at this same site. Mr Carter turned off his bore and within five minutes the eruptions and outflow completely subsided. By 0810 hrs NZDT on Thursday 7 February 1985 the pipe had been repaired and the hole refilled; the site was by then dry and cold (A.D. Cody, Fieldbook-9).

850313: At Utuhina Lodge today an eruption occurred during excavations around a geothermal effluent disposal soakhole, which had been decorated into a stonework vent named "Lord Knox". This original edifice was built in October 1964. At 1510 hrs on 13 March 1985, this site was flowing about 3 litres.second⁻¹ in a surging muddy stream which was 96.5°C, 3500 micromhos.cm⁻¹, pH 9.3 and 318 ppm chloride. Some of the water usually put into this "Lady Knox" soakhole was from the "Victorian Radium Pool". Bore RR713 was shut down for cleaning and RR290 was also shut. RR289, at the site of the blowout, had been grouted out prior to 1980 (A.D. Cody, Fieldbook-9).

860326: Hornblow's Well RR831 in Hamiora Place, Ngapuna, erupted and formed a crater about 10m diameter in the adjoining property. This eruption ejected about 100 cubic metres of material and occurred one day after the well was restarted, after being shut in all summer (Mr Hornblow, pers. comm. to ADC). After several days it was quenched then grouted, which successfully terminated all surface activity (A.D. Cody, Fieldbook-11; Daily Post, 27 March 1986; Burgess, 1986).

861221: During heavy rains a pipe burst in Woolworth's carpark, at the north end of Tutanekai Street. The break was about 3m north of bore RR184 and blew out a small crater about 0.3m diameter and 0.3m deep. This exposed a buried pipe which was noisily discharging steam and water through a small rupture. By noon on Monday 22 December the pipe had been repaired and the site was dry (A.D. Cody, Fieldbook-13).

870826: Today on the sulphur flats on the west bank of the Puarenga Stream, a hydrothermal eruption occurred following a site investigation drillhole by Murray North Ltd, for a proposed RDC sewerage works expansion. The drillhole, by Brown Bros. (Hamilton) reached about 30 m depth, then began to blow hot water powerfully up through the rods, knocking a spotlight off the masthead.

The rig was pulled out and about 20 minutes later a major blowout followed, forming a crater 3 m diameter and throwing ejecta to a radius of 5 m from the crater edge. By Thursday 27 August 1987 the hole was in strong constant ebullition and steaming steadily (P.I. Kelsey, site Geologist, pers. comm.; A.D. Cody Fieldbook-14).

By Thursday 9 March 1989 this crater formed by BH.567 was 86.7°C, pH 5.9, 1150 micromhos per cm (in situ), and 166 ppm chloride. It was a muddy dark grey, with continuous ebullition 10-25mm high (A.D. Cody Fieldbook-16; Photos by P. Kelsey).

880206: At c.1400 hrs a well at MacLeod's place, 30 Sophia Street, erupted out its uncapped head. This continued for about 3 hrs before being quenched but it meanwhile blew out a lot of ejecta and water over surrounding houses. Two days later the neighbouring property of Brandley, 32 Sophia Street, had subterranean percussions and steaming lawn, followed by a collapse forming a doline. The well was into a boiling zone and had ungrouted casing of only 19.5m depth, with no head valve (NZGS File U.16/468: Daily Post, 7th February 1988).

890320: At about 2400 hrs last night, well RR451 erupted a large vertical discharge of water. The wellhead had corroded and failed; eruption was found by Police, who contacted RWD. The following day the well was quenched and the headworks replaced (K. McCorkindale, Geothermal Inspector MOE; Gary Brown, RWD pers. comm.).

8912: Old well at Rotokawa School, opposite Airport: casing failed and a blowout occurred. RWD grouted it out. (ADC Fieldbook-17).

900403: Tuesday 3rd, well RR397 blew out through corroded casing and blasted crater of boiling muddy waters underneath Rewi's house at No. 23 Lake Road. Crater ~20 m³ size under house. RWD quenched well, which was ~5 m NE from NE corner of house, then cemented it permanently shut. Hole under house was filled with concrete on Monday 10th September (Daily Post, Friday 27/04/90 and Tuesday 11th September 1990; NZ Herald, Saturday 28th April 1990 and Monday 30th April 1990; AD Cody Fieldbook-18).

990118: Well RR205 blew out in Ohinemutu; Sam (Aroha) Mitchell's place, 7 Rangipaehere Street. Well was only 6.1 m total depth and had been abandoned for many years. It suddenly blew out and flooded house and garage with boiling waters on Sunday night, 17th January 1999. RWD quenched and grouted well closed. (AD Cody, Fieldbook-23; Daily Post, Tues. 19/01/99; NZ Herald 20/01/99).

0112: At 50 Sophia Street a concealed geothermal well at Green's property suddenly erupted and boiled following corrosion failure of its upper casing (AD Cody, Fieldbook-27).

020920: At Alpin Motel, Sala Street, Monitor Well M16 suddenly erupted at ~0300 hrs on Friday 20th September, discharging ~3-4 litres per second of boiling waters over surrounding ground (Dennis M^oErlane, pers. comm.).

0210?: At Pizza Hut, north end of Tutanekai Street, a well ruptured its casing and blew boiling waters over surrounding land (p.2, Daily Post, Saturday ?? October 2002).

021018: Friday late afternoon, well at Hot Rock Backpackers hostel on corner of Arawa and Ranolf Streets had a casing blow out and flooded scalding waters across driveway and washed away gardens. Quenched by Fire Department (AD Cody, Fieldbook-28).

0211: Well at Kowhai Colonial Motel was found to have a broken casing at ~28 m depth. Had been lifting silts for >1 year (RWD staff, pers. comm.; Gary Brown, pers. comm.).

In nature there are no rewards or punishments; there are consequences

- Horace Annesley-Vachell (The Face of Clay)

APPENDIX VII:

Types of Geothermal Activity

Surface geothermal activity can be grouped according to types of processes that are occurring and the nature of deposits and landforms which result. Surface manifestations of geothermal activity are caused by the effects of two extreme end member processes: deep geothermal waters reaching the land surface, and by steam and gases boiling off from a deep aquifer. A continuum of intermingling between these two end member processes also occurs, which produces many intermediate forms of surface effects and features.

Groundwater availability and mixing, or its absence, greatly alters forms and appearances of surface features, which occur because of the addition of water and dissolved oxygen contained in it. Air entrainment allows oxidation of sulphides within exsolved gases and geothermal fluids, which in turn produce strong acid attack on most rock forming minerals. To assist with classification of surface geothermal features, the following list describes what constitutes each class and form. This also allows uniformity when discussing these features.

Generally, below about 73°C photosynthetic algae ("blue-green algae" or cyanobacteria) can grow in waters containing sulphides and of alkaline, neutral or weakly acidic pH. Above that temperature photosynthetic algae do not grow and filamentous white to grey algae grow instead. Pools with only weak upflows of geothermal fluids or steam and gases are generally clear waters above about 73°C, but below that temperature these waters are usually opaque or cloudy white, due to colloidal sulphur produced from the sulphide oxidation metabolism by bacteria. Above ~73°C sulphur does not form but sulphates occur instead, so waters tend to remain clear.

Geysers: Springs with intermittent outbursts of boiling waters, where water is ejected by steam production. This is interspersed by quiescent episodes of recharge prior to the next eruption of water. Almost invariably, all are of neutral to alkaline deep sourced geothermal waters, which boil and eject water without any ejection of rocks or solids. Geysers are usually located close to a local ground water or stream water level; short lived in geological timescale. Acid water geysers are very rare; the only New Zealand example is Hakareteke (S49N) geyser at Waiotapu, which is a clear, sinter depositing acid geyser.

Neutral to Alkaline Springs: These are deep sourced geothermal water outflows without any significant mingling of shallow fresh waters. They may be either boiling or nonboiling, but are invariably clear waters, $>73^{\circ}\text{C}$, high chloride, low sulphate and saturated with dissolved silica. Dispersion of outflow at the surface usually results in deposits of amorphous silica on the spring walls and surface outflow channels, with algae and bacterial growths along cooling outflow plumes. Note that outflows do not have to occur across the land surface; many such springs flow into surrounding ground and appear as calm or boiling clear pools, yet have only underground outflow channels.

Fumaroles: Dry steam and gas vents without water droplets, usually discharging under pressure with audible noise of steam ejection. Most commonly found in active volcano craters and less commonly in geothermal systems.

Solfatara: Areas of hot barren ground boiling to the surface, which are typified by sulphur deposition, with exfoliating and heaving or buckling of the ground surface due to oxidation of sulphide to sulphur (or sometimes by sublimation of sulphur), which grows sulphur crystals in voids to heave ground apart in prominent mounds of sulphur cemented sediments. Associated with boiling conditions extending from the geothermal aquifer to the surface.

Uncommon in New Zealand, the best example being within White Island Crater and at the Puarenga Stream delta in Sulphur Bay, Rotorua.

Mud Pool: A viscous muddy pond that may build up mounds or ridges of mud as the pond dries out in dry or warm weather. Rainfall may dilute these muds to temporarily form a turbid muddy pool. Formed by steam and gas heating of surface ground; the acidic by-products attack the surrounding soil and materials to break these down into suspended solids. May be discoloured by small additions of sulphides, or creamy white if free of sulphides or sulphur.

Mud Cones (Mud Volcanoes): Steam and gas heated and altered ground with very little free water available to form pools or mud ponds. Highly viscous muds can then spatter away from gas vents to build up stiff mounds or cones. May break down in wet weather conditions, but rebuild in drier weather once more. Mud cones are a rare form of surface feature, although boiling geothermal ground is common.

Turbid Pools, Lakelets: Groundwater pools with significant amounts of gas and steam entering them to oxidise sulphides and produce acids, which attack and break down surrounding ground. Colloidal sulphur suspension produces turbid water and black sulphur or sulphides may produce a variety of colours. Usually these are warm, tepid, or even cold water pools. Above about 65°C these waters are clear, due to oxidation of sulphur to colourless and soluble sulphates.

Craters and Dolines: Circular or oval depressions forming distinct craters may form by either collapse or eruption. Collapse craters form by subsurface chemical and physical (tunnel) erosion of materials so that ultimately the ground surface falls into a void. Eruptions form craters by sudden production of steam to violently expand and throw open a crater, accompanied with production of airborne debris.

These are called hydrothermal eruptions, which are driven by physical changes of form (usually hot water to steam); they do not involve any chemical release of energy, as occurs in true explosions.

*Discovery consists of seeing what everybody else has seen and
thinking what nobody else has thought*

– Albert Szent-Gyorgyi (in I.J. Good – The Scientist Speculates)

INTRODUCTION TO APPENDICES VIII TO XI

The following four appendices are not submitted as part of this thesis, but are attached here because they supply useful and relevant information about the Rotorua Geothermal Field (RGF). In particular, they help to illustrate how surface geothermal activity in the RGF varies through time and that apparent influences to cause these changes have been discussed and considered by other studies.

Beware that you do not lose the substance by grasping at the shadow

- Aesop (Fables)

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CHANGES IN THERMAL ACTIVITY IN THE ROTORUA GEOTHERMAL FIELD

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Abstract—During a period when geothermal fluid was being withdrawn for energy use at an increasing rate, the level of natural hydrothermal activity in the Rotorua geothermal field declined to an all-time low in the mid 1980s. Total heatflow from a major hot-spring area fell by almost 50 percent, springs ceased their flow, and geysers displayed abnormal behaviour consistent with a low aquifer pressure. Since the enforced closure of bores within 1.5 km of Pohutu Geyser, signs of recovery, including a return to "normal" behaviour of Pohutu and Waikorohihi Geysers, a resumption of activity at Kereru Geyser, and an increase in water flow from some springs, have been recorded.

INTRODUCTION

The natural thermal surface activity associated with the Rotorua geothermal field is well known and has been described by many visitors to the area since the earliest European occupation of the region (Donaldson, 1985). Before that, the Maori used the natural features for a variety of purposes including cooking, bathing, heating and processing a range of natural products. Thermal areas have a special place in Maori culture and are listed among their *taonga* or most prized possessions. Thus, there is a long history of knowledge of the natural activity, but it is only in very recent years that this knowledge has been quantified.

This paper draws on the work and observations of many people, much of which has not been published. Reference to unpublished papers has been avoided as much as possible, but, if proper credit is to be accorded to the original observers, such reference must be made in some cases. In particular, many observations were recorded in the progress reports of the Rotorua Geothermal Monitoring Programme, prepared for the (then) Ministry of Energy of the New Zealand Government. The progress reports themselves are not publicly available, but the events recorded in them were there for all to see, and the reference to those reports in this paper serves to identify the original observer. Other material used here is based on data accumulated by one of the authors (ADC) since 1981, and is held in the files of DSIR Geology & Geophysics in Rotorua.

The distribution of thermal activity in Rotorua is shown in Figs. 1 and 2. The most spectacular and well-known area is Whakarewarewa, at the southern end of the city, with its geysers. Geysers are not seen anywhere else in the field, although one did once play in the north at Ohinemutu (Grange, 1937). Other thermal phenomena known at Whakarewarewa and elsewhere in the field include hot (some boiling) springs, hot pools (including Roto-a-Tamaheke, usually described as a lakelet, with a surface area of about 11 000 m²), hot mud (sometimes forming mud volcanoes), and fumeroles. Extensive sinter aprons demonstrate the long history of activity in the

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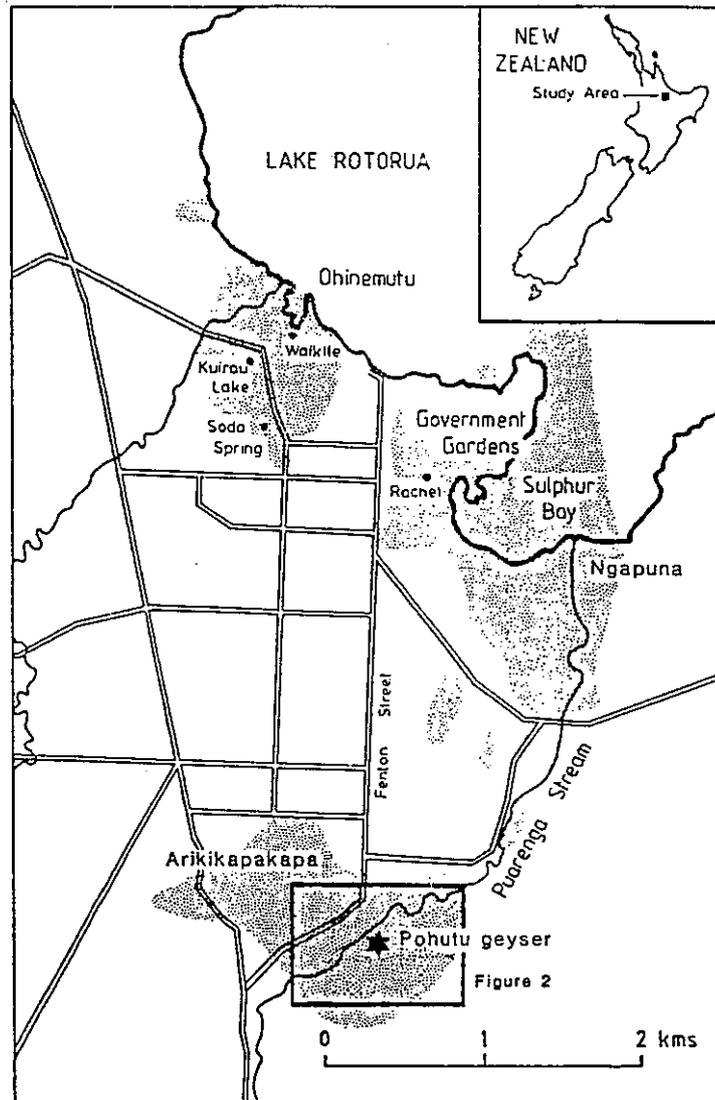


Fig. 1. Map of Rotorua City showing the location of the principal areas of hydrothermal activity and locations named in the text. The inset shows the location of Rotorua in the North Island, New Zealand and the area covered by Fig. 2 is shown.

area. The existence of sinter and hydrothermally altered rock, indicating the earlier presence of hot springs along a former high shoreline of Lake Rotorua is evidence of hydrothermal activity about 20 000-50 000 years ago (Wood, 1992). All the presently active thermal areas lie within, or are adjacent to, urban areas and so they are under almost constant observation, albeit by a multitude of generally untrained eyes.

The natural thermal activity is very important for the local tourist industry, providing both spectacular visual amenities and a source of heat for the very popular spa pools, offered as an attraction by many motels and hotels in the city. The "energy" use of the geothermal activity was just part of a growing application of the resource by the local populace to a variety of industrial and domestic uses, and since the late 1970s concern has been widely expressed that drawoff of

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thermal water was affecting the natural thermal features. Any substantial change in the natural activity would be of great significance to the tourist industry. When the Government decided in 1986 to close all of the bores within 1500 m of Pohutu, the best known and today the most spectacular geyser at Whakarewarewa, the reason given for this action was the protection of the natural activity from the changes that were occurring and were perceived to be placing in jeopardy the very existence of several great tourist attractions.

Since the mid-1970s, an increasing number of people have expressed the view that growing exploitation of the geothermal resource was having a direct and damaging effect on the natural activity. Without adequate records of the changes in the surface activity, or even a satisfactory estimate of the actual quantity of fluid drawn from wells, it was very difficult to show a convincing correlation between increasing drawoff and declining activity. However a picture was gradually built up that gave the Government reason to force the closure of many wells in the city.

The circumstances leading up to the Government's decision to close wells are summarised by Allis and Lumb (1992). Significant factors were:

- Continued decline and other changes in a group of springs close to a major production wells;
- Continued fall of pressure in an aquifer which fed many wells, observed as a water level decline in a number of monitoring wells established in the city between 1982 and 1984;
- Changes in the frequency, duration and character of eruptions of Pohutu geyser;
- The large total mass discharge from wells of around 31 000 tonnes per day (winter drawoff). This was estimated to be 40% of the natural deep hot upflow of the Rotorua system, and therefore further major impacts on surface features were considered to be inevitable.

These and other changes in the natural activity, particularly of the alkaline chloride features, are described in the following sections along with changes that have occurred since the closure of the wells. The paper is split into three main sections: the natural state of the field before significant exploitation; the period of relatively uncontrolled exploitation (up to 1986); and the period since 1986 when bores were closed down.

THE "NATURAL" STATE OF THE SURFACE MANIFESTATIONS AT ROTORUA

It is particularly difficult to form an exact picture of the truly "natural" state of the thermal features in Rotorua because, even from the earliest days of European settlement, there is evidence of human interference. Of great importance in this regard, are the engineering feats of Rotorua's Resident Engineer in the late 1800s, Camile Malfroy, who not only piped and channelled hot water between springs and baths around the city, but also built dams and channels around several natural features in an attempt to control their activity and ensure displays for visitors (Malfroy, 1891; 1892). Malfroy had made detailed observations of the activity at Whakarewarewa and, by diverting water on the surface, simulated the various natural situations that he had seen, and was able to influence the time and duration that several geysers would play.

A natural event which had a significant and lasting effect on the surface activity at Rotorua, was the eruption of Mt Tarawera, some 25 km distant, on 10 June 1886. Many contemporary accounts, including newspaper reports, refer to increased thermal activity in Rotorua immediately after the eruption. While many of these reports may have been made by untrained observers, those referring to some of the natural features are so consistent and persuasive that they leave little doubt that several features were affected, and that new features formed at this time. Among the new features, one of particular interest is the Prince of Wales Feathers, a geyser at Whakarewarewa. This geyser, called, by Malfroy (1891), "The Indicator" because its playing generally indicated an

imminent eruption of Pohutu, has no Maori name, suggesting that it did not exist before Europeans lived in the area. It was not included in a detailed map of Whakarewarewa based on fieldwork completed by the surveyor E.C. Goldsmith in April 1885, but the fieldbook of a geologist, A.P.W. Thomas, now held by the University of Auckland, records a visit on 18 July 1886 when a "new hole", close to Pohutu, was playing. The 23 June 1886 issue of the New Zealand Herald describes an artist as having "taken a series of views ... of the new geyser at Whakarewarewa."

Donaldson (1985), in his review of the long-term changes in thermal activity in the Rotorua-Whakarewarewa area, described many changes, not all of which are necessarily or obviously consistent with a declining geothermal field. There is a background of both decline and recovery of individual features against which it is difficult to detect a consistent trend, and it is only through a broad-based approach, which looked at the field as a whole, that this has been possible.

Bradford (1992a) has shown that, up to the time that bores were required to be closed, the seasonally averaged pressure of the shallow "production" aquifer, tapped by the many wells in the city, fell by about 0.5 to 0.7 bar. This pressure change is equivalent to a water-level fall in wells of about 5 to 7 metres and it is reasonable to suppose that, in its unexploited state, the field possessed more alkaline-chloride springs, some at higher elevations, and perhaps fewer steam-heated, acid-sulphate ones than it does today.

The effect of a falling water table is clearly demonstrated in Rotorua by the existence of extensive areas of sinter, many of which stand at a much higher elevation than any present-day alkaline-chloride springs, and could not possibly have been built up by today's out-flow of thermal water. From about 60 000 to 22 000 years ago, Lake Rotorua stood at about 360 metres above sea level following the blockage of a former lake outlet during the eruption of the Rotoiti Breccia (Kennedy *et al.*, 1978). About 22 000 years ago the lake level fell to 290 m a.s.l. and has remained in the range 278-293 m a.s.l. to the present day. During the period of high lake level, thermal springs discharged at much higher elevations than today and formed the high-level sinter deposits in the Utuhina Valley.

CHANGES IN THE NATURAL ACTIVITY DURING EXPLOITATION UNTIL 1986

Exploitation of the geothermal waters in Rotorua has increased steadily over the years and by 1944 approximately 50 geothermal bores were in use (Modriniak, 1945). The earliest drilling date identified by Modriniak was 1926, but wells may have been in use before this. The total output from these wells, during the winter months, was estimated to be no more than 450 tonnes per day. Geothermal bores proliferated from this time, to peak at about 400 in use, drawing some 31 000 tonnes per day in the winter of 1985 (Minister of Energy, 1985). Nearly all of the thermal water was drawn from aquifers in the top of either the Rotorua Rhyolite or the Mamaku Ignimbrite (Wood, 1992) and discharged into near-surface groundwater via "soak bores", generally less than 30 m deep.

The winter drawoff in 1985 was almost double the natural flow from Whakarewarewa of approximately 17 000 tonnes per day (Ministry of Energy, 1985). Based on measurements of chloride flux out of Lake Rotorua (Glover, 1992), and Glover's assumption that some 27 000 tonnes per day of "shallow soakage" from soak bores discharges through the lake bed, it can be concluded that the total natural outflow from the entire Rotorua field may be at large as 78 000 tonnes per day. Part of this discharge may be derived from a separate geothermal upflow indicated by high conductive heat flow through the lake floor between Mokoia Island and Rotokawa (Whiteford, 1992). Thus the winter drawoff from Rotorua bores represented a significant fraction of the natural mass flow from the Rotorua field. Although the pressure decline in the geothermal

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aquifer at Rotorua (0.5 - 0.7 bar) is small compared to that in other exploited fields in New Zealand with larger drawoffs (Bradford, 1992a) it is difficult to avoid the conclusion that bore drawoff has affected the natural surface features at Rotorua. Major effects of exploitation on hot spring discharge are documented for the Wairakei geothermal field (Glover, 1963 and 1965; Allis, 1981).

However, up to the early 1980s, little high quality information existed on which to base a reliable description of the natural state of the surface activity. Thus it was very difficult to demonstrate convincingly that the drawoff through the many shallow bores in the field was actually the cause of changes that were reported.

Summertime drawoff in the mid-1980s dropped to approximately 25 000 tonnes per day, and this was accompanied by a rise in pressure in the aquifer of about 0.07 bar (Bradford, 1992a). Small though this change was, those who were monitoring the natural activity (including one of the authors, ADC) observed changes in several springs which they could not relate to climatic changes and which were likely related to the seasonal variation in aquifer pressure. It should be noted here that Bradford also investigated long-term rainfall changes and concluded that about half of the pressure drop in the production aquifers resulted from a decline in rainfall, together with the increasing urbanisation of Rotorua City and the consequent diversion of runoff waters and ground drainage. A major conclusion of the monitoring programme (Ministry of Energy, 1985) was that, because seasonal changes in aquifer pressure reflected so closely the seasonal changes in drawoff, there must be a casual relationship and that a long-term increase drawoff was causing a long-term fall in aquifer pressure.

Because the Whakarewarewa area has been investigated in such detail, and because it contains so many prominent and well-known natural features, changes that have taken place here are treated separately from those in other parts of the geothermal field.

Whakarewarewa

Prior to the Rotorua Monitoring Programme, established by the New Zealand Government in 1982 (Allis and Lumb, 1992; Ministry of Energy, 1985), the only comprehensive survey of the natural surface features was one carried out from 1967 to 1969 by E.F. Lloyd of the New Zealand Geological Survey. Detailed results of this survey were not published, except in a popular summary by (Lloyd, 1975), but are available in the Survey's files. The Rotorua Geothermal Monitoring Programme included a re-survey in 1984 of all sites visited by Lloyd that were still accessible. Some 539 features were re-surveyed and a brief description of each, along with estimates of heatflow, for those features at which they could be made, was presented by Cody and Simpson (1985). The results of the two surveys are summarised in Table 1. Only a very small number of the springs at Whakarewarewa are mentioned in this paper and their locations are shown in Fig. 2.

Table 1. Changes in natural activity at Whakarewarewa 1967-1984
Data from Cody and Simpson (1985) and Simpson (1985)

	Number	1967/69 Heatflow MW	1984 Heatflow MW	Heatflow change MW
Features surveyed, total	539	141.4	94.9	
Heatflow obtained in both surveys	285	134.6	92.1	-42.6
Features with increased heatflow	95	15.8	28.6	+12.8
Features with decreased heatflow	160	111.6	56.2	-55.4
Features with unchanged heatflow	30	7.2	7.2	-
Features inactive in second survey	5	0.1	0.0	-0.1
Ground surface heat flow (1985)		10.3	7.9	-2.4

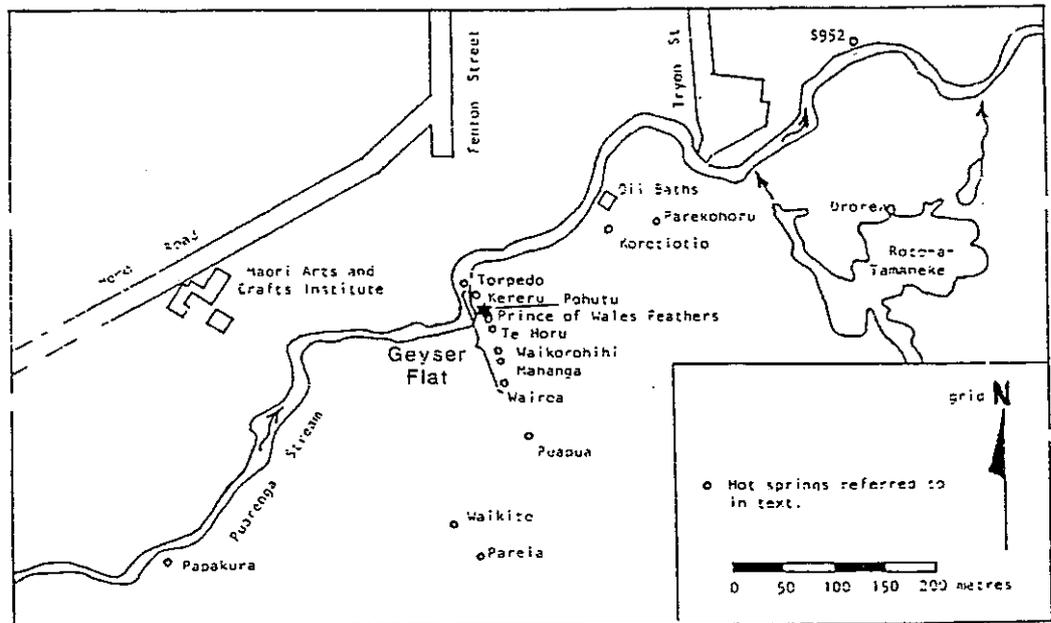


Fig. 2. Location of springs and geysers in the Whakarewarewa area.

Of the 539 features examined in both surveys, the heatflow of only 285 could be measured on both occasions and a net reduction in heatflow, in those re-measured springs, of almost 43 MW (over 30%) was indicated. Although, as Cody and Simpson point out, a direct and literal comparison of the two sets of data would be invalid because they were not always collected in the same meteorological conditions and because many of the features are subject to direct human interference, an inescapable conclusion was that thermal activity in the area had declined. Table 1 demonstrates the importance of carrying out a comprehensive survey of natural features: 95 had shown a combined increase in heatflow of over 12 MW (almost a doubling for that particular group of features).

Ground temperature measurements were also made along with the spring surveys (Cody and Simpson, 1985; Simpson, 1985) and heat flow through the ground surface, derived from these measurements is summarised in the bottom row of Table 1. The indicated reduction in heatflow of almost 25% is consistent with the spring data.

Further confirmation of a decline in the natural activity at Whakarewarewa came from chemistry of the springs. Grange (1937) reported that springs with acid sulphate and mixed waters were less numerous than the chloride ones. In the 1984 re-survey of springs at Whakarewarewa only 54 features out of 307 whose pH was measured, indicated alkaline or neutral pH. In addition, the number of chloride springs dropped from a reported 112 in 1968 to 100 in 1984 (Cody and Simpson, 1985). This trend of a decreasing number of chloride springs and increasing acidity is consistent with a drawdown of aquifer pressure and increased steam heating of near-surface waters.

Whakarewarewa is drained by the cold Puarenga Stream which typically flows at about $1.2 \text{ m}^3/\text{s}$ and is heated as it passes the thermal area from about 12°C to 20°C , predominantly by outflows of water from the surface features and a few springs and seepages in the stream bed. Heat and chloride flow into this stream along with chloride/sulphate ratio were monitored from late 1982, in the hope that any changes observed would reflect changes in overall thermal flow from all of the surface features of Whakarewarewa. Unfortunately, up to the time that bore closures began in 1986, no unequivocal trend in any of these parameters was seen. In 1985 there had been an

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unexpected increase in chloride flow, but this was later shown to be related to discharge from spring S952 (Fig. 2) which formed abruptly following a hydrothermal explosion after a nearby well casing had fractured (Glover, 1989).

The results from the 1967-69 and 1984 thermal activity surveys, and the apparent inconsistencies that can be seen when only small or selected groups of features are studied, show that a valid picture of the overall level of thermal activity can only be obtained through a comprehensive investigation. However, it is also true that careful observers of the area from both DSIR and the University of Auckland, although concentrating their observations on a small number of features, were convinced of a decline in overall activity and it is of interest to summarise the changing activity from a small number of features that were the subject of those observations. Fig. 3 shows periods of eruptive activity of eight geysers in the Whakarewarewa thermal reserve and of overflow of two other features outside Whakarewarewa.

Until March 1979, Papakura Geyser was actually a continually splashing spring, erupting water about 3 to 5 m high and overflowing 2-5 l/s at the surface (Bradford *et al.*, 1987). It is a key feature because its demise, in 1979, came after a very long period during which it was known to have faltered only three times: several days in 1924, a few hours 1927 and a few hours in 1953. It was the cessation of Papakura's eruptions which was directly responsible for the NZ Department of Scientific and Industrial Research (DSIR) calling for a monitoring programme in Rotorua (Allis and Lumb, 1992). Fig. 3 gives only part of the story because after its eruptions ceased, the water-level in the vent continued to fall and by 1986, when the Government called for wells to be closed, it was about 2 m below overflow and about 0.4 m below the level of the adjacent cold Puarenga Stream.

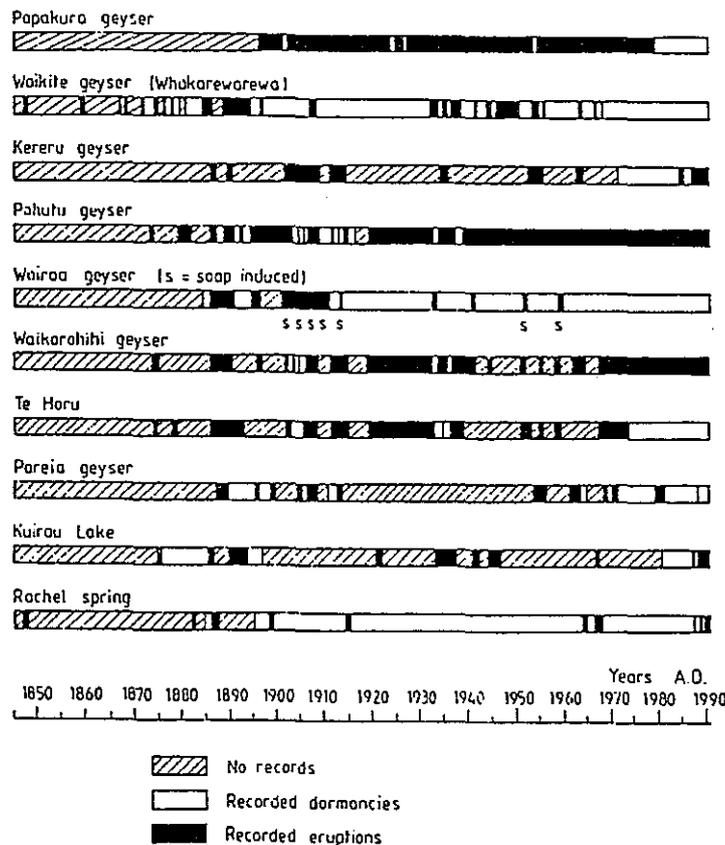


Fig. 3. Time logs of the activity of some major geysers and hot springs in Rotorua. For Kuirau lake and Rachel spring active episodes are those with boiling and surface overflow, whereas all other features are eruption geysers.

Before the turn of the century, Waikite and Wairoa Geysers were the principal and most spectacular features of Whakarewarewa. Waikite was prominently located almost 13 m above Geyser Flat, the site of most of the presently remaining geysers in the thermal reserve, and Rotorua's principal thoroughfare, Fenton Street, was aligned to provide an uninterrupted view of the geyser from the town (Smith, 1882). Eruptions from this geyser reached heights of 6-20 m, and remained consistently in this range until its most recent eruption in 1967. Because of its prominence, Waikite's activity has been carefully recorded since the late 1870s and, as is evident from Fig. 3, it has been extremely variable. It can also be seen from Fig. 3 that the current period of dormancy is no longer than that which occurred earlier this century. However, the present dormancy is accompanied by a dramatic lowering of the water-level in the geyser's vent, something not reported during the previous period of inactivity.

Natural activity at Wairoa Geyser, located on Geyser Flat below Waikite, was only documented for a few years in the late 1800s. It appears to have erupted only spasmodically, but its eruptions were generally very impressive, sometimes reaching 60 m in height. In the early years of this century, Wairoa was frequently induced to erupt by the introduction of soap into its vent, a practice forbidden by Malfroy during his tenure as Resident Engineer. It was "soaped" at least 80 times during 1901-1904, and on only four of these occasions did it fail to erupt (N.Z. Herald, 7 December 1904). Artificially induced eruptions, often for the benefit of distinguished visitors, continued until 1913 but it is not known whether there were any natural eruptions in this period. A single natural eruption is known to have occurred in December 1940 and the geyser is believed not to have erupted, naturally, since. In the 1950s a number of "soaped" eruptions were induced by scientists and the last of these known to be successful occurred on 9 March 1959 (DSIR Geology & Geophysics records). An attempt to induce an eruption only two months later failed and it is believed that no attempts have been made since this time.

During the periods between "soaped" eruptions, the water-level in Wairoa's vent fell to about 2-3 m below overflow, although it was reported as much as 5.5 m below overflow on one occasion in 1955 (DSIR Geology & Geophysics records). In 1982, at the beginning of the monitoring programme, the water-level stood at 2.8 m below overflow and progressively fell to 4.1 m by mid 1987 (Bradford *et al.*, 1987). During this period the temperature of the water in the vent fluctuated between 99 and 93°C. The drop in water level was not necessarily to be viewed with alarm, in the light of its history of such low water-levels. However, its water chemistry and previous links with other geysers identified by tracer experiments indicated that a significant change had occurred. No chemical analysis of Wairoa geyser water is known of before 1982, when it was found to be highly acidic (pH <2) although it was still a clear, boiling spring (Cody and Simpson, 1985). Prior to this, its water was assumed to have been alkaline on the basis of a connection, demonstrated by tracer dye, to the known alkaline geysers Pohutu, Waikorohihi and Te Horu (Lloyd, 1975). Subsequent tracer tests in 1985 (Cody and Simpson, *ibid*) failed to show the connection found earlier and it was concluded that a change in water feed to the vent had occurred.

Pohutu, Waikorohihi and Te Horu are three interconnected features, all of which geysered or overflowed periodically until early 1972. For at least 120 years prior to 1972 Te Horu, a large vent adjacent to Pohutu, had been a true geyser with eruptions and large surface overflows. In 1972 it stopped overflowing and by 1987 its water-level had fallen "several metres" below overflow (Bradford *et al.*, 1987). This somewhat vague description of its water-level was necessary because, historically, it has always fluctuated over a range of about 10 m, although in recent years it remained below overflow (McLeod, 1987). Concern that the water-level, at its lowest point, might be below that of the nearby cold Puarenga Stream led to intensive monitoring of this feature for two years. The drop in reservoir pressure suggested by such a large fall in water-level was particularly significant because Te Horu was known to be closely connected to other features on Geyser Flat, implying that these must also have experienced a similar decline in feed pressure

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(Bradford *et al.*, 1987).

Te Horu's overflows are estimated from photographs and observers' accounts to have been about 200 litres per second until the late 1960s. During 118 days of continuous monitoring in 1958-1959, both Pohutu and Te Horu geysers played about five times daily with a total duration of about 13 percent of the time (Cody, 1986a). Te Horu's average outflow temperature was about 60°C. The cessation of this flow, assuming it was not being diverted to other discharging features, indicates a decline in average surface heat flux (relative to an ambient temperature of 20°C) of about 4 MW.

Waikorohihi geyser has never been one of Rotorua's spectacular features and was often neglected in nineteenth century descriptions of Whakarewarewa. However, Fig. 3 shows that this geyser has displayed few confirmed periods of dormancy. In the early 1900s it was possibly the most active of all the Whakarewarewa geysers, usually erupting to 6-12 m, and during this period is reputed to have played for 229 days without ceasing (Gooding, 1913).

Instrumental monitoring of Waikorohihi began in February 1984, making possible a detailed comparison of its activity with that of other features on Geyser Flat. On the basis of these data, held in the files of DSIR Geology & Geophysics, both the daily number of eruptions and the total daily duration of eruption time, for Waikorohihi and Pohutu show a correlation ($r=0.72$). Pohutu's eruptions (see below) also have a marked correlation with wind direction ($r=0.8$), explained by Weir *et al.* (1992) through the intermediary action of Te Horu cauldron. In the early 1980s, Waikorohihi's eruptions became weaker and often faltered when either Pohutu or its other neighbour, Prince of Wales Feathers geyser, began to erupt. In 1985-1986, Waikorohihi developed abnormally long periods of dormancy, typically lasting 20-35 hours, compared with about 1 hour which was previously considered to be usual.

Pohutu is the largest and most conspicuous of all the geysers presently active at Whakarewarewa. It is the best known to the general public, featuring on tourist posters and postage stamps, and virtually serving as a symbol of New Zealand tourism. When the Government decided that wells in Rotorua must be closed, distance from Pohutu was used to determine those to which this would apply.

Observations of Pohutu's eruptive activity extend back into the late 1870s, but it was the early 1900s before detailed eruption data were routinely recorded. Although in subsequent decades such data collection sometimes lapsed for years at a time, it is clear that by the 1970s Pohutu geyser had become more active than ever previously observed. Indeed, during Malfroy's time as Engineer in Rotorua, Pohutu, in its natural state, was "sometimes inactive for several months" (Malfroy, 1892). By diverting surface waters from other geysers on Geyser Flat, Malfroy set out to change this state of affairs and was able to induce regular eruptions of Pohutu twice every twenty-four hours. Regular geyser displays continued for several years, while he was there to maintain his "special works" (Malfroy, 1892). By the 1930s, eruptions of Pohutu had become quite rare, with one period of dormancy lasting at least three years (Donaldson and Cody, 1984).

Fig. 4 is a series of histograms showing the distribution of the duration of individual eruptions of Pohutu. Although from 1900 to about 1920 eruptions may have been infrequent, a much larger percentage of those eruptions lasted over one hour than at any time since. After the 1920s, the distribution of eruption duration settled down to a fairly consistent uni-modal, skewed pattern with a predominance of eruptions lasting 15 to 30 minutes, and very few, if any, lasting less than 5 minutes. This situation remained until 1982, after which the distribution began to adopt a bi-modal form and by 1986 about 17% of all eruptions were of less than 5 minutes duration, with almost half lasting less than 10 minutes. Another characteristic of Pohutu's eruptions in mid-1986 is that, after the first two to five minutes, they frequently degenerated into a lower energy, splashing display, rather than maintain the unfaltering full column of boiling water, typical before this time (Cody, 1986b).

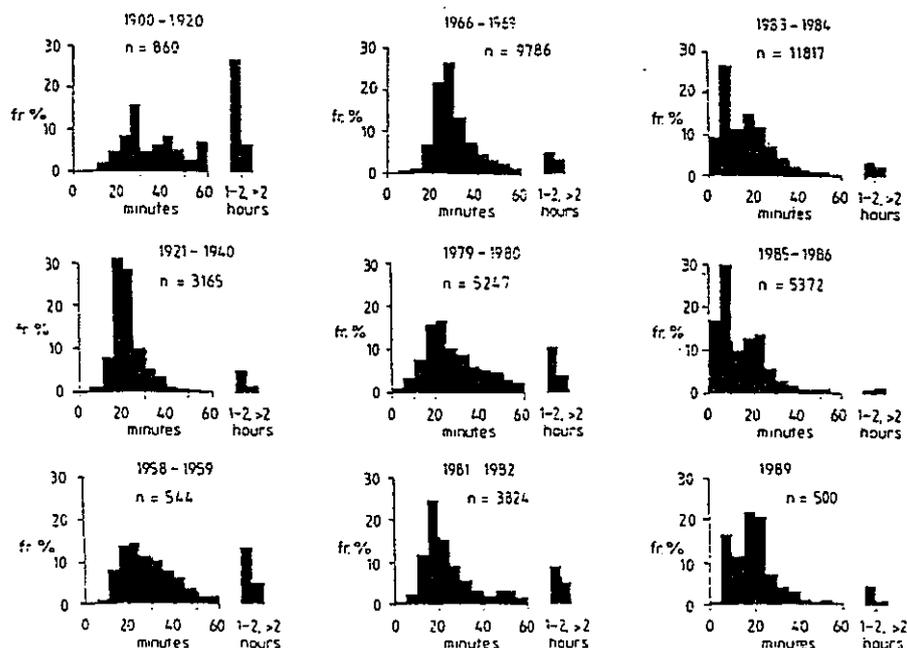


Fig. 4. Histograms of Pohutu geyser eruption durations showing the percentage of eruptions whose duration fell within the time limits shown on the x-axis. Groupings are five-minute intervals up to one hour, then 1-2 hours and more than 2 hours. Each histogram is for the range of years shown, and the number of eruptions (n) in each sample is indicated. Note that n is not the total number of eruptions in the given period.

Another group of springs at Whakarewarewa, important in raising an awareness of possibly deleterious changes taking place within the aquifer, is the Ororea group, located immediately north of the hot lakelet Roto-a-Tamaheke (Fig. 2). These springs discharge water of relatively high chloride concentration (up to 800 mg/l) and include two that boiled continuously prior to 1982. In 1982, during cold water injection into a new well being drilled only 150 m away, these two boiling springs ceased ebullition and their water level dropped, along with that of Roto-a-Tamaheke and Parekohoru spring to the west (Bradford *et al.*, 1987, Lloyd, 1983). These springs all resumed flow and boiling after about a week, but a fall in their chloride concentration appeared a few weeks later. The well was shut in during this period. In late April 1983, both Ororea springs displayed pronounced falls in temperature, water-level and chloride concentration, but on this occasion there was no accompanying recession of Roto-a-Tamaheke or Parekohoru. While the July 1982 recession was short-lived, and could be related to cold water circulation losses during nearby drilling activity, after the 1983 failure no sustained recovery occurred for almost four years. The only historically known previous failure of these springs had been in the 1940s when there was a prolonged and total failure of all spring activity in the Roto-a-Tamaheke area. However, until this time the Ororea springs had been continuously and intensively pumped over many years to supply both the Ward and Spout Baths complexes (DSIR Geology & Geophysics files). The presence of thin sinter beds within lake sediments below the present sinter surface, attests to many earlier episodes of low water-level in Roto-a-Tamaheke during prehistoric time.

Roto-a-Tamaheke is the largest thermal feature in the Rotorua geothermal field. Although the outflow from this lakelet varies greatly because of artificial drawoff to a nearby bath-house, its heatflow was estimated, in 1984, by Cody and Simpson (1985) to be approximately 33 MW, compared with 60 MW in the 1967/69 survey. This fall in heatflow is attributable to both a drop

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in temperature (from 64 to 49°C) and a reduction in flow (from 15 to 2 l/s at one of the outlets). Taking the 1967/69 and 1984 heatflow figures at their face value (perhaps questionable, because of the great fluctuation in the outflow from the lakelet), suggests that the fall in heat flow from Roto-a-Tamaheke alone may account for some 60 percent of the total decline from the whole of Whakarewarewa. This change appears to be disproportionately large, as the feature provides only about 40 percent of the total heatflow from Whakarewarewa, according to Cody and Simpson (1985).

Bradford (1992b) describes the flow changes from Roto-a-Tamaheke between 1984 and 1990 in detail. Her total heatflow value of approximately 8 MW in 1984 includes only the heat in the outflowing water, whereas values presented by Cody and Simpson (1985) included estimates of evaporation and radiation as well. Unfortunately, repeated determinations of heatflow from the lakelet have not been made on a sufficiently uniform basis to allow a valid comparison between Bradford's (1992b) value and those reported by Cody and Simpson (1985). A very rough comparison suggests that the heat in the outflowing water in 1990 (given by Bradford as 12-16 MW) may have been similar to that in 1967/69 (*cf* Cody and Simpson's all-inclusive value of 60 MW).

Features outside the Whakarewarewa area

Although Whakarewarewa is the most well-known area of natural thermal activity within the Rotorua geothermal field, other natural features occur, particularly in the northeast of the city: at and around Ohinemutu and the Government Gardens; near the mouth of the Puarenga Stream, and at Ngapuna. The historic activity of two of these features, Kuirau Lake near Ohinemutu and Rachel Spring in the Government Gardens, is shown at the bottom of Fig. 3.

Donaldson (1985) suggested that the features near Ohinemutu might be fed from a source separate from that at Whakarewarewa because of the relatively minor decline in activity there, compared with the large amount of fluid being withdrawn from the nearby downtown Rotorua City area. Recent chemical studies (Stewart *et al.*, 1992; Giggenbach and Glover, 1992) support this notion. Although Donaldson remarked upon the relatively minor decline in natural surface activity, he still noted that significant changes have taken place to account for the differences reported by various observers over the years. For example, at Ohinemutu, a geyser, rather confusingly also called Waikite, played until about 1865. A pool of the same name remained but appears to have declined to the point of being just "a few puddles" by 1985, by which time its broad basin was largely filled with debris and soil.

Kuirau Lake has displayed a varied behaviour since the 1880s with many episodes of no flow and low temperatures (Bradford *et al.*, 1987). In the 1970s and 1980s its outflow was erratic and weak (0-5 l/s) and about neutral (pH 6.5-7.0), remaining so until the time of the enforced bore closures in the city.

Since the mid-1940s, Rachel Spring has been the only remaining alkaline spring in the Government Gardens. In a report from 1847 (Johnson, 1847) it is described as erupting in a roaring jet 1-2 m high, and occasionally to 5 m. For many years water has been pumped from this spring to supplement thermal bore water that supplies the nearby public baths, the "Polynesian Pools". Rachel spring has a circular vent, some 10 m in diameter, and in prehistoric time overflowed to establish an extensive surrounding apron of sinter. Most of this sinter has long since been destroyed, following modifications to the spring outlet designed to increase and divert its flow to provide a supply to the baths in the 1880s. During periods when the spring was not pumped, its water level varied between about 600 and 1300 mm below the former outlet, but both water-level and temperature would rise during pumping. Although during the present century the spring has typically been calm, below overflow and below boiling temperature, it has occasionally erupted explosively with strong overflows; the most recent events, prior to the bore

closures, were in 1964 and 1966-67. Up to the time of the compulsory bore closures the spring was described by Bradford *et al.* (1987) as having shown neither seasonal nor progressive changes that might be associated with a gradually increasing bore drawoff in the city. However, its flow may have been affected by 12 bores within about 100 metres of the spring, drilled before 1964. It is by no means in its natural state and, even in 1991, continues to be pumped several days a week to supply the baths.

CHANGES FOLLOWING THE BORE CLOSURES

During the mid-1980s aquifer pressures continued to drop (see Bradford, 1992a: figs 3 and 4), even though very few new wells were drilled. Simultaneously, Pohutu geyser displayed an unprecedented trend in its eruption pattern, as already described, that many interpreted as indicating imminent failure. Advised of these two trends, the government of the day demanded that wells within 1.5 km of Pohutu be "closed", i.e., cemented up. Formal Closure Notices were not issued until June 1987, but the Government had made its intentions clear before the 1986-87 summer, and several wells were closed before it became compulsory. The Government also introduced a field-wide punitive resource rental, and required that installations supplied with hot water from the bores be brought up to the standard set out in a new Code of Practice (SANZ, 1987). These measures tended to make the operation of a geothermal bore uneconomic, unless it supplied a large demand.

One hundred and six producing wells were closed under the Government's compulsory closure scheme and many others were also closed, generally because of the new high cost of their continued operation. By July 1988 approximately 200 wells were still in use, with daily production down to an estimated 10 500 tonnes (Bradford, 1992a). By 1990, drawoff had further declined to about 7000 tonnes per day (Timpany, 1990). There was an immediate effect on pressure in the production aquifers, seen in the rise in water-level of several monitor wells. By early 1990 this had risen as much as 1.8 metres (0.18 bar) (Bradford, 1992a: figs. 3 and 4).

Since closures commenced, many natural springs have shown visual or physically measurable recovery, unprecedented in the last few decades. Brief descriptions of the more notable recoveries are given below.

Pohutu geyser has resumed longer, full-column, high energy eruptions and by 1989 the short (less than 5 minute) eruptions, that had become common from 1983 to 1986, had virtually ceased. From a small sample of eruptions in 1989, almost 10 percent were of more than one hour's duration, compared with less than 2 percent in 1985-86 (see Fig. 4). Continued visual observations of this geyser suggest that the increased proportion of long eruptions still persists.

Kereru geyser, about 40 metres north of Pohutu, erupted in February 1987 for the first time in more than ten years. It continues to do so, typically erupting 8-15 metres high in a series of gradually rising, pulsating jets that last 30 seconds or so, with copious overflows (about 50-100 l/s). These large eruptions presently occur several times per week. This recovery is interesting because it preceded the compulsory closures. However, several nearby bores were shut in before closure was enforced. The suggestion that such an early closure of bores was widespread is supported by the marked rise in water-level in some monitor wells early in 1987 (see Bradford, 1992a: fig. 3).

Pareia geyser, some 40 metres from the dormant Waikite Geyser, had not erupted since 1981, remaining calm and quiet until it began, quite abruptly, erupting for two days at the end of December 1987. The water-level in the geyser's vent was abnormally high from October 1987 until February 1988. During this period, one of the authors (ADC) was able to collect a water sample from the vent, for the first time ever. This water was alkaline and high chloride, as

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predicted for its location.

The Torpedo, a geyser in the bed of the Puarenga stream, immediately west of Kereru Geyser, also began erupting in December 1987. This geyser had not been described until Malfroy (1891) attributed its existence to the modifications that he had made on Geyser Flat. The noisy, thumping eruptions that began in December 1987 were the first to be recorded for several decades. The eruptions continued for some weeks, but the time of their cessation was not recorded, and there is no record of their having recommenced.

The re-starting of two geysers at Whakarewarewa during December 1987 suggests that some particular event may have caused this new, but short-lived activity, although nothing of note has been conclusively identified. However, there had been a small, shallow earthquake with a Richter magnitude (M_L) 3.5 on 31 October 1987, located in the southwest of the Rotorua Caldera. It is suggested that the briefly renewed activity was a result of this and a coincidence of favourable atmospheric (pressure) and climatic (rainfall) conditions, combined with higher pressure in the aquifer at this time. It is possible that such events will become more common.

Wairoa geyser, described above as having acid sulphate water when analysed in 1982, has shown no signs of renewed eruptive activity. However for a week in December 1989, its water was found to have become alkaline, low in sulphate and higher in chloride. It has subsequently reverted to its usual acid-sulphate and lower chloride state. This brief inflow of alkaline-chloride water coincided with a small earthquake ($M_L=3.0$), which was felt strongly by many people in Rotorua on 7 December 1989. The earthquake was shallow (less than 10km), and its epicentre was in the nearby Whakarewarewa Forest.

One of the authors (ADC) was prompted by the 7 December 1989 earthquake to inspect several thermal springs immediately for changes that may have occurred. In the afternoon following the earthquake, a small quantity of sand and gravel was found splattered around the vent of the Prince of Wales Feathers geyser. It was composed of pyritised silica and appeared to have been ejected from the vent. The activity of this geyser has remained at a high level ever since its formation in June 1886, including during the period of major bore drawoff, but ejecta of this type had never been seen before.

Recovery in the flows of heat, mass and chloride from the lakelet, Roto-a-Tamaheke, are described by Bradford (1992b). By 1990 the heatflow, above 0°C, in the water discharging from the lakelet was 12-16 MW, having increased from about 8 MW in 1984. Bradford noted the interesting contrast between this recovery, which was gradual (over three years), and that of the aquifer pressure, seen in the monitor wells, which was almost immediate, sometimes recognisable within days of the closure of nearby wells. A corresponding, generally gradual recovery is also seen in both mass flow and chloride flow from the lakelet, but it is interesting to note that there was a sharper rise in chloride during the summer of 1986/87 (Bradford, 1992b).

Rachel Spring in the Government Gardens, described above as having been heavily modified with channels constructed to supply a nearby public bath house, displayed a remarkable recovery almost two years after the first bores were closed. Typically, the spring would stand below overflow with a temperature about 85°C, but in October 1988 it began a strong, oscillating boiling with an overflow of about 15 litres per second. It continued in this state for almost four months until mid February 1989 when its water-level declined to about 0.8 metres below overflow. In July 1989, strong boiling and overflow re-commenced and since then this condition has alternated with periods of calm and no overflow, the boiling periods generally lasting longer than the calm ones.

For many decades, Kuirau Lake had an erratic, weak discharge of acidic water, but by 1988 this state had changed to one of strong (45-60 l/s), alkaline (pH 7.0-8.1) outflow which has remained throughout 1991. Its present outflow is higher than observed at any time since the 1940s. The nearby Soda Spring abruptly resumed hot (70°C) alkaline discharge in January 1989, the first

natural flow from this feature for about 30 years.

Although the area of compulsory bore closure did not extend to the Government Gardens and Kuirau Lake, many of the bores in this area are controlled by public bodies who have taken significant steps to reduce their net withdrawal of thermal water by variously installing downhole heat exchangers, re-injecting effluent water back into the production aquifer, or by totally ceasing well drawoff. The renewed activity at Rachel Spring and Kuirau Lake is consistent with the pressure recovery evident in nearby monitor wells and the marked reduction in drawoff that has occurred in this part of the field.

CONCLUSIONS

Natural thermal activity in Rotorua has been very variable throughout documented history, but at no time in the past had it fallen to a lower level than in the mid 1980s. From 1967/69, when the first comprehensive survey of activity at Whakarewarewa was carried out, to 1984 when the survey was repeated, there was a decline in total heatflow of more than 30 percent.

Many alkaline flowing hot springs, including geysers, have undergone deleterious changes or failures in recent decades which had been unprecedented in the record of over 140 years. These changes and failures coincided with, and were consistent with, a fall in average aquifer pressure during a period in which people in Rotorua were increasing their use of geothermal energy. Indisputable evidence of a causal relationship between aquifer pressure and bore drawoff was obtained during the Rotorua Geothermal Monitoring Programme.

Changes in the activity of a number of features, observed after the compulsory closure of a large number of bores in 1987-88, undoubtedly indicate a recovery. The activity of Pohutu geyser, the object of widely expressed concern in 1986 when it displayed numerous short, splashing eruptions and very few long ones, has now almost reverted to its former state. Waikorohihi geyser no longer displays long dormancies that were evident in the mid-1980s and Kereru geyser has large eruptions again. Sporadic recovery of other geysers has been observed but, so far, their recovery has not been sustained. In the north of the city, the increased activity of Rachel Spring and Kuirau Lake is consistent with the reduction in bore drawoff that has occurred in area.

Roto-a-Tamaheke, the largest single natural feature in the Rotorua geothermal field, has recovered to a level of activity similar to that found when the first comprehensive survey of Whakarewarewa was carried out in 1967/69.

The enforced closures of 1987 were extremely controversial, but they have constituted an essential step in preserving the natural activity at Whakarewarewa. The success of this action has shown that, with appropriate management of the field, the natural activity can be retained.

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Unless one is a genius, it is best to aim at being intelligible

- Anthony Hope (The Dolly Dialogues)

APPENDIX IX:

PROCEEDINGS
of
**NEDO INTERNATIONAL
GEOTHERMAL SYMPOSIUM**

**March 11&12, 1997
at Sendai, Japan**

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EFFECTS OF BORE CLOSURE AT ROTORUA, NEW ZEALAND

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Abstract

The waning of natural surface activity, in particular the geysers and hot springs at Whakarewarewa, in the late 1970s and early 1980s, prompted a fear that Pohutu and other geysers would soon be lost. Geothermal and hydroelectric development has destroyed most of New Zealand's geysers. Public concerns led to the establishment of a government funded monitoring programme in 1982, resulting in the government-funded enforced closure of many Rotorua wells in 1987.

Pressures rose sharply during the bore closure programme in 1987-88 and subsequently have continued to rise gradually. The bore closure programme reduced withdrawal by about 60%. During the period of high geothermal fluid withdrawal the level of natural hydrothermal activity at surface features declined by about 50% and several geysers ceased erupting. Since the enforced closure of bores, some surface features have shown signs of recovery and eruptions have resumed from one geyser. Other features have shown no signs of recovery.

Introduction

The Rotorua Geothermal Field of New Zealand is recognised internationally for its setting within the Taupo Volcanic Zone (TVZ) and in particular for its local geothermal manifestations which include the Whakarewarewa hot springs and geysers. Geysers are a relatively rare natural phenomenon Worldwide and Pohutu is New Zealand's largest surviving example. The extraction of subsurface fluid ($\sim 120 \text{ Ktd}^{-1}$) for geothermal power led to the demise of geyser activity at Wairakei, while many geysers at Orakei Korako were flooded after the construction of a hydroelectric scheme (Lloyd, 1972). Although there are over 20 geothermal fields within the TVZ, only four have been noted for their geyser activity: Wairakei, Orakei Korako, Rotomahana and Rotorua.

Public sensitivity to the intrinsic and tourism values of New Zealand's few remaining geysers increased during the 1980s as geyser and hot spring features failed due to the subsurface extraction of geothermal fluid. These concerns, along with a realisation that there was no quantified estimate of the actual volume of fluid extracted, or adequate records of the changes in the surface activity, led to the establishment of the Rotorua Geothermal Monitoring Programme in 1982. This programme soon established the winter daily mass discharge from wells was around 31 000 tonnes (td^{-1}) and represented about 40% of the natural deep upflow of the Rotorua system (Ministry of Energy, 1985).

In the early 1960s and again in the mid-1970s, mass flows via wells increased as additional wells were drilled (Allis and Lumb, 1992). During this time the level of natural hydrothermal activity declined to reach an all time recorded low in the mid-1980s (Cody and Lumb, 1992). In 1986 the Government initiated a bore closure programme and a charging regime for remaining well discharges. Subsequently fluid pressure in the Rotorua system, represented by the water level in the monitor bores, showed strong recovery. Several hot springs and some, but not all geyser activity have shown signs of rejuvenation.

Geological-Geophysical Setting

The Rotorua system, as defined by surface activity and shallow drillholes, covers about 12 km² and is associated with the margin of the Rotorua Caldera (Fig. 1). Thompson (1974) described the regional geology, and Crafer (1974) commented on drillhole geology of Rotorua. Wood (1985) developed a geological model of the Rotorua aquifers, revising it in Wood (1992).

The principal production aquifers are the caldera forming Mamaku Ignimbrites and younger rhyolite domes under the city. Poorly permeable lacustrine siltstones interbedded with sands, gravels and tephra cap the aquifers and form an aquitard. The Whakarewarewa hot springs feed from fractured ignimbrite inside an embayment of the caldera's southern boundary (Wood, 1992). Rotorua City rhyolite lava domes comprise a buried N-S ridge under the city containing mostly sub-boiling water (up to 190°C), which flows laterally through the outer fractured and permeable carapace. Surface activity in the Kuirau-Ohinemutu area is related to structural controls (Kuirau Fault) along the west flank of the northern dome.

Geophysical and geochemical studies indicate the field has an area of 18 - 28 km² at about 500 m depth and a natural heat flux of 430 ± 30 MW. About a third of its area and over half its heat and mass flux occur beneath southern Lake Rotorua (Allis and Lumb, 1992; Glover, 1992).

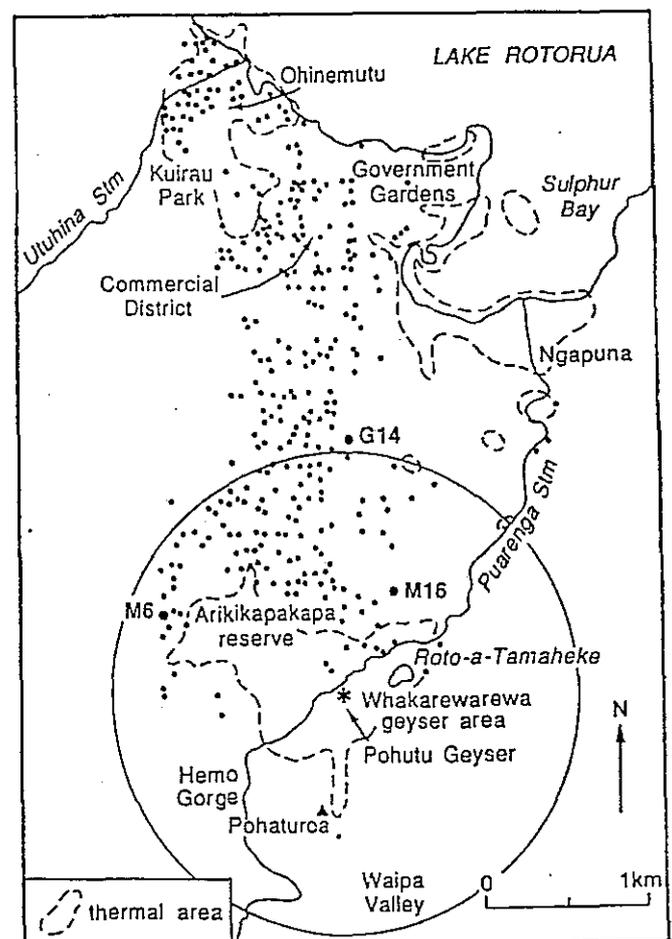


Figure 1: Map showing distribution of wells in 1985, monitor wells and main surface hot spring areas. The circle denotes the area in which all wells were closed.

Exploitation History

Many of Rotorua's residents have taken advantage of the geothermal waters by drilling wells to extract the hot fluids. These fluids were used for both domestic and commercial heating, with some of the largest commercial users being Government Department offices, hospitals and major tourist hotels (Ministry of Energy, 1985). The first geothermal wells in Rotorua were drilled during the 1920s, with close to 750 wells having been drilled since then. Some of these were replacement or standby wells and some wells were not replaced after casing failures or blockages, so the actual number of wells in use reached a maximum of around 500 in 1985. At that time, the total well discharge was estimated to be 25 000 tonnes day⁻¹ (td⁻¹) (290 kg s⁻¹) during summer months, rising to 31 000 td⁻¹ (360 kg s⁻¹) during winter months. Only an estimated 5% of the discharge fluids were reinjected to production depths (typically 100 - 200 m). Most of the waste liquid was put into shallow soak holes (<20 m depth) and, contravening a local by-law, into storm water drains. Approximately half the fluid extracted was for residential use and half for commercial use. However, because many wells in the residential sector were shared by several households, 1500 of the total 1840 geothermal users were residential. The dominant commercial sector user in 1985 was tourist accommodation which used 20% of the total discharge (Ministry of Energy, 1985).

The effect of the bore closure programme, when 106 wells within 1.5 km of Pohutu geyser were cemented up (most during 1987), and a charging regime for remaining well discharges was implemented, was a reduction of the total well discharge to about 30% of 1985 levels by 1989 (Timpany, 1990). The average summer drawoff in 1990 was estimated to be 10 280 td⁻¹ (118 kg s⁻¹) increasing in winter by 1040 td⁻¹ (12 kg s⁻¹). The commercial sector now accounts for 68% of the total discharge, and the reinjected mass has risen to 31% of the discharge (Timpany, 1990). The net mass withdrawal from the field in 1990 had decreased to close to 20% of the 1985 level. By late 1992, only 141 wells were producing 9500 td⁻¹, with 5100 td⁻¹ being reinjected (Grant-Taylor & O'Shaughnessy, 1992).

Rotorua Geothermal Field Pressures and Water Levels

A network of geothermal monitor (M) wells was established in 1982, with up to 24 of these located throughout Rotorua city, typically 80 - 180 metres deep. They either stand open to atmosphere or where under-pressure are shut in so that no discharge can occur. Since 1987, total numbers of producing wells has fallen and total withdrawal mass has also been dramatically reduced. By 1995 about 200 wells produced a total of ~11 500 td⁻¹, of which ~7 000 td⁻¹ was being reinjected, leaving a net fluid loss of ~4 500 td⁻¹ to shallow groundwaters. Within a few more years nearly all this net loss should stop, as reinjection is a mandatory requirement of any water right permit renewal.

M-well responses

All M-wells showed a sudden water level or pressure rise during late 1987 of ~2m, with continual ongoing gradual recoveries to date. M-16 is typical of wells into ignimbrite aquifers and M-6 rhyolite aquifers (Fig. 2). The same general trends are present in all M-wells,

although cool waters entering the ignimbrite from the west and proximity to Lake Rotorua at the north cause some wells to show additional short term responses.

Bore Field Management Today

The primary geothermal source aquifer is Mamaku ignimbrite, with outflows from this into the fractured outer layers of buried rhyolite domes and into shallow permeable sediments. Since forced closures of many wells in 1986-87, remaining wells have been progressively modified to reinject waste waters (typically $\sim 80^{\circ}\text{C}$) back to source aquifers via disused or specially drilled deep disposal wells.

All water rights to use geothermal wells are short term (~ 3 -5 years) and further renewal of these permits is conditional upon deep reinjection of all waste waters. The intention is that within a few years time nearly all well waste waters will be reinjected back to source aquifers, with the aim of maintaining fluid mass. The Geothermal Institute (Auckland University) has made studies of 30 reinjection wells using production and reinjection pairs (called doublets); to date no adverse effects of reinjection have been identified.

Prior to forced well closures in 1986-87, some 500 wells were in production producing up to $31\,000\text{ td}^{-1}$ in winter months, falling to $\sim 25\,000\text{ td}^{-1}$ in summer. Nearly all this produced water mass was then discarded into shallow groundwaters, or illegally into surface drains.

Surface Features

Surface features are generally alkaline, high chloride - low sulphate waters typical of deep waters found in neighbouring wells. Many of Rotorua's geysers and flowing hot springs have shown responses to the sudden reduction of well drawoff in 1987. Although no precise early measurements of total natural outflow are available, estimates are that all hot springs and geysers produced $\sim 17\,500\text{ td}^{-1}$ in 1960s, $\sim 13\,500\text{ td}^{-1}$ in 1986 and $\sim 20\,000\text{ td}^{-1}$ in 1992. This change in outflow of hot springs follows expected trends and is consistent with more geothermal fluids now being available for natural spring outflows. Some areas of natural springs showing significant recovery are mixtures of groundwaters and increased upflows of deep geothermal fluids, but these are given less attention due to the complication of the

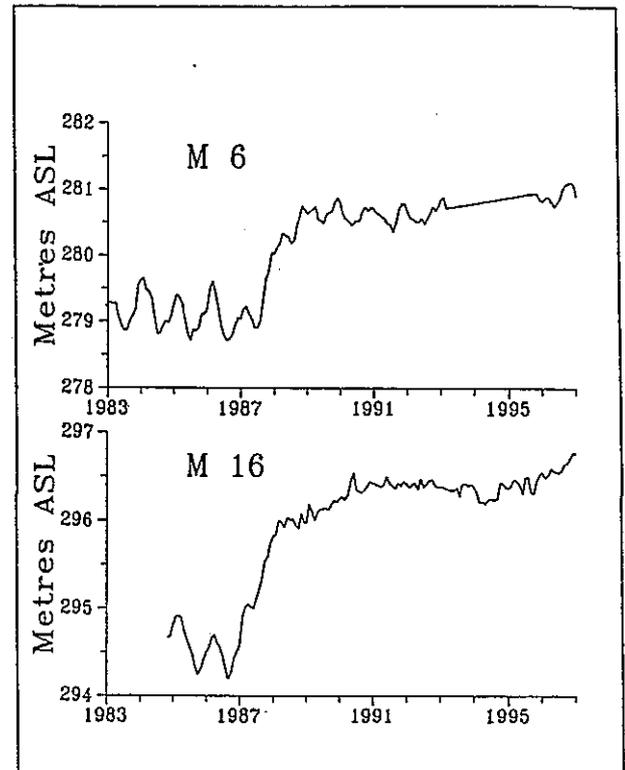


Figure 2: Time series plot of the water level in monitor wells M-6 and M-16.

groundwater availability.

Many springs and geysers have up to c.150 years of intermittent recorded information, but only a few large springs and geysers have substantial quantitative data spanning many decades; today geyser activity is confined to Whakarewarewa. On Geyser Flat there are seven intimately connected and interactive geysers, such that data from any single one of these is itself not indicative of total trends there.

At Geyser Flat, historical qualitative data presents a clear picture of significant decline in outflows and geyser activity during 1950s - 1980s and a pronounced recovery since 1987 to present day. The geysers are fed from the ignimbrite aquifer. These changes are briefly summarised as follows:

Te Horu Geyser: Through historical times up until 1972, this geyser used to erupt 2-7 metres (m) high with about 100 litres per second (lps) outflows, which occurred 10-15 times day. Since 1972 eruptions have ceased and not resumed to present day (February 1997).

Kereru Geyser: Eruptions 10 - 15 m high several times a week until 1972, from when no eruptions are known until they resumed in January 1988. Since then these have occurred every few days and occasionally up to seven per day have been observed in daylight hours.

Waikite Geyser: This last erupted in March 1967 and its vent remained dry and weakly steaming until June 1996, when its previously 8.5 m deep dry vent suddenly filled with boiling waters to within 2.5 m of overflow. It is the highest elevation of any historically active geyser or hot spring at 315 m asl, compared with 302 m asl for Pohutu geyser and 280 m asl for Lake Rotorua. Waikite water levels remain high and boiling. It didn't respond to soap in January 1997.

Pohutu Geyser: Pohutu geyser erupts ~21 m high, 25 - 60 times each day, spending a total of ~35 - 60% of any day in eruption. Its eruptions have not shown any changes conclusively related to well closures of 1986-87. During 1950s - 1980s, Pohutu showed a pronounced shift to more frequent but shorter duration eruptions, possibly consistent with reduced aquifer pressures. However, it is intimately connected with six other nearby geysers and the total mass and heat flows from Geyser Flat have not been quantified. To date it continues to have numerous short eruptions (2-5 mins).

Wairoa Geyser: This last erupted naturally in December 1940, but was soaped into huge eruptions (up to ~50 m high) in late 1950s on many occasions. Since then its water level fell to >4.5 m below overflow and became acidic (low chloride - high sulphate). In early 1996 its water level rose to 3.2 m below overflow boiling powerfully; it remains so.

Okiana Geyser: During late 1970s and early 1980s no eruptions were observed. However, since c.1992 it has been reliably erupting every 25 - 35 minutes to ~7 m high.

Papakura Geyser: This geyser stopped erupting in March 1979 after a very long period (c. 90 yrs) during which it was known to have faltered very briefly only 3 times. It was the cessation of Papakura's eruptions which was directly responsible for the initiation of the monitoring programme. This feature has not recovered.

Parekohoru Spring: In 1985-6 this spring ceased outflowing for several days each winter. Since 1988 there have been no further cessation and boiling surges have recommenced, similar to reports earlier this century.

Outside of Whakarewarewa to the north, near the southern shores of Lake Rotorua, two large springs fed from the rhyolite aquifer have undergone significant changes consistent with well closures and higher water levels as measured in M-wells (Fig. 2).

Rachel Spring: This is the sole remaining boiling, flowing alkaline spring in the Government Gardens. Prior to 1987, its last overflow and boiling episode was in 1967, but since then until 1987 its water level had remained at 1.2 - 1.7 m below overflow (70 - 80°C). Since late 1988 it has been continually flowing 7 - 12 lps, boiling and high chloride waters. It still has brief cessation of overflow, but these last only a few days and water level has never fallen more than 0.1 m below overflow since 1988.

Kuirau Lake: From late 1940s - 1987 this large hot spring (~5 000 m²) was only warm (~45 - 50°C), acidic, low chloride and without any overflows. Since 1988 it has been consistently overflowing ~50 - 60 lps at ~80°C, high chloride alkaline waters.

The consistently high water levels and large overflows of Rachel Spring and Kuirau Lake are the most visible of all spring recoveries following well closures in 1986-87. Geysers require prolonged observation to witness eruptions and so the general public are less familiar with geyser activity changes, although quantitative instrumental records confirm that most geysers have shown a significant improvement in activity since well drawoff was forcibly reduced in 1986-87.

Summary

Forced closures by central Government was a matter of great animosity and resistance. Subsequent water level recoveries measured in M-wells, resumed overflows of hot springs and resumed eruptions from several geysers is consistent with reduced well drawoff returning more geothermal waters to natural surface spring outlets (i.e. hot springs and geysers). Fluid pressure beneath Rotorua has recovered about half the inferred drawdown caused by a combination of exploitation and a long-term decrease in rainfall prior to the mid 1980s (Bradford, 1992). Geyser activity and hot springs have subsequently been rejuvenated, with some springs overflowing for the first time in over 30 years (Cody and Lumb, 1992).

Acknowledgements

The authors thank John McIntosh (Environment Bay of Plenty) for the use of the water level data from M-6 and M-16 monitor wells to illustrate the recovery in the Rotorua Geothermal Field.

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Nature is often hidden; sometimes overcome; seldom extinguished

- Francis Bacon (Essays)

APPENDIX X:



PERGAMON

Geothermics 29 (2000) 573–592

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GEOTHERMICS

Response of the Rotorua geothermal system to exploitation and varying management regimes

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Abstract

Exploitation of the Rotorua geothermal system started in the 1920s, but during 1967–1986 the number of wells and mass withdrawal greatly increased. Natural surface activity waned in the 1970s, prompting public concern, which led to a monitoring programme (1982), enforced closures of many wells (1987), and punitive royalty charges (1987). During the well closure programme, mass withdrawal was reduced by about 60%. Within one year, water levels increased by 2 m and pressures by 0.02 MPa. Since then, levels and pressures have continued to rise gradually. Many surface thermal features have shown recovery: geysers have resumed stronger or longer duration eruptions, springs have recommenced or strengthened overflows, and the frequency of hydrothermal eruptions has decreased. Some failed geysers have not yet recovered, indicating recovery is slow or that the bore closure programme may not guarantee recovery of all surface features. © 2000 CNR. Published by Elsevier Science Ltd. All rights reserved.

Keywords: Thermal features; Geysers; History; Management; Recovery; Rotorua; New Zealand

1. Introduction

The Rotorua geothermal field is recognised internationally for its setting within Rotorua caldera and the Taupo Volcanic Zone (TVZ)(Fig. 1), and in particular

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for the geysers and hot springs at Whakarewarewa thermal area (Fig. 2). Geysers are a rare natural phenomenon world-wide, and Pohutu geyser at Whakarewarewa is one of New Zealand's two largest surviving examples. Although there are over 20 geothermal fields within the TVZ, only five have been noted for their geyser activity: Wairakei, Orakeikorako, Waimangu–Rotomahana, Waiotapu and Rotorua. In the early 1950s, some 220 geysers existed in New

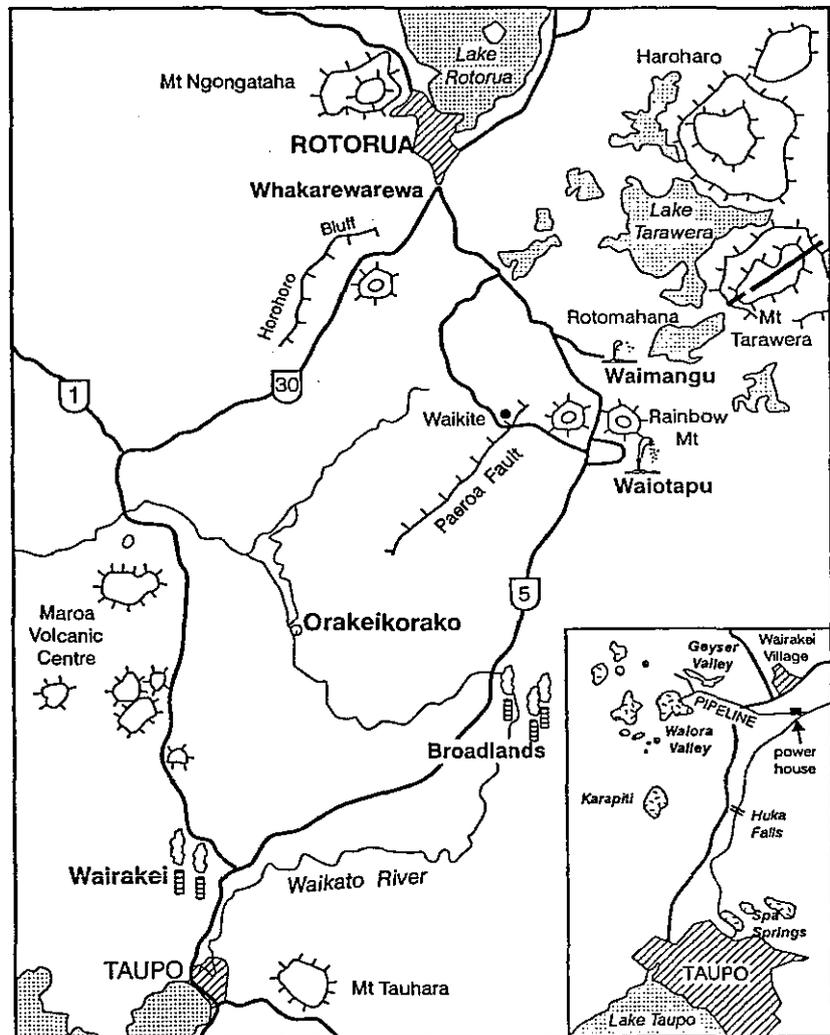


Fig. 1. Map of Rotorua-Taupo area showing the location of Rotorua, Wairakei, Orakeikorako, Waimangu, Rotomahana, Spa, Ohaaki/Broadlands, and Waiotapu.

Zealand, but by 1990 only about 55 remained; essentially all losses are directly attributable to human interference with the geothermal systems.

New Zealand has a poor history with respect to recognising the need to protect geysers and hot springs. At Wairakei, 80 km south of Rotorua, extraction of fluids (about 120,000 tonnes/day 120 kt/d) from wells for geothermal power commenced in the 1950s and within a few years all geysers (about 70) and alkaline hot springs (about 240) had ceased flowing (Glover and Hunt, 1996). At Orakeikorako (55 km south-west of Rotorua), about 70 geysers were flooded after river levels rose by about 18 m during the construction of a dam for a

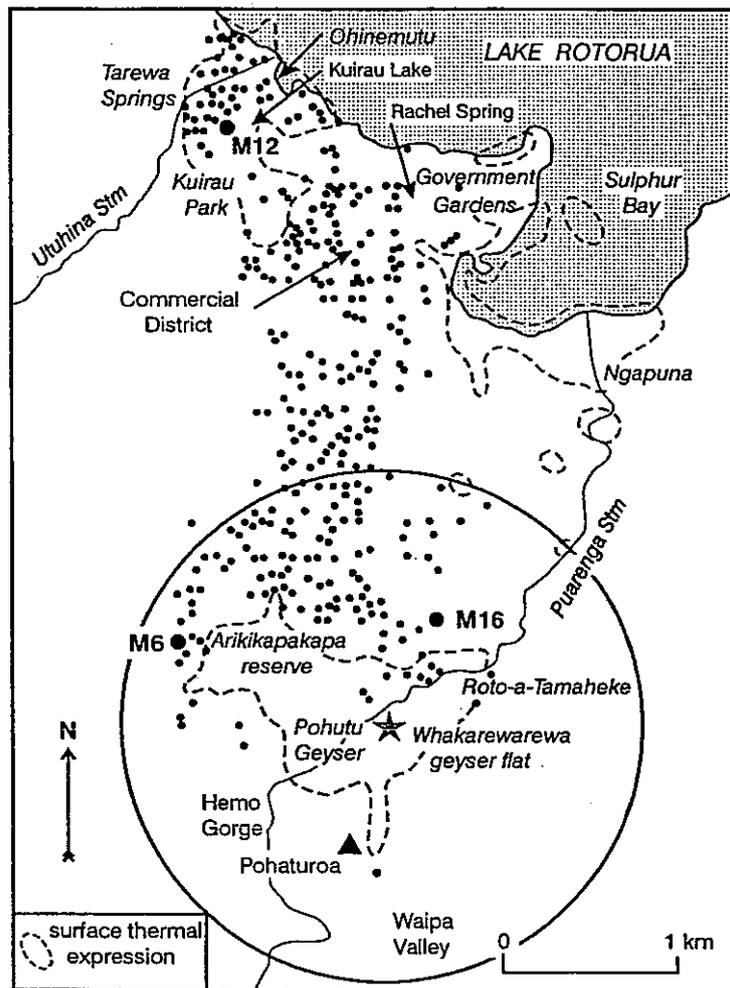


Fig. 2. Map showing the distribution of wells in 1985, monitor wells and main surface hot spring-geyser areas. The circle denotes the area in which all wells were closed.

hydroelectric power scheme (Lloyd, 1972). At Taupo, river works for a hydroelectric power scheme resulted in all geysers at the spa being destroyed in the 1950s (Glover and Hunt, 1998). Field testing for geothermal power production at Ohaaki (Broadlands) from 1967 to 1971 resulted in a large flowing spring being quickly destroyed (Glover et al., 1996).

In the early 1960s and again in the mid-1970s, mass flows from Rotorua wells increased sharply as additional wells were drilled (Fig. 3), firstly as a result of national electricity shortages in the 1950s and 1960s and secondly as a consequence of oil shortages and price rises in the 1970s (Allis and Lumb, 1992). During these times, the level of natural hydrothermal activity in Rotorua declined, to reach an all-time recorded low by the mid-1980s (Cody and Lumb, 1992).

During the early 1980s, public sensitivity to the intrinsic and tourism values of New Zealand's few remaining geysers increased, as geysers and hot springs in Rotorua progressively failed due to extraction of geothermal fluids via well drawoff. These concerns, together with a realisation that there was no quantified estimate of the volume of fluid extracted in Rotorua, or adequate records of the changes in the surface activity, led to establishment of the Rotorua Geothermal Monitoring Programme in 1982. By 1985, this programme had established that the winter daily mass discharge from all wells was around 31 kt/d, which represented about 40% of the natural deep upflow of the Rotorua system (Ministry of Energy, 1985; see also articles in the *Rotorua Geothermal Field*, Special Issue of *Geothermics* 21 (1/2), 1992). In 1986, central government initiated a bore closure programme and a punitive charging regime for remaining well discharges.

In this paper, we examine the history of some of the important natural thermal features, and the effect the bore closure programme and charging regime have had on them.

2. Geological–geophysical setting

The Rotorua system, as defined by surface activity and shallow drillholes, covers about 12 km² and is associated with the southern margin of the Rotorua caldera. Thompson (1974) described the regional geology, and Crafer (1974) commented on drillhole geology of Rotorua. Wood (1985) developed a geological model of the Rotorua aquifers, and revised it in 1992 (Wood, 1992).

Principal production aquifers are the caldera-forming Mamaku Ignimbrite, and younger rhyolite domes under Rotorua city. The overlying, poorly-permeable, lacustrine siltstones (interbedded with sands, gravels and tephra) cap the aquifers and form a vertical aquitard. At Whakarewarewa, the hot springs feed from fractured ignimbrite inside an embayment of the southern caldera boundary (Wood, 1992). Fluids are thought to ascend from depth into the Mamaku Ignimbrite via faults. In Rotorua city, the rhyolite lava domes comprise a buried north–south trending ridge under the city, exposed only at Pukeroa (“Hospital Hill”, central business district). This aquifer contains mostly sub-boiling water (up

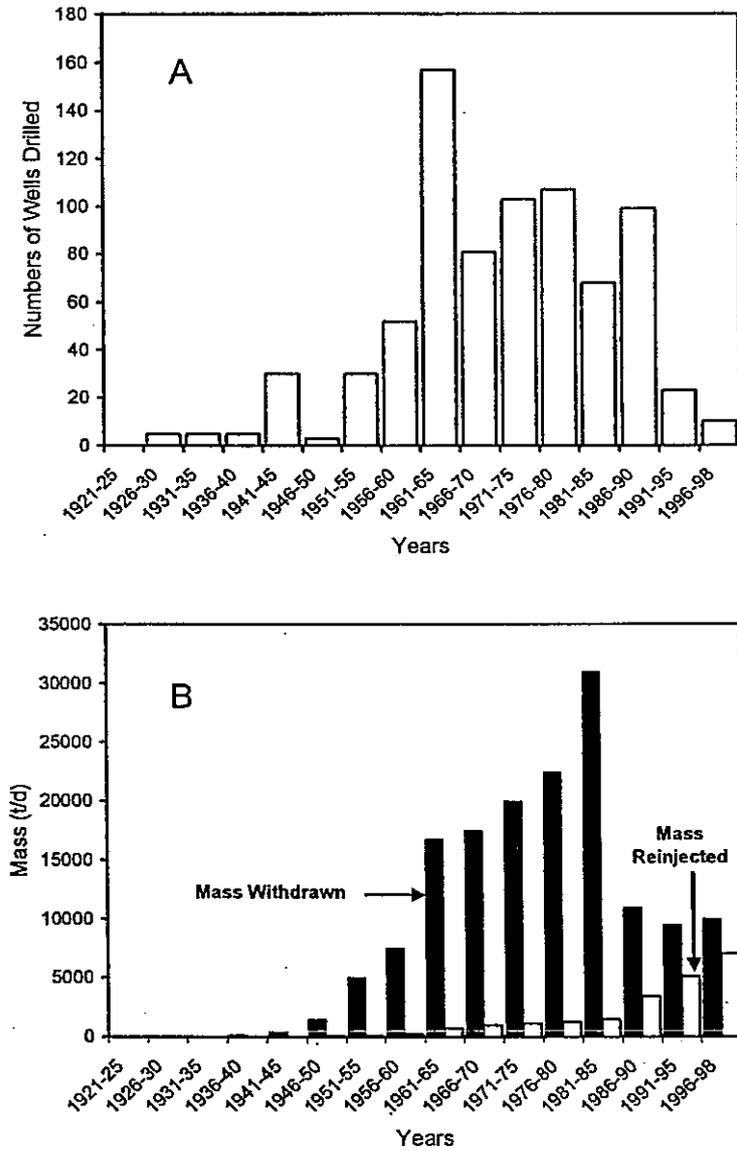


Fig. 3. Plots showing the number of wells drilled with time (A), and the mass of fluid withdrawn and reinjected (B). Note that not all wells drilled were new production wells; many were replacements for older, failed wells. The pattern of numbers drilled, however, show peaks which coincide with electricity shortages in the 1950–1960s and the oil shortages (and petrol price rises) of the 1970–1980s. Also, during 1987–1989, at least 92 new wells were drilled after the government forced closure and royalty programmes were imposed. This peak of new wells represents a sudden exploitation of a flaw in the existent legislation.

to 190°C), which enters via faults along the eastern flanks of the domes, and then flows laterally (westwards) through the outer, fractured and permeable, rhyolite carapace. Surface activity in the Kuirau Park-Ohinemutu area is associated with the Kuirau Fault, along the western flank of the northern rhyolite dome.

Geophysical and geochemical studies indicate that the field has an area of 18–28 km² at about 500 m depth, and a natural heat flux of 430 ± 30 MW. About one-third of its area, and over half of its heat and mass flux, occur beneath the southern part of Lake Rotorua (Allis and Lumb, 1992; Glover, 1992; Whiteford, 1992; Hunt, 1992).

3. Exploitation and management history

3.1. Borefield use

Many Rotorua residents have taken advantage of the underlying geothermal fluids by drilling shallow wells (20–200 m deep) to extract hot water. These fluids are used for both domestic and commercial heating; some of the largest commercial users were government department offices, hospitals and major tourist hotels (Ministry of Energy, 1985). The first geothermal wells in Rotorua were drilled during the 1920s, and by 1944 there were at least 50 wells in use (Modriniak, 1945). By early 1998, over 1150 wells had been drilled, although many of these were replacement, standby or reinjection wells (Fig. 3a).

Many wells were not replaced after casing failures or blockages, so the actual number of producing wells is less than the total drilled, reaching a maximum of around 500 in 1985. At that time, the total well discharge was estimated to be 25 kt/d (290 kg/s) during summer, rising to 31 kt/d (360 kg/s) during winter.

In 1985, only about 5% of well discharge fluids were reinjected back to the production aquifer (typically 20–200 m depth), with most waste waters being discharged into shallow soak holes (< 20 m depth) and, contravening a local by-law, into the storm-water system. Approximately half the fluid extracted was for residential use and half for commercial use, and about 1500 of the total 1840 geothermal users were residential. The dominant commercial sector user in 1985 was tourist accommodation, which used 20% of the total discharge (Ministry of Energy, 1985). The bore closure programme of 1987–88, instigated by central government, resulted in 106 wells within 1.5 km of Pohutu geyser (Fig. 2) being cemented shut (most during 1987). This, together with the punitive royalty-charging regime for all remaining wells, resulted in the closure of a further 120 wells outside the 1.5 km radius of Pohutu geyser. The effect of both forced closures and the royalty charges was a reduction of total well discharge to about 30% of 1985 levels by 1989 (Timpany, 1990). Average summer drawoff in 1990 was estimated to be 10.28 kt/d (118 kg/s), increasing in winter by 1.04 kt/d (12 kg/s) to a total of 11.32 kt/d (130 kg/s). The commercial sector then accounted for 68% of the total discharge, and the mass reinjected had risen to 31% of total well discharge (Timpany, 1990).

Net mass withdrawal from the field in 1990 had decreased to nearly 20% of the amount in 1985. By late 1992, the 141 wells in use were producing 9.5 kt/d, with 5.1 kt/d being reinjected (Grant-Taylor and O'Shaughnessy, 1992). In 1997, well production was still around 10 kt/d, but of this about 7 kt/d was being reinjected back to source depths (O'Shaughnessy, pers. comm. ADC).

3.2. Legislation and management

In 1953, central government passed the Geothermal Energy Act 1953, which defined geothermal waters as those being above 70°C and from depths >61 m. Well owners were required to obtain licences, unless use was for domestic purposes and the well was <61 m deep.

On 2 October 1968, the Rotorua City Geothermal Empowering Act 1967 was passed into law, giving the Rotorua district council control of all geothermal use within the city. Despite the requirement to issue licences, no licences were ever issued during the 19 years the Act was in force. This Act focussed upon safe exploitation of geothermal energy, with no regard for sustainability of the resource or protection of surface thermal features.

Public and scientific concerns expressed in 1979 when Papakura geyser ceased erupting resulted in the Rotorua district council imposing a moratorium (in 1980) on any new wells being drilled within a 1.5 km radius of Pohutu geyser. However, replacement of existing wells was allowed in this zone, with often farcical consequences. Typically, many small diameter wells were replaced with larger diameter and much deeper ones. For example, a property with a well (50 mm diameter, 20 m depth) supplying a domestic residence could be bought by a company and redeveloped as a motel complex; this well was then alleged to have "failed", and replaced by another (100 mm diameter, and up to 160 m depth) from which a much greater quantity of hot water and steam was drawn.

Extraction of geothermal water within a 1.5 km radius of the Pohutu geyser was therefore allowed to increase significantly under that policy. This lack of effective management contributed to central government revoking the 1967 Rotorua City Act in 1986, and simultaneously imposing a forced closure of all wells within a 1.5 km radius of Pohutu geyser. The Rotorua district council may secretly have welcomed this intervention by central government, because it removed from them any need to enforce locally unpopular management conditions.

A punitive annual royalty charge was also imposed on all remaining Rotorua wells (O'Shaughnessy, 2000), commencing 1 April 1987. These were deliberately set at a high level and calculated on the maximum possible well discharge and temperature, regardless of actual use. Depending upon what part of the city a well was located, this led to many anomalies; i.e. a single pensioner could have incurred royalty fees of NZ\$15,000 per year, whereas a large motel with a low pressure/low temperature well might have paid only NZ\$ 600 per year. Royalty charges were, however, very efficient in further reducing total well drawoff during 1987–1992. During 1987–1988, many people took advantage of an opportunity for

free closure by cement grouting to escape the annual royalty charges. This resulted in a greater reduction of well drawoff (approximately 125 wells closed) than did the enforced closures of wells.

In October 1991, the Resource Management Act became law. This Act redefined geothermal waters as being any fluid at 30°C or more, regardless of source depth. Also, it was administered by regional councils (regional government), thereby removing the opportunity for local city and borough councils to loosely interpret the Act for their own self interest and commercial advantage.

3.3. Current bore field management

Since forced closures of many wells in 1986–87, well use has progressively included more reinjection of waste waters (typically at 60–80°C) back into the source aquifers via disused or specially drilled, deep disposal wells. At present, permits for geothermal wells using shallow soakage disposal are only valid for three years, and renewal is conditional upon a change to deep reinjection of all waste waters. The intention is that within a few years time nearly all geothermal waste waters will be reinjected back to source aquifers, with the aim of maintaining fluid mass in the geothermal aquifer. Well owners currently reinjecting waste waters back to the source aquifers have been issued permits for 10 years.

Studies of 30 reinjection wells in Rotorua, using production and reinjection pairs (called doublets), have shown no adverse effects of reinjection. In only two wells was any return of waste waters detectable (Pan et al., 1991; Pan, 1991).

Prior to the forced well closures in 1987, at least 376 wells were taking up to 31 kt/d in winter months, falling to about 25 kt/d in summer. Nearly all this extracted water mass was then discarded into shallow groundwaters, or (illegally) into surface drains. Less than 5% was then being reinjected back to the production aquifer. Since 1987, the total number of wells has fallen from about 500 producing a total mass of about 31 kt/d, to about 200 producing 11 kt/d in 1995. By 1995, 7 kt/d of about 11.5 kt/d was being reinjected, leaving a net fluid loss of about 4.5 kt/d being disposed into shallow groundwaters. Within a few more years this net fluid loss should reduce to near zero, as reinjection of waste waters back to source is a mandatory requirement of all water right permit renewals.

4. Changes in field pressure and water level

A network of geothermal monitor (M) wells was established in 1982, with 24 of these located throughout the city. They are typically 80–180 m deep, and stand open to atmosphere or, if under pressure, they are shut in so that no discharge occurs. Dataloggers record variations in water level within these wells.

During late 1987, all M-wells showed a sudden water level or pressure rise of 1–

2 m (0.1–0.2 bars, 0.01–0.02 MPa pressure), with continual ongoing gradual recoveries to date totalling 2–2.5 m. M16 is typical of wells into ignimbrite aquifers, and M6 and M12 are typical of wells into rhyolite aquifers (Figs. 2 and 4). The same general trends in water level and pressure are present in all M-wells, although relatively cool waters entering the ignimbrite from the west and proximity to Lake Rotorua to the north cause some wells to show additional short-term responses.

5. Changes to surface thermal features

Discharges from thermal features at the surface in Rotorua are generally alkaline, high chloride - low sulphate waters, similar to the geothermal waters found in neighbouring shallow wells. Although no precise early measurements of total natural outflow are available, estimates are that all hot springs and geysers at Whakarewarewa produced about 34 kt/d prior to any exploitation, and 25 kt/d by 1967 (Mahon, 1985). The geysers and most large flowing hot springs have

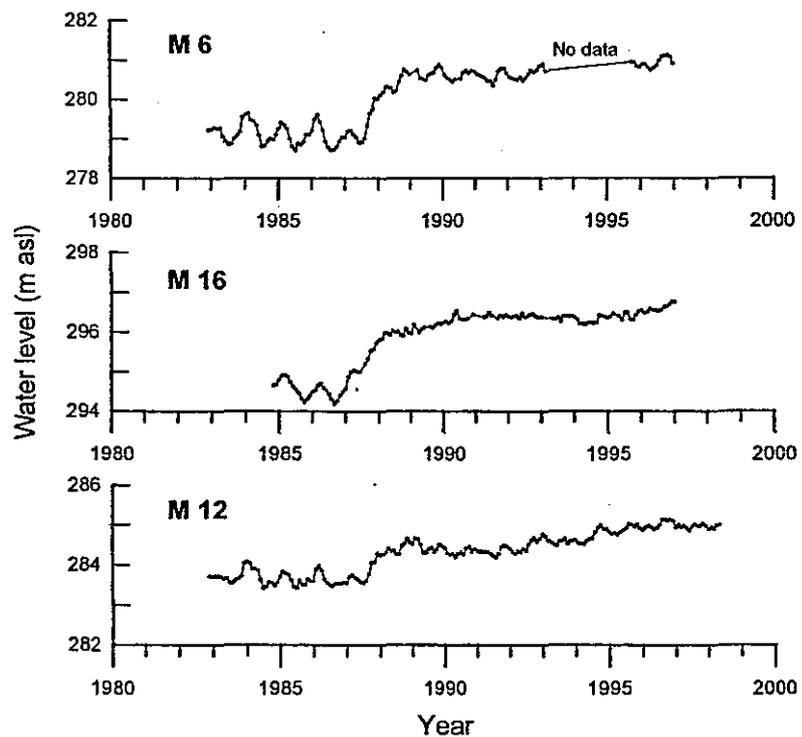


Fig. 4. Changes in water level in monitor wells M6, M12 and M16. Locations of the wells are shown in Fig. 2.

shown responses to the sudden reduction of well drawoff in 1987: at Whakarewarewa, the springs produced about 8.39 kt/d in 1982–85 (Glover, 1985), which increased to about 9.24 kt/d in 1989–1990 (Glover, 1992). The changes in outflows from hot springs show an inverse relationship to bore discharge, and are consistent with more geothermal fluid now being available for natural spring outflows, as a consequence of reduced well drawoffs (Scott and Cody, 1997).

Many springs and geysers have up to 150 years of intermittent recorded information, but only a few large springs and geysers have substantial quantitative data spanning many decades. The discussion below is restricted to features with relatively complete records of behaviour, or those not influenced by human activities.

5.1. Southern springs and geysers

In the southern areas of Rotorua city, natural geothermal activity is concentrated in the Whakarewarewa Valley and Arikikapakapa Reserve. Geysers and flowing boiling alkaline hot springs, acid springs, mud cones, mud pools, turbid acidic groundwater pools and solfatara all occur in Whakarewarewa. Adjoining this area to the northwest is the Arikikapakapa Reserve, which contains numerous cool turbid acidic lakelets, boiling mud pools and barren solfatara. It is underlain by a boiling zone, so that its surface features are almost entirely the products of gas and steam alteration, and interactions with surface groundwaters. A significant chloride outflow also occurs within Arikikapakapa Lake, indicating some deep geothermal upflows there. Further to the west, on the shores of a small lake (Tangatarua), old sinter deposits confirm the existence of prehistoric overflowing alkaline springs in this area.

5.2. Whakarewarewa; Geyser Flat

At present, geyser activity in Rotorua is confined to Whakarewarewa, where at least 65 extinct geyser vents are recognised. On Geyser Flat there are seven intimately connected and interactive geysers, such that data from any single one are not indicative of overall trends of Geyser Flat activity. Natural changes are also occurring here, such as, silica deposition changing flowpaths and conduit dimensions, compounding the problems of interpreting geyser changes through time.

At Geyser Flat, qualitative historical data from the 1890s, and later instrumental and visual records from the 1950s, present a clear picture of declines in outflows and failing geyser activity during the 1950–1980s, but with a pronounced recovery since 1987 to present day (Fig. 5). Natural changes also appear to be affecting Geyser Flat; for example, the rupturing of Te Puia Fault on 16 August 1984, 18 October 1988, 7 December 1989 (when pyritised ejecta were erupted out of Prince of Wales Feathers geyser), 27 March 1991 and again on 16 May 1991 (Cody, 1989; 1991). The 18 October 1988 rupturing of Geyser Flat created a new geyser, situated about 3 m north of Prince of Wales Feathers

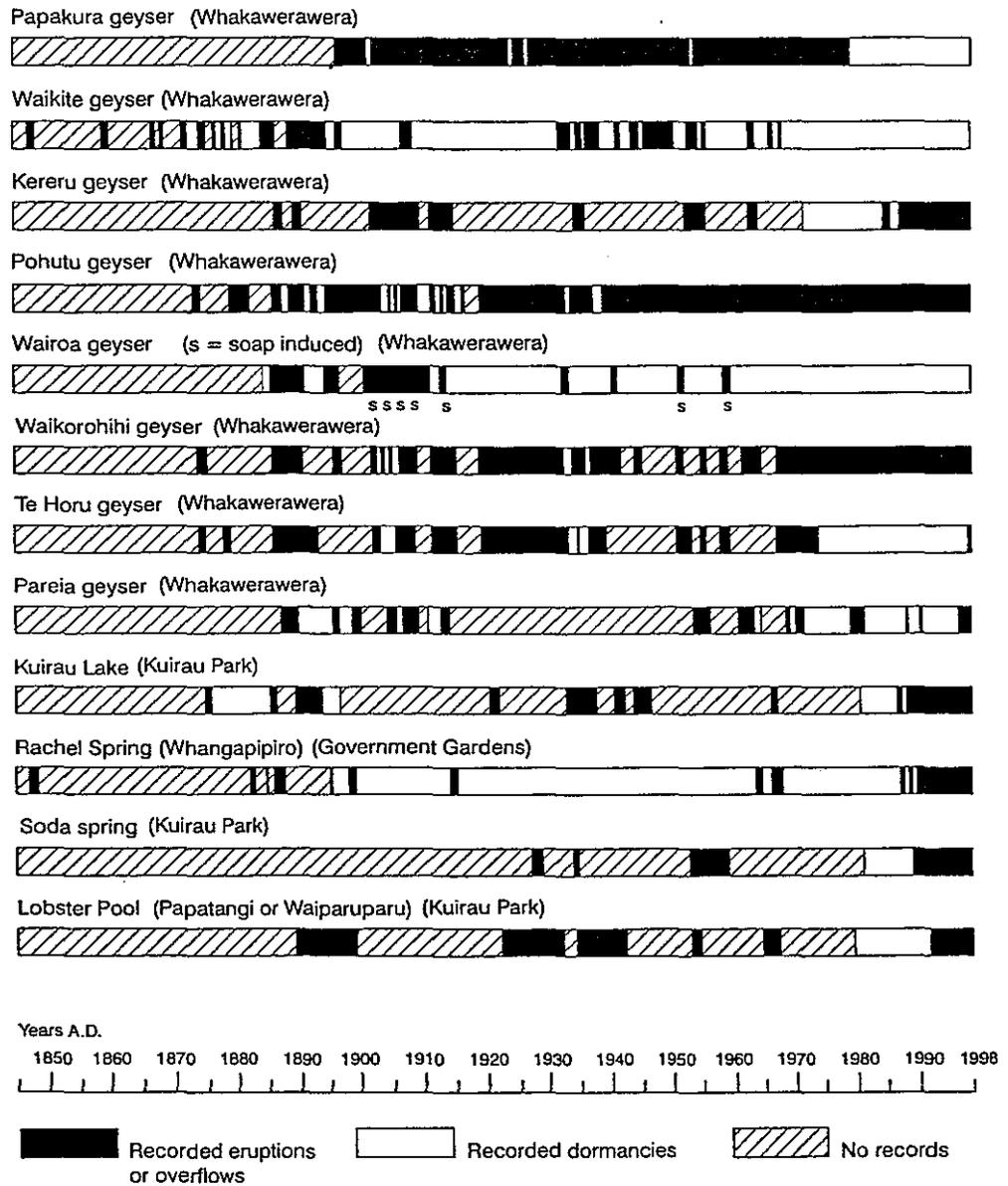


Fig. 5. Histogram of changes in spring and geyser activity with time.

Geysers. This new geyser plays 1–3 m high and remains active to date. Similarly, the Prince of Wales Geysers commenced erupting in June 1886 following the volcanic eruption of Mount Tarawera, 20 km east of Whakarewarewa (Thomas, 1886; NZ Herald, 22 and 23 June 1886; NZ Herald, 28 July 1886; Otago Daily Times, 22 June 1886).

Eruption behaviour of Pohutu Geysers, the largest geysers on Geysers Flat, also appears to have progressively undergone an exchange of function with Prince of Wales Geysers, about 2 m north of Pohutu. In the 1970–1980s, Prince of Wales Geysers typically erupted strongly just prior to eruptions of Pohutu and Waikorohihi geysers and ceased soon after Pohutu stopped. Since 1993, Prince of Wales Geysers has rarely ceased erupting and a conspicuous consequence of this change has been the killing of all algae, so that its surrounds are now white sinter instead of the previously orange and brown algae growths. Between 1966 and 1986, the activity of Pohutu Geysers changed to more frequent but shorter eruptions with lesser, and subsequently no long duration events by 1996 (Fig. 6). Late in 1997, long duration eruptions recommenced (Cody, 1998a), with about 20% now lasting 30–50 min (Fig. 6). All these geysers are fed from the Mamaku Ignimbrite aquifer, and their historic activity is briefly summarised below.

5.2.1. Pohutu geysers

Full column eruptions of Pohutu typically reach up to 21 m high, and can occur 10–60 times each day, historically averaging 30–60% of any day in eruption (Fig. 6). During the 1960–1980s, Pohutu showed a pronounced shift to more frequent but shorter duration eruptions, possibly as a consequence of reduced aquifer pressures. However, its total daily eruption times showed no significant change. Pohutu is intimately connected with six other nearby geysers, and the total mass and heat flows from Geysers Flat have not been fully quantified. In late 1986, it underwent a period of several months with no strong full column eruptions but many long episodes of dry steam emission, a phenomenon unseen before or since then. Eruptions of Pohutu have not shown any changes conclusively related to the well closures of 1986–87, except for the disappearance of dry steaming emissions. At present, it continues to have numerous short eruptions (2–5 min), but recordings from December 1997 to February 1998 show a shift to longer duration eruptions (Fig. 6; Cody, 1998a).

5.2.2. Te Horu geysers

Through historical times till about 1972, this geysers used to erupt 2–7 m high with about 100 l/s outflows that occurred as frequently as 10–15 times each day. The tourist walkway at that time crossed the outflow path of Te Horu and tour parties were often delayed from proceeding further until Te Horu had ceased erupting. Since about 1972, all eruptions and boiling have ceased, with no resumption or evidence of any significant recovery until recently. In January 1998, water began rising to reach levels not observed since 1972. Then in December 1998, minor overflows occurred, followed in March–April 1999 by stronger

overflows; however, some may be induced by the waters erupted by Pohutu flowing into the Te Horu basin.

5.2.3. Wairoa geyser

This last erupted naturally in December 1940, but was soaped into huge eruptions (up to about 50 m high) on many occasions in the late 1950s. Since then, its water level has fallen to >4.5 m below overflow and the water has become acidic (low chloride–high sulphate). In early 1996, its water level rose to 3.2 m below overflow, with continuous powerful boiling and it remains so to date.

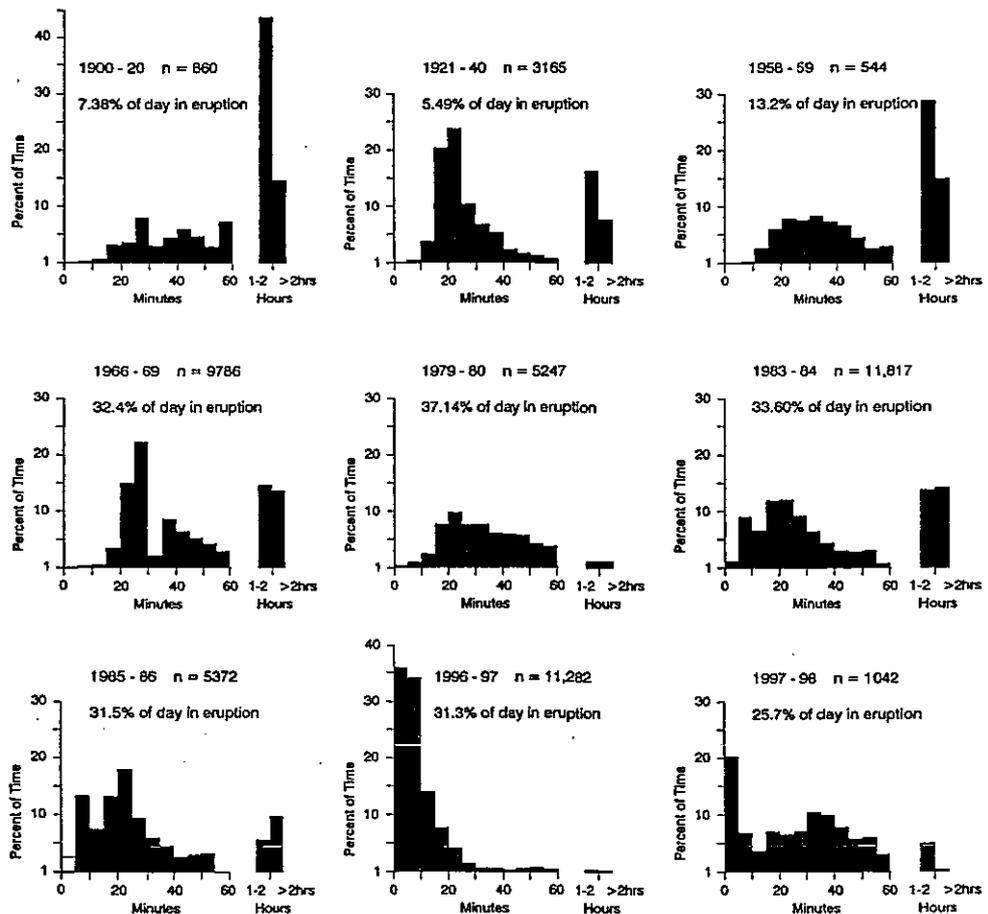


Fig. 6. Plots showing the amount of time per day Pohutu Geyser is in eruption, during different time periods.

5.2.4. *Kereru geyser*

Eruptions 10–15 m high, several times a week, occurred till about 1972; since then, no large natural eruptions are known until they resumed in January 1988. From then on, moderate to large eruptions have occurred every few days or weeks, and occasionally up to seven per day have been observed in daylight hours. It remains active to date, with an exceptionally long eruption (about 5 min) occurring on 12 November 1997 (NZMACI Guide Oriwa, pers. comm. to ADC).

5.3. *Whakarewarewa; other geysers and springs*

5.3.1. *Papakura geyser*

This geyser stopped erupting in March 1979 (Grant and Lloyd, 1980), after a very long period (about 90 years) during which it was known to have faltered very briefly only three times (Cody and Lumb, 1992). The cessation of eruptions from Papakura was directly responsible for initiating the Rotorua geothermal monitoring programme in 1981. Papakura has not recovered to date, although in October 1997 the fluid in the vent had heated to about 60°C and become clear and alkaline once more, although still without any boiling or eruptions since 1979.

5.3.2. *Waikite geyser*

This last erupted in March 1967; since then the vent has remained dry and weakly steaming. In June 1996, its previously 8.5 m deep and dry vent suddenly filled with boiling water, which rose to within 2.3 m of overflow. In June 1997, its water levels retreated suddenly to > 8 m depth, but returned in late 1998 to about 3 m below overflow. An analysis of waters collected in 1996 showed very low chloride and high sulphate concentrations, confirming an absence of deep geothermal waters. This behaviour may be influenced by its elevation (315 m a.s.l.) which is the highest of any historically active geyser or hot spring in Rotorua (c.f. 301 m for Pohutu Geyser and 280 m for Lake Rotorua).

5.3.3. *Okianga geyser*

This geyser was created by people cutting an outflow channel from a boiling hot spring to supply water to a washing pool (Lloyd, 1975). During the late 1970s and early 1980s no eruptions were observed, but since about 1992 it has been reliably erupting every 25–35 min to about 7 m high (Luketina, 1996; Cody, 1998a).

5.3.4. *Parekohoru spring*

In 1985–86, this spring ceased overflowing for several days each winter, the first such stoppages known in historical times. Since 1988, there has been no further cessation of flows. Boiling surges with large overflows recommenced in 1995, similar to reports of earlier this century and from which it gained its European name of the Champagne Pool. These boiling surges continue to date.

5.4. Northern Rotorua city springs

Near the southern shores of Lake Rotorua, large springs in the Government Gardens, Kuirau Park and Ohinemutu areas (Fig. 2) are fed by the rhyolite aquifer. These have also undergone significant changes consistent with higher water levels as measured in M-wells (M-12, Fig. 4).

5.4.1. Rachel spring

This is the sole remaining boiling and flowing alkaline spring in the Government Gardens. Prior to 1987, the last recorded overflowing and boiling episode was in 1967. From then until 1987, its water level had remained at 1.2–1.7 m below overflow, and the temperature at 70–80°C. However, since late 1988 it has been continually boiling and flowing at 7–12 l/s. It still has brief cessations of overflow, but these stoppages last only for a few days and since 1988 its water level has never fallen more than 0.1 m below overflow.

5.4.2. Kuirau lake

For about two years in the early 1940s, the levels, flows and temperatures in this large hot spring (about 5000 m²) were monitored by NZ Geological Survey to investigate its use as a possible supply of hot water to the public ward baths. Their findings were that it had too varying water levels and temperature to be considered as a reliable hot water supply. From late 1940s to 1987, the water was warm (about 45–50°C), acidic, low chloride, and there was little or no overflow. However, from 1988 until November 1997, Kuirau Lake consistently overflowed at 40–60 l/s and 70–80°C, high chloride and low sulphate alkaline waters. The rise and heating of Kuirau Lake since 1988 has killed all the vegetation surrounding its shores, including *manuka* and *kanuka* trees up to 5 m high and 20–30 years old, which had grown since the lake cooled in the late 1940s. Since December 1997, outflow has fluctuated between about 25 and 50 l/s, with activity showing an apparent inverse relationship with the nearby Tarewa springs.

5.4.3. Tarewa springs

Over the last 14 years, water levels have typically been about 1.5 m below overflow (Cody, 1998b) in this area. In March 1998, several of the larger Tarewa springs, within Kuirau Park, commenced boiling once more and in some cases their water levels rose to overflow. In July 1998, geysering activity occurred in three of the springs. Two features had been infilled or built over while inactive, and their reactivation has created considerable interest and highlighted new issues regarding the reactivation of hot springs.

5.4.4. Other springs

The consistently high water levels and large overflows of Rachel Spring and Kuirau Lake are the most conspicuously visible spring recoveries in northern Rotorua following the well closures of 1986–87. Other notable changes in Kuirau Park include the resumption of hot alkaline overflows from the Soda Spring in

1988, which, since some time between 1953 and 1966, had been constantly below overflow, cool and often dry (Cody, 1989). Similarly, Waiparuparu (Lobster Pool) has filled, heated up and resumed overflows since 1992, after being dry or at low levels and cool since the 1940s. This pool was popular for bathing amongst early settlers in the 1880s, before public bath houses became common.

6. Hydrothermal eruptions in Rotorua

In historical times (1845–1998), explosive hydrothermal eruptions have occurred throughout Rotorua city, with at least 91 events being recorded. The frequency and distribution of these appear to show a correlation with large scale disturbances of the Rotorua geothermal field imposed by both human and natural activity (Fig. 7). The 10 June 1886 volcanic eruption of Mount Tarawera (about 20 km east of Rotorua) caused pronounced changes in thermal activity throughout Rotorua, with many previously extinct or passively flowing springs suddenly boiling, erupting and overflowing. At Geyser Flat (Whakarewarewa), the Prince of Wales' Feathers Geyser was created and Wairoa Geyser resumed eruptions. Many hydrothermal explosions and resumed hot spring overflows also occurred in the weeks and months following the eruption (Smith, 1886; Dansey, undated; NZ Herald, 15 June 1886; Auckland Evening Star, 10 June 1886).

During the 1890s, there was rapid urban development as the town of Rotorua was established and settled. The Ohau channel draining Lake Rotorua at its northern end was straightened and widened to take steam boats through to Lake Rotoiti. This led to sudden changes in the level of Lake Rotorua, which had previously fluctuated naturally. In the 1900s, the level of Lake Rotorua was finally

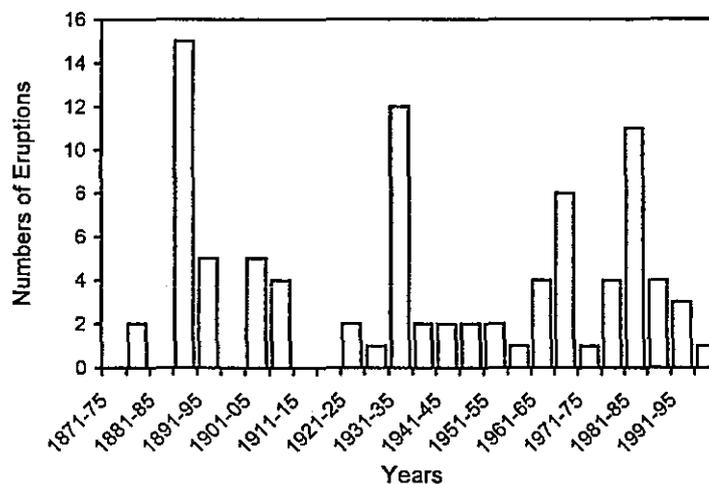


Fig. 7. Time series plot showing the occurrence of hydrothermal eruptions.

controlled to prevent lake level fluctuations. The Puarenga Stream delta, at the southern end of Sulphur Bay (Fig. 2), is an area of high steam flow, where spectacular large hydrothermal explosions were common in the 1890-1900s. Hydrothermal explosions have continued sporadically to date in the delta, the latest being an eruption on 7 March 1996, when a shallow crater of about 15 m diameter was formed during an eruption that lasted less than an hour.

In the early 1890s, a railway line was built into Rotorua. The construction works to establish this line along the western and southern margins of Kuirau Park (Fig. 2) resulted in extensive drainage of the previously swampy, peaty ground. Writers at that time attributed several hydrothermal explosions there to the effects of the recent drainage works. In the late 1920-1930s, well drilling commenced in Rotorua, using hand-operated rigs. This initial episode of well drilling may also have caused disturbances in the shallow boiling parts of the geothermal field.

The 1950-1960s was a time when national electricity shortages and blackouts were common, so that the Rotorua borough council actively encouraged residents to drill hot water wells to provide alternative heating. In the 1970s, New Zealand first experienced oil shortages and then large price increases of imported oil, which again resulted in Rotorua citizens embarking on increased well drilling and hot water drawoff, as more people sought alternative sources of heating.

The numbers of known hydrothermal explosions through time in Rotorua city are shown in Fig. 7. Numbers used include only those events for which good descriptions are available identifying a natural feature as the source; well casing blowouts and geothermal pipeline explosions are all excluded. It is probable that more hydrothermal eruptions have occurred, as historic records are not complete.

Hydrothermal explosions in Rotorua city appear to follow episodes of disturbance to the geothermal field, particularly those induced by human activities, such as changing lake levels or drilling. The higher rates of occurrence for hydrothermal eruptions (Fig. 7) broadly correlate with the following perturbations: the 1886 Tarawera eruption, lake level changes and drainage activities in the 1890s, commencement of drilling in the 1930s and the extensive drilling activity of the late 1960s to late 1980s (cf. Fig. 3). The number of events has declined since the bore closure programme was initiated.

7. Summary

The exploitation history of the shallow portion of the Rotorua geothermal field is an interesting story of encouraged exploitation, followed by realisation of the consequences and the introduction of management policies to correct them. Well exploitation has only been from the very shallow upper aquifers (20-200 m depth), and the deeper aquifer has never been drilled or exploited. Consequently, the changes induced in the field attributed to well drawoff and subsequent recoveries of pressures, water levels and spring flows may not be directly

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comparable to other geothermal fields (in New Zealand or worldwide), where much greater and deeper drawoff has occurred.

In Rotorua, well drawoff reached a peak of about 31 kt/d in 1985, with a natural outflow of about 60 kt/d. In other highly exploited New Zealand geothermal fields, drawoff has greatly exceeded natural outflows. For example, at Wairakei, wells (500–1500 m deep) have drawn off about 120 kt/d since the late 1950s, compared to a pre-development natural outflow of 34 kt/d (Allis, 1981). At Ohaaki (Broadlands), about 43 kt/d drawoff has occurred from wells since 1989 (Cody and Christie, 1992), compared to a pre-exploitation outflow of 2 kt/d (Browne, 1974). In both of these examples, greater volumes of deeper geothermal fluids have been drawn off than has ever occurred in the Rotorua geothermal field.

Natural thermal features at Rotorua appear to have been preserved or show signs of recovery by management intervention before well drawoff reached excessive quantities. It was also before large-scale inflow of cooler fluids occurred around the field margins, allowing recovery of pressure and surface flows to springs before thermal degradation had destroyed their conduits and vents.

Forced well closures by central government in 1987 were met with much animosity and opposition. However, the subsequent water level recovery measured in M-wells, resumption of overflows from hot springs and eruptions from several geysers are consistent with the reduced well drawoff, allowing more geothermal waters to reach natural surface spring outlets. This confirms the success of the closure programme and other management strategies of the late 1980s. Fluid pressure beneath Rotorua has recovered about half the inferred drawdown caused by a combination of exploitation and a long-term decrease in rainfall prior to the mid 1980s (Bradford, 1992).

Acknowledgements

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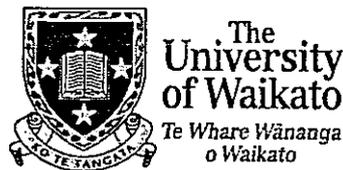
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*Discovery consists of seeing what everybody else has seen and
thinking what nobody else has thought*

– Albert Szent-Gyorgyi (in I.J. Good – The Scientist Speculates)

APPENDIX XI:

Geological Society of
New Zealand
Annual Conference 2001
27th - 29th November, Hamilton
"Advances in Geosciences"
Fieldtrip Guides



Edited by
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UNIVERSITY OF WAIKATO



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Field Trip FT1

Rotorua Geothermal Field – Management, Monitoring and Surface Features

Ashley D. Cody

*Geothermal Consultant
Rotorua*

FIELD TRIP OVERVIEW

We will depart Hamilton at 8 am and drive to Rotorua via Highways 1 and 5 across the Mamaku Plateau. We will meet up with the trip leader, Ashley Cody at Kuirau Park at approximately 9.30 am. People should have old footwear and be prepared to walk thru damp or mud covered/dusty ground. We will walk around Kuirau Park; visiting in particular the 26/01/01 eruption site and out to Tarewa Road house sites impacted by resumed hot spring activity. Returning to the park area we will see instances of well casing failure, tree die-off, and ground subsidence problems in this part of the geothermal field.

We will then drive to the New Zealand Maori Arts and Crafts Institute, via the Hospital production and reinjection monitor wells. We will have lunch here where toilets are available, and it is an opportunity for field trip participants to wander around the institute viewing carvers and exploring the model Maori village.

After lunch we will walk to Geyser Flat in Whakarewarewa, then onto Waikite Geyser where hopefully we will see Pareia playing. Here we can examine in detail features of active hot spring systems and climb into an extinct geyser. From Whakarewarewa we will travel a short distance to the Forest Research Institute then onto the Roto-a-Tamaheke hot lake and springs. Time permitting we may be able to visit other features in this area. We are due back in Hamilton around 5.30 pm, requiring a departure from Rotorua at approximately 4 pm.

INTRODUCTION

The natural surface features of the Rotorua Geothermal Field (RGF; Figure 1) are a valuable commodity to local people and have been so ever since their arrival here in the 14th century. The RGF has provided hot water for bathing and cooking and the surrounding warm ground made for comfortable living conditions, with many sites having great cultural significance.

In the late nineteenth century, visitors were attracted to Rotorua to see unique geothermal sights, which in turn led to settlement to support growing tourism in the Rotorua area. Following the destruction of the Pink and White Terraces at Rotomahana during the volcanic eruption of Mount Tarawera on 10 June 1886, alternative geothermal sights in Rotorua were then opened for tourism. Today tourism is a significant economic activity for Rotorua city and district, worth in the order of \$310 million per year and providing 18% of all local employment (Butcher, et al., 2000).

The Rotorua Geothermal Field (RGF) is perhaps unique worldwide because it now has a legally constituted management plan in place since 1991, which aims to reverse the previously encouraged well drawoff and use of hot water. The aim of this plan is to protect the natural surface geothermal activity as well as allow some limited well draw off, all principally for sustainment of local tourism. The way this plan has been designed and implemented is discussed in detail elsewhere (O'Shaughnessy, 2000; Scott and Cody, 2000).

HISTORY OF EXPLOITATION AND MANAGEMENT POLICIES

The first hot water wells in Rotorua were drilled by hand-operated rigs mounted on shear legs, some time in the 1920s. Early newspaper records describe a well blowout at the Utuhina Lodge motel on Lake Road, beside the Utuhina Stream. In the 1940s at least 70 wells were known of and their temperatures, flows and pressures described by Modriniak (1945). All these wells were within the northern and central business district (CBD) of the Rotorua township, with no wells south of Devon and Sala Streets.

In the early to middle twentieth century, drilling of wells for hot water was free of jurisdiction by any controlling body. As a result, large quantities of hot water were taken and disposed of into ground waters, with no concern at all for efficiency of use or contamination of ground waters. During the 1950s a severe shortage of electricity Nationwide lead to Rotorua people drilling more hot water wells to heat homes and domestic water. At this time Inspectors made spot raids on homes to check for illegal use of electric space heaters. To be caught using electric heaters meant an instant fine and sometimes disconnection of the entire house from electricity!

In the 1970s nationwide oil price rises and supply shortages resulted in another period of geothermal well drilling in Rotorua, as more people sought alternative energy supplies for domestic and commercial heating. Numbers of wells drilled in Rotorua per year and total quantities of waters drawn off from hot water wells all show these sudden increases in use (Table 1)

Table 1 Summary of well numbers and mass withdrawals (in tonnes per day) through time (from O'Shaughnessy, 2000).

	1985	1992	1998
Total well drawoff	29,000	9,100	9,500
Net withdrawal	27,500	3,800	2,900
Reinjection back to source	1,500	5,300	6,600
Domestic well drawoff	14,000	2,200	2,100
Commercial well drawoff	15,000	6,900	7,400
Total Natural Outflows	~50,000	~70,000	~80,000
Total number of producing wells	450	225	175

TYPES OF GEOTHERMAL FEATURES

Geothermal Features are all those surface manifestations of geothermal activity: geysers, neutral to alkaline hot springs and pools; fumaroles; turbid acid pools and lakelets; mud pools and mud cones; barren warm or hot ground and solfatara; dolines and craters (collapse and eruption).

These features can usually be grouped according to whether they are produced by: neutral to alkaline geothermal water outflows (often saturated with silica); by weaker upflows of those waters mixing with surface waters; or by gas and steam heating of ground waters or dry ground. These processes occur through a continuum of gas and steam through to alkaline geothermal waters, with varying amounts of groundwater and air greatly influencing the surface forms. This is due to the supply of oxygen allowing oxidation of sulphides to produce strongly acidic conditions (see Appendix 1).

Alkaline to neutral flowing springs are most numerous at Ohinemutu and Kuirau Park in the north and at Whakarewarewa in the south of the RGF. A few occur on ground surrounding the shores of Sulphur Bay at Ngapuna and in Government Gardens. Most common are turbid weakly acid ground waters mingled with geothermal water upflows, or of steam and gas heated ground and surface waters. In the absence or scarcity of surface water, mud cones or hot barren ground form, with examples across the whole RGF. Geysers are very rare, with these restricted to only Whakarewarewa in recent years. However, at brief intervals and throughout historical time, geysers have occurred in Ohinemutu and Kuirau Park.

From recent work compiling a database of all known geothermal features, surface activity is shown to be concentrated around Ohinemutu and Kuirau Park in the northwest; around the western and southern shores of Sulphur Bay and the Puarenga Stream delta; and in Arikikapakapa and Whakarewarewa in the south. In this southern group, flowing alkaline clear springs only occur along the banks of the Puarenga Stream through Whakarewarewa.

SURFACE ACTIVITY CHANGES

Flowing hot springs (~70-100 °C) of near neutral to alkaline pH (~6.7 to >9) with high chloride (~500-1500 ppm) and low sulphate (~10-80 ppm) contents are preferred spring types for monitoring purposes in the RGF. These spring types best represent deep geothermal fluids reaching the ground surface with a minimum of fresh ground water admixing and/or minimal surface residence time in which to allow oxidation processes due to atmospheric and freshwater exposure.

All large flowing hot springs in the RGF have shown varying extents of visual and measurable changes through time, exclusive of those which have undergone obvious and direct human interferences with their surface outlets, etc. Events such as hydrothermal eruptions and ground collapses have also occurred but these are of generally insufficient frequency to allow correlations or trends to be recognised to date.

SOUTHERN SPRINGS AND GEYSERS

In the southern areas of RGF (Figure 2), geothermal activity occurs as steam and gas heated features through Arikikapakapa Reserve and west of Old Taupo Road to Tangatarua. South of Hemo Road along both banks of the Puarenga Stream, Whakarewarewa Valley contains numerous thermal features of all types, with the only presently active geysers in the RGF. Thermal activity also extends south across Pohaturua Hill towards Waipa as extensive tracts of steam heated ground and mud pools. East of Sala Street at its junction with Scott Street, an isolated area of weakly acidic flowing hot springs occurs in the Puarenga Stream channel, but there is no sinter nor any silicified sediments present.

Arikikapakapa Reserve has no alkaline flowing springs nor any sinter deposits, although a chloride upflow occurs within Arikikapakapa Lake, which overlies the postulated position of the Inner Caldera Boundary Fault (ICBF) described by Wood (1992). Old, prehistoric sinters outcrop on the northwestern shores of Tangatarua Lake, but at present these areas contain solely steam and gas heated thermal features.

To the northeast side of Arikikapakapa an area of boiling ground extends into residential housing along the south side of Sophia Street. Several weakly active fumaroles and dolines (collapse craters) are present, with sporadic problems to properties due to sudden dieback of shrubs and trees, melting of plastic down pipes and gutters, collapse of driveways, underfloor heating problems, etc. These heating episodes are exacerbated by extremes of groundwater levels following unusual patterns of both drought and rainfall which persist for several weeks or months at a time. In June 2001 two houses here had claims being assessed by Earthquake Commission for geothermal damage.

In Whakarewarewa valley, geyser activity has undergone significant changes in the past few decades and throughout historic records. Most large hot springs and geysers here (Figure 2) have been monitored for several decades, with ongoing monitoring done at least once every month since c.1983.

Geyser Flat, Whakarewarewa

At least 65 geyser vents are recognisable through Whakarewarewa Valley today, although it is most unlikely that any more than a handful have ever been active at the same time. Natural changes are continually occurring here to alter the activity and existence of geysers and hot springs. For example, earthquakes break conduits; erosion and decomposition collapse ground.

Since the 1950s nine geysers have been active at Whakarewarewa thermal area of which six have been active in the 1990s. On Geyser Flat seven geysers are intimately connected over a north-south lineation named Te Puia Fault by Lloyd (1975), who proved the existence of shallow and rapid (<24 hrs) connections with a series of dye

tracings during the 1950s-60s. In recent years, visual and instrumentally recorded variations of activity between geysers have often been detected.

As a consequence of shallow interconnection between geysers, it is not possible to make reliable predictions of impending eruptions for any individual geyser, although overall patterns of activity have been recognised by many people and especially by staff and guides at NZ Maori Arts and Crafts Institute (NZMACI). Using qualitative data from the 1890s-1920s and instrumental recordings from the 1950s onwards, geyser activity has been compiled that shows a clear trend of failing geysers during the 1950s-80s, with some significant improvement and recovery of activity since 1987 (Figure 3).

Silica deposition changes the dimensions and flow rates of conduits and channels. Another cause of change to these geysers is the rupturing of flow channels and diversions or total closure of conduits by earthquake shaking. On many occasions in historical time, sudden changes to one or more geysers at Whakarewarewa have been attributed to an earthquake felt a short time before the changes. Caretakers' written reports give details for some of these events (Ingle, 1914).

In the 1980s-1990s several episodes of ground rupture at Geyser Flat have been observed and recorded, where earthquakes have been felt and recorded immediately prior to finding new fractures across the sinter terraces and with newly deposited ejecta of angular gravels and sands surrounding geyser vents there. For example, fractures of Te Puia Fault across Geyser Flat have been found on: 16 August 1984; 18 October 1988; 7 December 1989 (pyritised ejecta thrown out of Prince of Wales Feathers (PWF) geyser); 27 March 1991 and 16 May 1991. The fracturing of 18 October 1988 created a new geyser about 3 m north of PWF geyser. This new geyser played 2-3 m high and was active until early 1999 by when its vent had become almost totally closed off with silica deposition.

Similarly, PWF geyser itself was created by the 10 June 1886 eruption of Mount Tarawera, 20 km east of Whakarewarewa and newspaper accounts of the day tell of the new geyser alongside Pohutu (Thomas, 1886; NZ Herald, 22 and 23 June 1886; NZ Herald, 28 July 1886; Otago Daily Times, 22 June 1886).

Most recent was the unusual disturbance at Geyser Flat found on 28 February 2001, when Te Horu was opaque with fine silts and its outlet channel contained abundant fine silts and sands, which also lay on the terrace surfaces surrounding Pohutu and PWF. Wairoa geyser was also contained very muddy water; all of these geysers usually being clear and free of any fine materials. It is possible an earthquake swarm centred beneath Rotorua city on 20 February 2001 may have caused ruptures at Geyser Flat to produce the muddy discoloured waters. Muddy water and a lot of gravel and silt ejecta deposits were also found here in early October 1999; several felt earthquakes occurred on 14-19 September 1999.

Pohutu Geyser

Pohutu geyser has changed its eruption styles throughout historical time and has continued to change dramatically in recent years. Sometimes Pohutu eruption characteristics have shown changes consistent with changing aquifer pressures. For example in July-August 1986 Pohutu lapsed into a continuously steaming phase, ejecting droplets of water but with no outflows at all. This behaviour was unprecedented then and has not been seen since.

In 1997-98 recordings showed Pohutu had changed to numerous short duration eruptions of 2-5 minutes occurring up to 60 or 80 times per 24 hr day. By 1999 some of these short duration eruptions had blended into longer plays and from 17 March 2000 until 17 April 2001 it played continuously, mostly as a full column ~20m high.

April and May 2001 were months when Pohutu geyser rarely had any full column eruptions at all, with a few lasting only a minute or less. However, from the start of June 2001 it resumed longer and more frequent full column eruptions, with 5- 10 minute durations being seen often each day and occasionally up to twenty minutes. It also once more resumed complete dormancies between eruptions, more typical of its activity before 1998.

Prince of Wales Feathers Geysers

Prince of Wales Feathers (PWF) geyser was created by the 10 June 1886 eruption of Mount Tarawera. It is 2.5 m north of Pohutu geyser at the edge of the prominent sinter mound enclosing both PWF and Pohutu. During 1886-1901 it was known by guides and caretakers as "the Indicator" due to it then beginning to play shortly before Pohutu geyser. In 1901 the Caretaker named it the Prince of Wales Feathers geyser, in honour of the Royal visit that year.

In 1992 NZMACI guides noticed the sinter terraces surrounding PWF had become white instead of their previously orange and brown due to algal growths. This change coincided with PWF changing to nearly continuous eruptions lasting >95% of each day, whereas before then it had only played <75% of each day in many discreet eruptions. The increased outflows of hot water killed off the algal growths, which do not tolerate a continuous 70 °C or above.

Since 1992 PWF has maintained this very high proportion of eruption every day, so that its sinter surrounds have remained barren of algae and have instead become opalescent with silica deposition over about 150m². PWF also played nearly continuously through March 2000 to April 2001 while Pohutu was in constant eruption. Since April 2001 PWF has also developed discrete eruptions once more, generally accompanying those of Pohutu. It also has resumed long dormancies.

Te Horu Geyser

Te Horu is a large (~7 m diameter) open vent immediately south of Pohutu and until c.1972 was a true geyser, with 10-15 eruptions every day accompanied by large overflows. Photographs of these eruptions from the 1920s show eruption columns ~5-7m high. However, since the early 1970s no true geyser activity has ever been seen from Te Horu. During the 1980s its waterlevel was always below overflow and oscillated over up to 5m height change within an hour or so, but only reaching to within ~2m of overflow level.

In the late 1990s, Te Horu waterlevel began rising progressively higher at the peak of its cyclical fluctuations and in 1999 it resumed overflowing once more. However, since 1999 these overflows have always been below boiling (<76°C) and always coincide with Pohutu eruptions. It now appears that Te Horu is totally blocked, so that no upflow is occurring into Te Horu and it instead now catches and holds the erupted waters from Pohutu geyser alongside.

Mahanga (Boxing Glove) and Waikorohihi Geysers

The name Mahanga was supplied by a Tuhourangi elder Paora Tamiti, who accompanied and assisted Goldsmith in his survey of Whakarewarewa, which was printed in 1885. Mahanga geyser is also known as Boxing Glove, in allusion to the shape of its enclosing sinter mounds. It is ~20m south of Pohutu and 4m south of Waikorohihi geyser. However, its first known eruption in historical record was in October 1961 (Lloyd, 1975), although its previously dormant vent had the long established name of Mahanga. A few descriptions of geyser activity on Geyser Flat in earlier decades and in the 1800s are very similar to Mahanga, although no names were given to conclusively establish this.

Through the 1980s, recordings of Mahanga geyser showed it erupted 23-25% of each 24 hr day, usually 13-20 seconds long and occurring every 60-80 seconds. Eruptions were 3-5m high with weak overflows of <1 lps. Eruptions would often become shorter and further apart whenever Pohutu or Waikorohihi were erupting, at which time Mahanga could occasionally miss an eruption, or play only 1-2m high with no overflows.

From 1999, Mahanga geyser has become erratic and its periods of activity have become progressively less. In 1999 it would go several days without any eruptions at all and by 2001 it has become rare to see it erupt at all, with days or weeks of inactivity being normal.

During the 1980s Waikorohihi geyser typically erupted for 55-65% of each day as 12-15 or more eruptions 5-8m high and with overflows of 5-10 lps (Cody, 1986). During the 1990s it also became less frequently active and during 2000 no eruptions were seen while Pohutu was continuously erupting. Several short eruptions were seen in April 2001, but none since.

Kereru and Wairoa Geysers

Kereru geyser is at the northern base of Geyser Flat terrace, on a lower terrace alongside the Puarenga Stream. It is rarely ever seen in eruption but usually boils continuously with splashes 1-3m high and weak overflows. However, from c.1972 until January 1988 no eruptions were ever seen. Eruptions are generally very short lived, typically only 15-25 seconds duration but 7-20m high with large overflows of water crashing over the lower terrace. It has been observed to erupt up to seven times in one daylight period of <9 hours and the longest eruption known is of about five minutes occurring on 12 November 1997.

Kereru geyser has been active throughout historical time although no eruptions were seen during c.1972-1987. This episode without any known eruptions is consistent with lowered geothermal aquifer pressures and waterlevels at a time of maximum well drawoff. However, Kereru's activity remains unclear, as eruptions have no apparent relationship to any other geyser activity. A possible explanation may be its different water chemistry

from the rest of Geysir Flat vents, as there is consistently about 20% less chloride and tritium isotope results indicate fresh water inputs.

Wairoa geyser is about 15m south of Mahanga geyser, also on Te Puia Fault. It has not erupted naturally since 10th December 1940 (RMP, 11/12/40) although it was soaped into many large (~40-50m high) eruptions during the late 1950s. By 1981 its water level was ~4.5m below overflow, extremely acidic (high sulphate - low chloride) and continuously boiling. In 1996 its waterlevel rose to ~3.2m below overflow but it is otherwise unchanged to date.

Other Whakarewarewa Geysers and Hot Springs

During recent decades several episodes of sporadic and short lived geysering have occurred from other long known geysers. However, no trend or apparent relationship to any other activity or well use is recognised. At the eastern end of Roto-a-Tamaheke (Figure 2) spring S435 geysered many times daily 3-5m high in the early 1980s, but its vent was physically damaged by human intervention and it has not geysered since.

Okianga geyser (spring S488) played ~5m high every 35-60 minutes throughout most of the late 1980s to late 1990s (Luketina, 1996; Cody, 1998). In the early 1980s it rarely erupted at all, with some eruptive episodes correlated to increasing activity with lowered air pressures and vice versa. By 1999 the ground surrounding it had opened several new boiling flowing new vents and to date all geysering activity has ceased.

Waikite Geyser

Waikite is on top of a prominent sinter dome at 315m asl and Fenton Street was built to face this geyser at its southern end. Its eruptions were always very erratic and last erupted in 1967. During the 1980s Waikite was always blocked with sinter rubble and weakly constantly steaming. In the early 1990s a collapse of the sinter blockage opened the vent once more, which can now be sounded with a leadline to 8m depth onto a rocky floor.

Twice during 1990s the vent has filled to 3.2-3.5m depth of overflow with clear constantly boiling waters, but each time the water has been <5ppm chloride and very high sulphate, indicating it is only steam and gas heated fresh water.

Pareia Geyser

Located on the southeast end of Waikite Mound. Through historical time it has only erupted for a few months or years followed by years of inactivity. It erupted during February to April 1981, and then remained dry and calm until a few eruptions all on 30 January 1991. In 1998 it began erupting once again and has remained active ever since, typically erupting 2-4m high for about one minute, occurring at half to one hourly intervals.

Papakura Geyser

Papakura geyser was historically active until March 1979, when it ceased all boiling and geysering activity (Grant and Lloyd, 1980). Until then it had only been known to stop playing on three occasions, twice in the 1920s and once in the 1950s, each stoppage lasting only a few days or weeks (Cody and Lumb, 1992). However, it appears to have ruptured its vent with the 1979 cessation and has now become isolated from the geothermal aquifer, so changes no longer relate to underlying geothermal conditions. It is interesting to note that the cessation in the 1950s was accompanied by discharge of muddy waters and sandy ejecta being thrown around its vent, suggesting conduit rupture.

Parekohoru and Korotiotio Springs

The historical European name for Parekohoru has been the Champagne Pool in allusion to its continuous fizzy ebullition and occasional boiling surges. This type of activity had ceased by the late 1970s, but resumed in 1989 and continue to date. During the years in which no boiling surges occurred, Parekohoru ceased all overflow for several days at a time during July and August 1986, the only such stoppage ever known.

Throughout the 1990s and up to at least the time of writing in July 2001, it has typically been calm (~96-97 °C) and flowing (~2 lps), but occasionally boiled and surged in a large overflow (~15-20 lps) for a minute or less, with these episodes recurring every hour or so. A conspicuous feature of these boiling surges is the powerful percussive ground thumping that is keenly felt to ~20m radius of the pool margins.

Korotiotio Spring (Oil Bath Spring) is ~30m west of Parekohoru and has seven small vents within an area of ~3m x ~10m. All vents are at a common waterlevel ~0.5m below surface overflow, which weakened and

faltered in 1979 and ceased in 1980. Throughout historical times Korotiotio has had many hydrothermal eruptions.

ROTO-A-TAMAHEKE AREA

East of Whakarewarewa Village the large hot lakelet Roto-a-Tamaheke occupies a broad shallow valley impounded by silica sinters deposited by numerous boiling springs. In historical times, outflows from the lake and its surrounding springs have been altered by human intervention on many occasions and the boiling of its neighbouring springs has also ceased for years at a time. Physical and legal battles contesting the diversions of outflows were manifest in the 1890s and again in the 1930s.

In 1997 the Ororea Group of springs (S350-354) ceased boiling and flowing and in March 2001 all boiling of the western lakeside springs (S377 area) abruptly ceased. By late May the Hirere Bath (also known as the Down Bath) could only be filled once a day, instead of being constantly filling with hot water as before. By June 2001 many pools around the northern and western margins of Roto-a-Tamaheke had fallen to 1.2-2m below overflows and cooled, with no outflow at the eastern outlet nearest Forest Research Institute and with no boiling around the entire lake. This change is unprecedented since 1981 and is similar to the widespread collapse of boiling and flowing around here during 1938-1945.

KUIRAU PARK AND OHINEMUTU HOT SPRINGS

Kuirau Park has been conspicuous during 1989-2001 for its resumed hot and boiling outflows from long dormant, cooler and nonflowing springs. Many of the historical and post 1987 well closure changes have been described by Cody and Lumb (1992), Scott and Cody (1997) and also Scott and Cody (2000).

At the northern end of the park (Figure 4), Kuirau Lake has resumed continuous hot (70-80 °C) and alkaline (pH 7-7.6) outflows of 7-20 lps since bore closures and then Public Hospital reinjection of well waste waters during 1987-1989. Continuously high waterlevels have progressively invaded surrounding groundwaters, with an ongoing pattern of newly forming warm water filled collapse holes nearby.

To the western side of Kuirau Park (Figure 4), the Tarewa Group springs have filled again, commenced flowing and resumed boiling since March 1998. This sudden change is attributed by neighbours there to sharply felt local earthquakes of that time. Previous such hot spring activity had ceased in November 1981. To at least the time of writing, Tarewa Group springs have continued to invade surrounding ground, with accompanying newly formed hot water holes opening, mud pool blowouts and vegetation dieback. Four houses (Nos. 16 and 20 Tarewa Road) have since been removed or demolished due to persistent hot spring activity.

While risen waterlevels in the geothermal aquifer are the primary cause of these hot spring changes, other factors make Kuirau Park and Ohinemutu vulnerable to this resumption of hot spring activity. The entire area is low lying, with ground waters at only 1-2m depths. Widespread lake and stream sediments provide high lateral permeability at very shallow depths, intercalated with impermeable lake muds and spring sinters. Direct human activity is strongly implicated in these hot spring changes, as ground level has been raised by ~0.8m or more over 16-24 Tarewa Road prior to and since building developments there.

Along the eastern side of Kuirau Park parallel to Ranolf Street, widespread hot spring and pool waterlevel rises and reheating has occurred since 1987 and is ongoing (Figures 3 and 4). The Jaycee Monument and Lobster Pool (Papatangi-Waiparu) area has filled and heated so that many shrubs have been killed by hot waters and newly flowing alkaline boiling springs have developed. By the public footbaths supplied by Soda Spring, ground heating has progressively killed shrubs and trees. For example, in May 2001 a 46 year old Dawn Redwood was removed as it had recently died and was beginning to tilt over.

Further south beside Ranolf Street, in the area of Radium Bath, a large oak tree (c.45 yrs old) and several well established large rhododendrons and camellia trees have also been killed during the past few years. Toot and Whistle childrens' playground has been fenced due to recently formed soft hot wet ground; and the bordering old netball courts have developed two large (~2m and ~7m diameter) hot flowing pools within the paved courts. In June 2001 the cricket pitch again formed a collapse hole, which is now filled with warm water.

Ongoing changes to surface activity are not restricted to Kuirau Park but are also progressively occurring throughout Ohinemutu. In Ariariterangi Street, a modern home has been abandoned due to boiling beneath the concrete floor; nearby a neighbour has lost several large trees due to scalded roots; and an abandoned well has begun boiling and erupting alongside a residence. In Whittaker Road a home has had a hot pool begin overflowing and killing surrounding lawns.

To the time of writing, resumption and increase of geothermal activity across this part of Rotorua has been progressive and ongoing. Hot waters are heating, rising and beginning to boil, after many decades without hot waters at such shallow and problematic levels. Factors such as excessive intense short duration rainfall and local earthquakes are strongly implicated in triggering many of these changes, although underlying geothermal aquifer waterlevel rises since 1987 (Figure 3) are changes that were absent during the 1930s-1980s, when well numbers and drawoff were uncontrolled.

GOVERNMENT GARDENS, SULPHUR BAY AND NGAPUNA

Few alkaline flowing springs have ever existed here in historical times. Upflow of geothermal waters is occurring but it is also mixing with lake waters to produce turbid acidic waters. Rachel (Whangapipiro) Spring is the largest and most conspicuous alkaline flowing spring, which has had many episodes of flowing and nonflowing, boiling and nonboiling. Around its margins are substantial beds of silica cemented freshwater mussel shells, the result of cooking use in pre European times. Nearby here, Oruawhata or Malfroy's Geysers have boiling alkaline waters at only ~2m depths, but no surface outflows or ponding occur any longer. These were modified by Malfroy in the 1890s to provide a reliable hot water supply for the nearby Blue Baths, but inadvertently also created spectacular geysering, which became a notable attraction until their demise in the late 1950s (Malfroy, 1891).

Since the bore closure program of 1987-88, Rachel spring has overflowed and occasionally boiled, with its waterlevel typically ranging within about 750mm or less from overflow. Prior to 1987 it did not overflow or boil for many decades apart from a brief eruption in 1966. Around Sulphur Bay and Ngapuna increased outflows of hot waters is noticeable but these areas are away from easy public view and so it is likely that some changes are not reported. However, monitoring around here confirms that the Ngapuna springs have heated and increased outflows substantially since 1987-88, with the hotter outflows having killed areas of adjoining manuka shrubs.

CAUSES OF CHANGE TO SURFACE ACTIVITY

Intensive monitoring of the RGF commenced in 1981 and with the benefit of ongoing management monitoring, several factors are now seen as causing changes to the style and intensity of geothermal activity. These can be natural events such as unusual rainfall intensities or shortages; earthquakes; and ground cementation by sinter or sulphur.

Human induced effects include lowering the geothermal aquifer pressure by well drawoff; the physical infilling or excavation of hot springs; artificially draining ground waters and the diversion of rainfall infiltration by stormwater catchment as part of the urbanisation process. Kissling (2000) identifies months of double or treble the eighty year average monthly rainfalls as being times when unusual geothermal activity is most likely to occur. Similarly, exceptionally drier months are also associated with unusual geothermal changes, particularly in the late nineteenth and early twentieth century before Lake Rotorua levels were controlled. During that period, prolonged very low waterlevels were times when very large hydrothermal eruptions occurred around the Puarenga Stream delta in Sulphur Bay. Today dry months often result in mud pools drying and becoming inactive, although this is a transient surface effect only.

At the Puarenga delta in Ngapuna, hydrothermal eruptions have occurred throughout historical times and have continued up to the present time, the latest known blowing out a crater about 8m diameter sometime in early February 2001, on the east banks of the Puarenga some 50m from the lakeshore. Here the strongly boiling solfataric activity is supplying sulphide gas, which is oxidising to sulphur in the near surface ground waters. Meanwhile the stream is continually depositing a its bedload of alluvium, which becomes cemented by the sulphur deposition. This in turn forms an aquiclude that eventually over pressures and erupts. At the Puarenga delta, the timing of these hydrothermal eruptions suggest that fluctuating levels of Lake Rotorua may be the final triggering process.

Identification of an actual causative mechanism which results in some abrupt geothermal change to a geyser or hot spring may therefore be difficult to recognise with certainty, due to several underlying processes leading to the final vulnerability from an otherwise simple event that in itself has occurred many times without producing the same result.

Therefore the identification of the underlying causes of changes in geothermal activity are in some instances recognisable, but often these changes are the result of cumulative effects from more than one process. For example, during years of falling aquifer pressures and therefore progressive cold groundwater invasion of the geothermal aquifer margins, Papakura geyser abruptly ceased eruptions in March 1979 and became cooler, acidic and solely steam-heated. This may have been triggered by local earthquakes, but with falling aquifer pressure creating the initial stress.

HEAT FLOW IN WHAKAREWAREWA

One of the fundamental tenets of the Bore Closure Program in 1987-88 was that bore closure would prevent the slow but progressive decline in natural thermal activity and return it to some state with natural output at an increased level; at the same time as the geothermal aquifer pressure increased. Response of the natural features was much more equivocal and slow. The response of features such as geysers and hot pools is difficult to assess on an individual basis, but is discussed in more detail elsewhere. There are certainly some areas which show considerable increase in output, almost (in the case of Kuirau Park), to the point of alarm. In other areas the responses are more varied.

Estimates of total geothermal water outflows for Whakarewarewa are of around **34,000 tonnes per day (tpd)** before any well drawoff and about 25,000 tpd by 1967 (Mahon, 1985). The natural mass outflow from the whole RGF is estimated at **80,000 tonnes per day**, based upon known chloride concentrations of the deep fluids and the mass outflows of chloride in the Ohau Channel draining Lake Rotorua (Glover, 1992).

All neutral-alkaline springs with large outflows (>2 lps) showed responses in flow and temperature consistent with increased well drawoff up until 1987 and to the greatly reduced well drawoff after then. During 1982-1985, all springs at Whakarewarewa produced about 8,390 tpd (Glover and Heinz, 1985), which increased to about 9,240 tpd by 1989-1990 (Glover, 1992).

In general the larger features have shown the greatest response, with rather small and often reducing changes in their outputs. Overall, the outputs from groupings of features are similar to those of 1967 and much larger than from the same groupings in 1984. Overall total output for features has increased by 80% over values of 1984 and is now within 10% of the 1967 value, which is the most reliable estimate for spring discharges when the field was only lightly stressed by well drawoff.

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APPENDIX 1: Types of Geothermal Activity

Surface geothermal activity can be grouped according to the types of processes that are occurring and the nature of the deposits and landforms which result. The surface manifestations of geothermal activity are caused by the effects of two extreme end members: deep geothermal waters reaching the land surface; and by steam and gases boiling off a deeper aquifer. A continuum of intermingling of these two processes produces many intermediate forms of surface effects and features. Groundwater availability and mixing, or its absence, greatly alters forms and appearances, which occurs because of the addition of water and dissolved oxygen contained in it. Air entrainment also allows oxidation of sulphides within the exsolved gases and geothermal fluids.

To assist with classification of surface geothermal features, the following list describes what constitutes each class and form. This also allows uniformity when discussing these features.

Geysers: Springs with intermittent outbursts of boiling waters interspersed by quiescent episodes of recharge prior to the next eruption. Almost invariably are of neutral to alkaline deep sourced geothermal waters, which boil and eject water without any ejection of rocks or solids. Usually located close to a local ground water or stream; short lived in geological timescale. Acid water geysers are very rare; the only New Zealand example is Hakareteke (S49N) geyser at Waiotapu is a clear, sinter depositing acid geyser.

Neutral to alkaline springs: Deep sourced geothermal water outflows without any significant mingling of shallow fresh waters. May be boiling or nonboiling but are invariably clear water saturated with dissolved silica. Dispersion at the surface usually results in deposits of amorphous silica on the vent walls and surface outflow channels, with algae and bacterial growths along cooling outflow plumes. Note that outflows do not have to occur across the land surface; many such springs flow into the surrounding ground and appear as calm or boiling clear pools, yet having underground outflow channels.

Fumaroles: Dry steam and gas vents, usually discharging under pressure with audible Most commonly found in active volcano craters and less commonly in geothermal systems.

Solfataras: Areas of hot barren ground typified by exfoliating and heaving or buckling of ground surface due to oxidation of sulphide to sulphur (or possibly sublimation of sulphur), which grows crystals in voids to heave ground apart in prominent mounds of sulphur. Associated with boiling conditions from the geothermal aquifer to the surface. Uncommon in New Zealand, the best example being within White Island Crater and at the Puarenga Stream delta into Sulphur Bay, Rotorua.

Mud Pool: A viscous muddy pond that may build up mounds or ridges as the pond dries out in dry or warm weather. Rainfall may dilute the mud to temporarily form a turbid muddy pool. Formed by steam and gas heating of surface ground; the acidic by-products attack the surrounding soil and materials to break these down into suspended solids. May be discoloured by small additions of sulphides, or creamy white if free of sulphides or sulphur.

Mud Cones (Mud Volcanoes): Steam and gas heated and altered ground with very little free water available to form pools or mud ponds. Highly viscous muds can then spatter away from gas vents to build up stiff mounds or cones. May break down in wet weather conditions, but rebuild in drier weather once more. Mud cones are a rare form of surface feature, although boiling geothermal ground is common.

Turbid Pools, Lakelets: Groundwater pools with significant amounts of gas and steam entering them to oxidise sulphides and produce acids, which attack and break down surrounding ground. Colloidal sulphur suspension produces turbid water and black sulphur or sulphides may produce a variety of colours. Usually warm or tepid, or even cold water pools. Above about 60-65 °C these waters are clear due to oxidation of sulphur to colourless and soluble sulphates.

Craters and Dolines: Circular or oval depressions forming distinct craters may form by either collapse or eruption. Collapse craters form by subsurface chemical and physical (tunnel erosion) of materials so that ultimately the surface falls into a void. Eruptions form craters by sudden production of steam to violently expand and throw open a crater, accompanied with production of airborne debris. These are called hydrothermal eruptions, which are driven by physical changes of form (usually hot water to steam); they do not involve chemical release of energy as occurs in explosions.

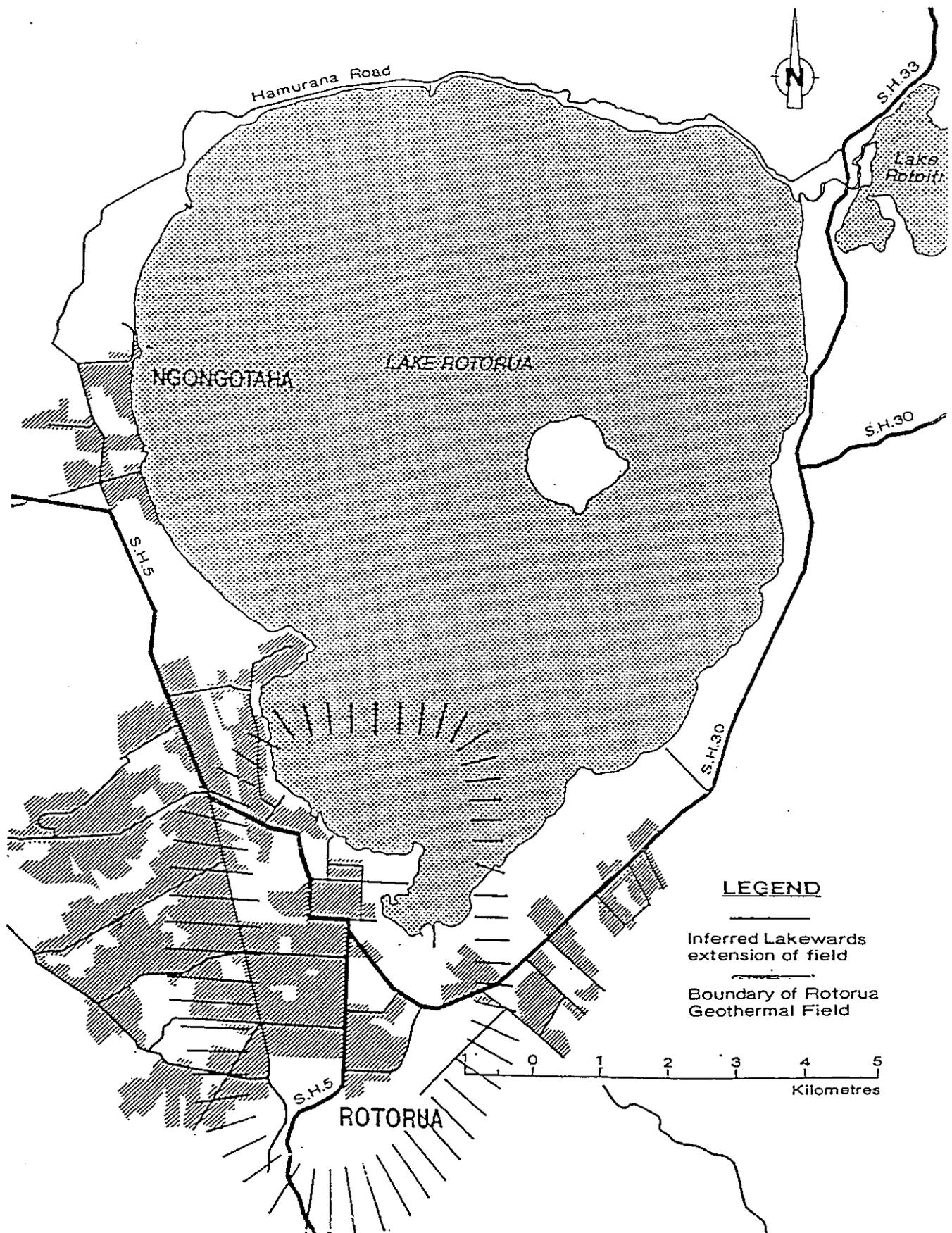


Figure 1 Location of the Rotorua Geothermal Field. Dashed lines indicate boundary delineated by 20 ohm metre contour. Note that the Eastern Rotorua Geothermal Field between Mokoia Island and the airport and Rotokawa is not shown.

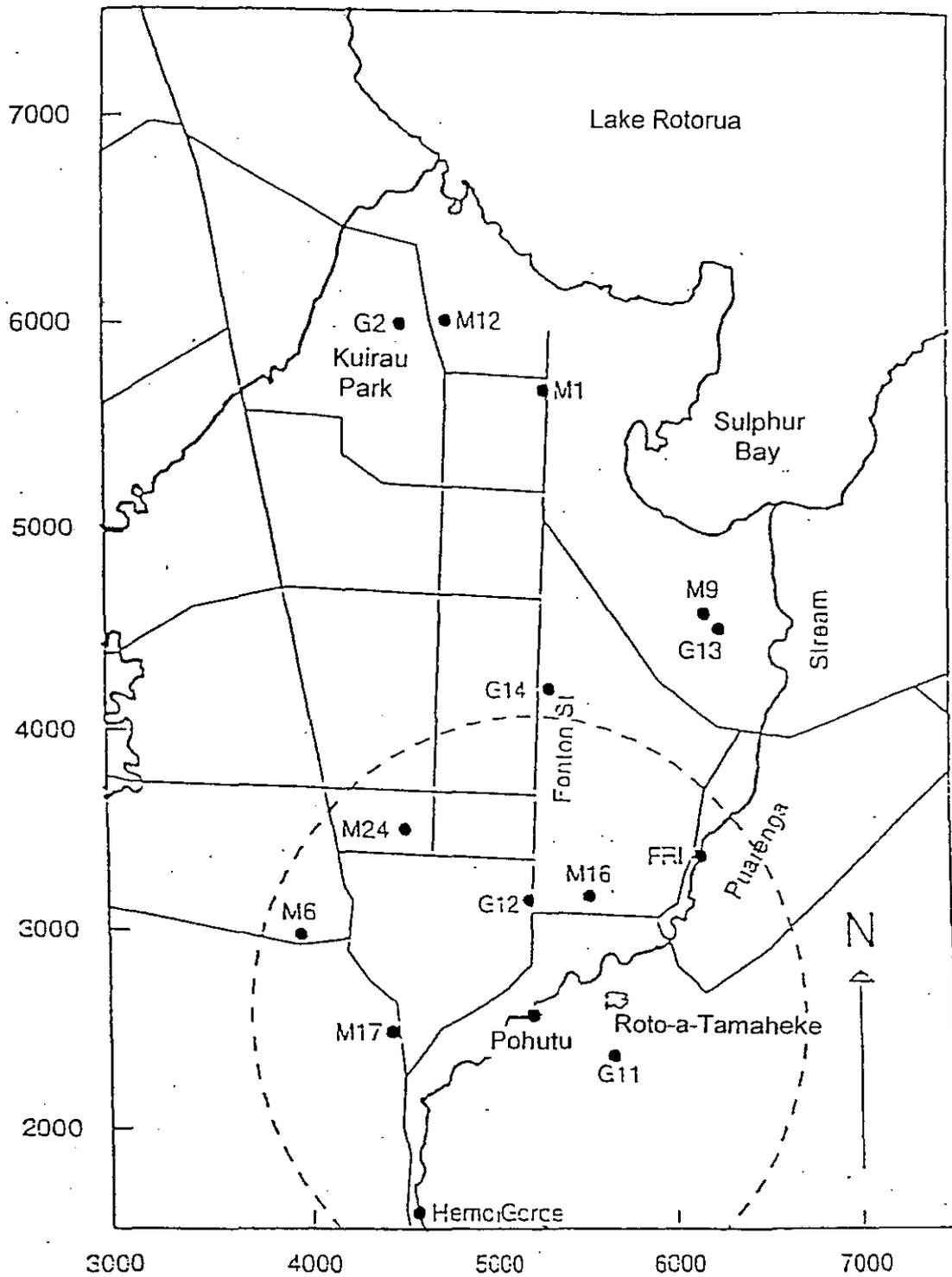


Figure 2 Geothermal monitor wells (M-series) and shallow groundwater wells (G-series). Pohutu geyser and Puarenga Stream gauging sites at Forest Research Institute (FRI) and Hemo Gorge are also shown. Dashed circle is 1.5 km radius exclusion zone about Pohutu geyser.

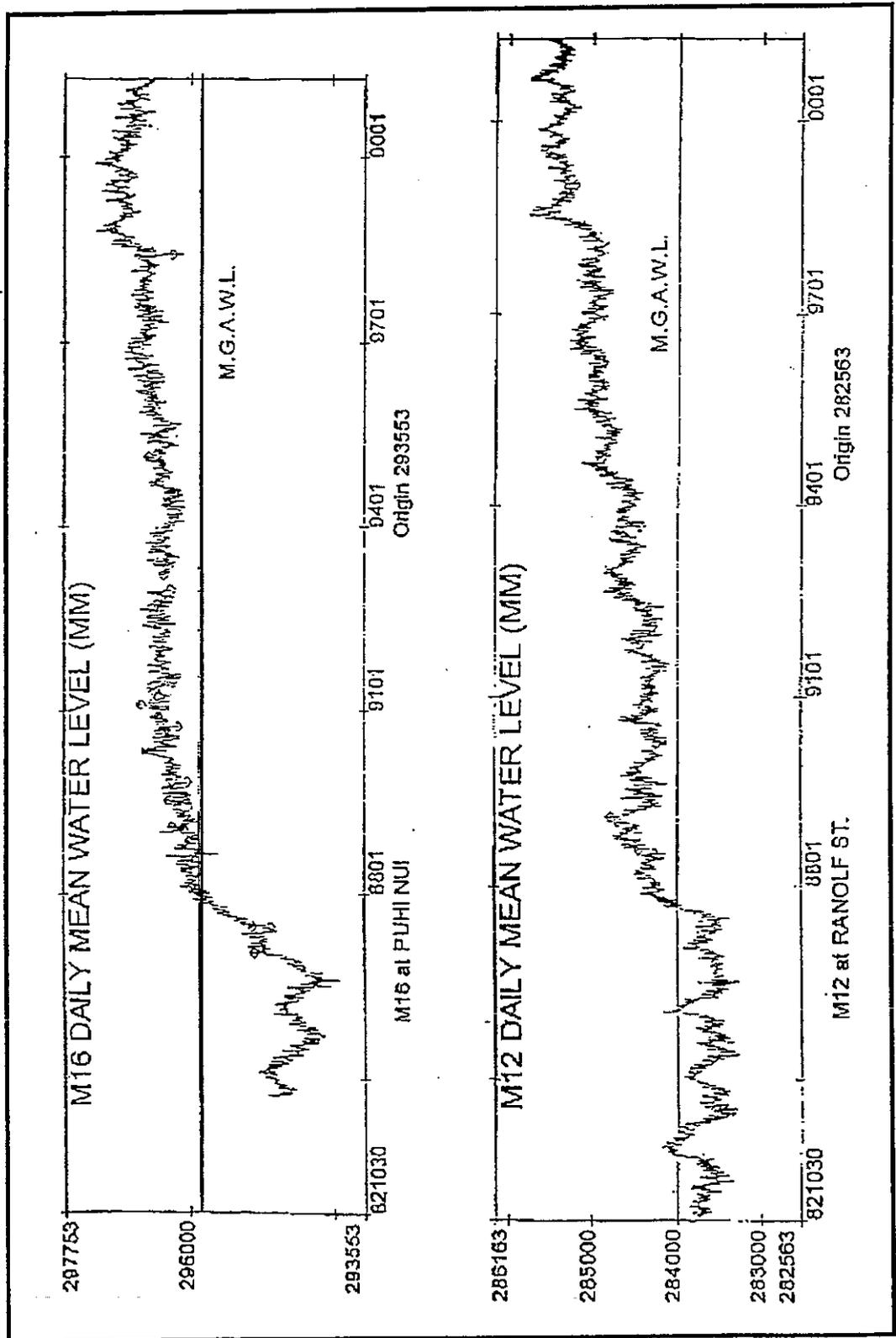


Figure 3 Water levels in two monitor wells M16 (ignimbrite aquifer, Sala Street), and M12 (rhyolite lava aquifer, Hospital Hill). Levels are in millimeters above mean sea level, corrected for atmospheric pressure effects. MGAWL is the minimum geothermal aquifer water level in each well. The management plan provides for drastic immediate well closures should levels fall to these values! See Figure 2 for well locations.

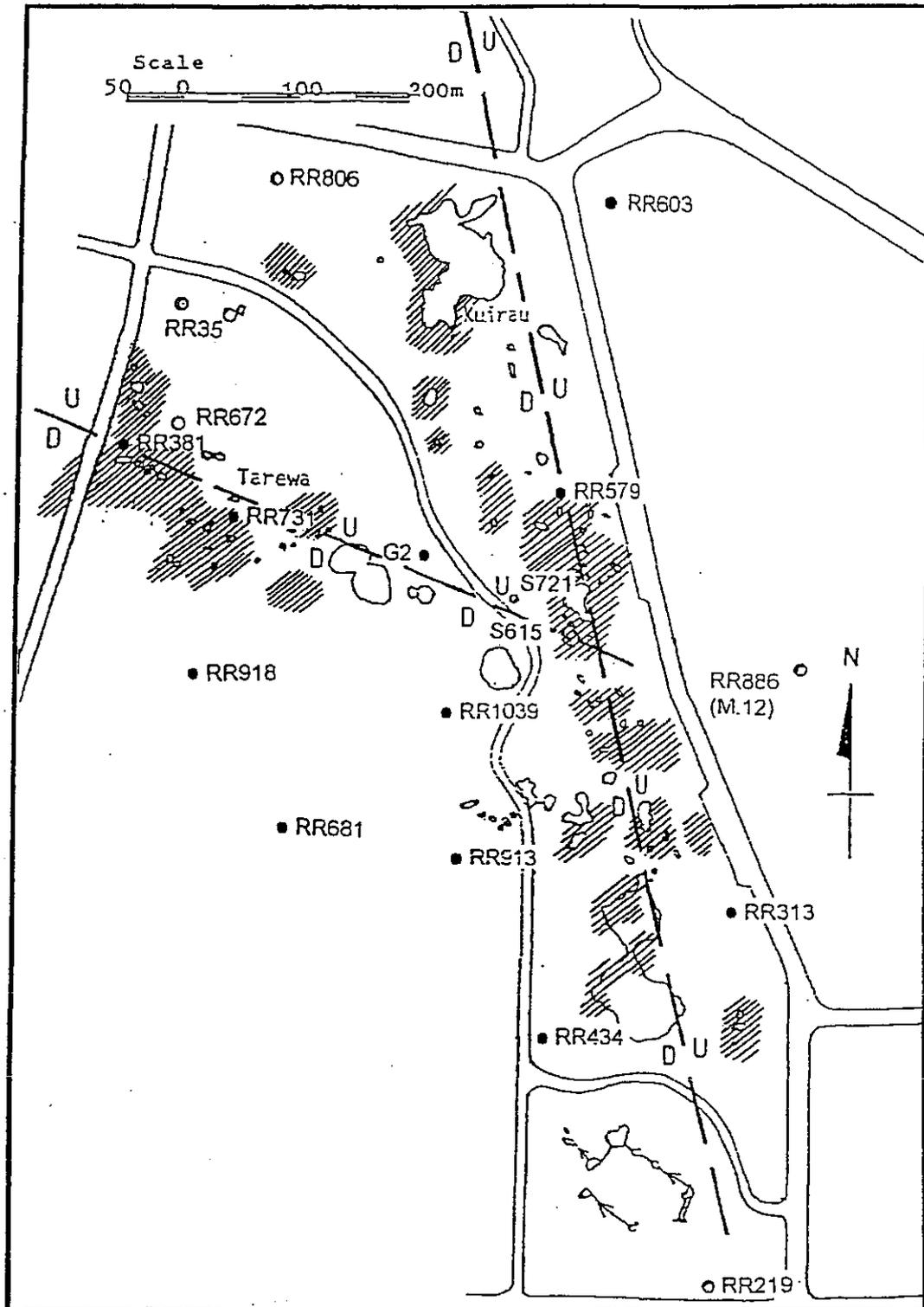


Figure 4 Kuirau Park showing some of the larger surface pools and thermal features and previous or existing wells (RR series). Hachures show areas of silica sinter, indicating areas of previous or current spring overflow sites. S721 is the site of the 26/01/2001 hydrothermal eruption. S615 is approximate site of August 1966 eruption crater. Fault lines are inferred only.