Geological Society of New Zealand

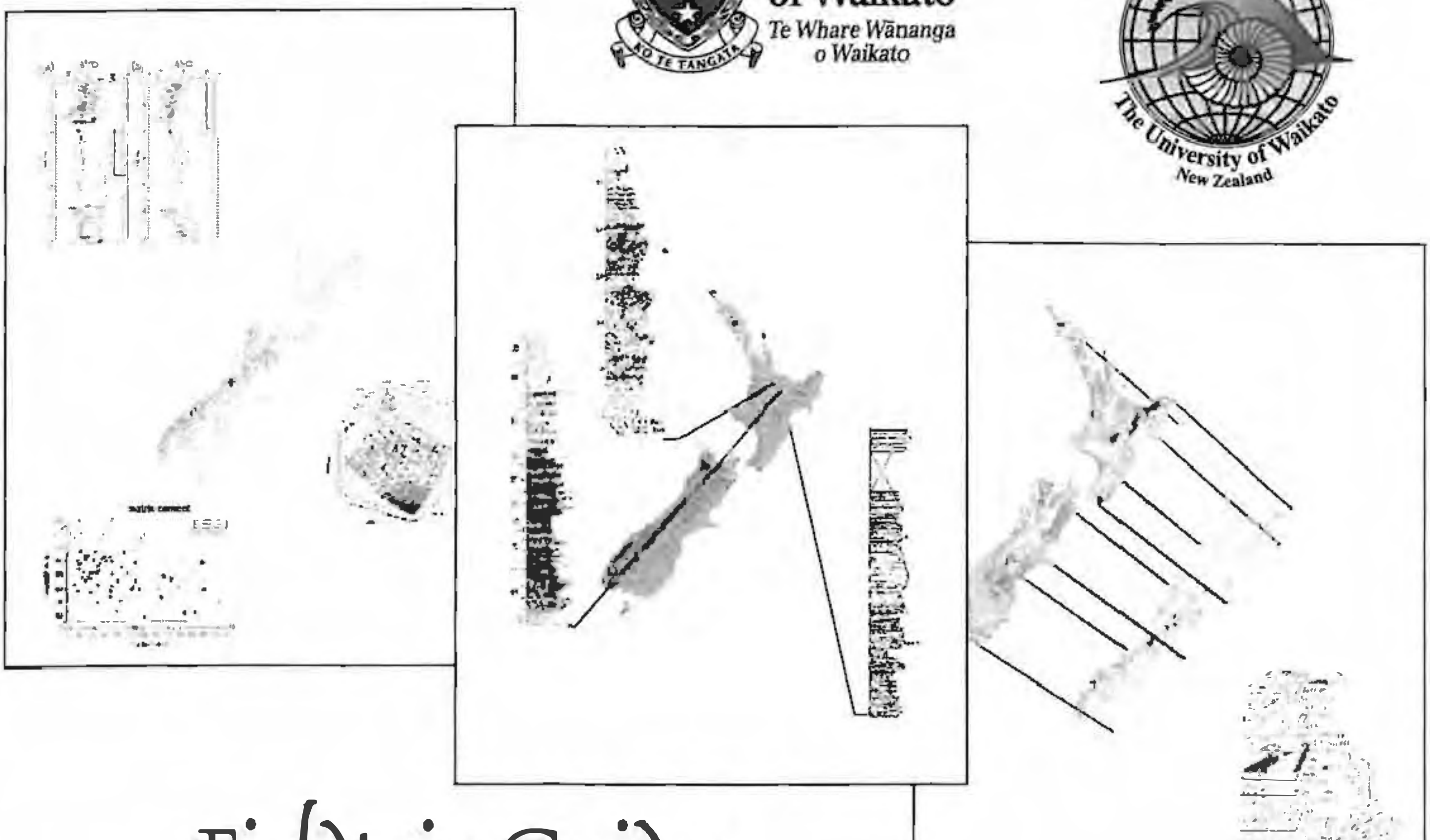
Annual Conference 2001

27th - 29th November, Hamilton

"Advances in Geosciences"

The University of Waikato
Te Whare Wānanga o Waikato

Earth Sciences
The University of Waikato
New Zealand



Fieldtrip Guides

Bibliographic References:

Abstracts & Programme

Lowe, D.J., Cooke, P.J. and Pallentin, A. Editors (2001): Abstracts & Programme, Geol. Soc. of NZ Annual Conference 2001 "Advances in Geosciences", Univ. of Waikato, Hamilton. Geol. Soc. of NZ misc. publication 110A.

Fieldtrip Guides

for entire guidebook

Smith, R.T., Editor (2001): Fieldtrip Guides, Geol. Soc. of NZ Annual Conference 2001 "Advances in Geosciences", Univ. of Waikato, Hamilton. Geol. Soc. of NZ misc. publication 110B.

for separate guide (e.g.)

de Lange, W.P. (2001): Coastal hazards of coastal Bay of Plenty. In: Smith, R.T. (Editor), Fieldtrip Guides, Geol. Soc. of NZ Annual Conference 2001 "Advances in Geosciences", Univ. of Waikato, Hamilton. Geol. Soc. of NZ misc. publication 110B, x-yp.

GIS Workshop

Fuchs, A., Pallentin, A. and Vonk, A., Editors (2001): GIS Workshop, Geol. Soc. of NZ Annual Conference 2001 "Advances in Geosciences", Univ. of Waikato, Hamilton. Geol. Soc. of NZ misc. publication 110C.

Geological Society of New Zealand

Annual Conference 2001
27th - 29th November, Hamilton
"Advances in Geosciences"

Fieldtrip Guides

The University of Waikato
Te Whare Wānanga o Waikato

Edited by
Richard T. Smith
Department of Earth Sciences, University of Waikato, Private Bag 3105, Hamilton

2001 CONFERENCE FIELD TRIPS

CONTENTS

Pre-Conference Field Trips, Monday 26 November

Post-Conference Field Trips, 29 November – 2 December

Acknowledgements

The organizing committee is very grateful to all the field trip leaders for their valued contribution to the success and diversity of the 2001 GSNZ annual conference.

We also greatly appreciate the financial assistance of **Solid Energy North**, **Kennedy Park Top 10 Accommodation, Environment Waikato,** and **The University of Waikato Department of Earth Sciences**, which has made these conference field trips possible.

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 met 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 Pohaturoa 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 the10 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 $150m^2$. 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 Geyser 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 choride) 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 the1920s 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 recognisible, 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.

REFERENCES

Bradford, E.; Cody, A.D.; Glover, R.B. 1987: "Rotorua hot spring data". Geothermal Report 11, Department of Scientific and Industrial Research, Wellington. 160pp.

Butcher, G.; Fairweather, J.R.; Simmons, D.G. 2000: "The economic impact of tourism on Rotorua". Toursim Research and Education Centre Report No. 17, Lincoln University, Christchurch.

Cody, A.D. 1986: "Eruption summaries of Pohutu and Waikorohihi geysers, Whakarewarewa" in Lumb, J.T. (Editor) "Rotorua geothermal monitoring program progress report 30 September 1986". Published by Department of Scientific and Industrial Research, Wellington.

Cody, A.D. 1986a: "A summary of all known failures or unusual changes to alkaline springs in the Rotorua geothermal field in the past fifty years" in Lumb, J.T. (Editor) "Rotorua geothermal monitoring program progress report 30 September 1986". Published by Department of Scientific and Industrial Research, Wellington.

Cody, A.D. 1998: "Geyser eruption records from Whakarewarewa". Environment Bay of Plenty, 30pp. (unpublished report).

Cody, A.D.; Lumb, J.T. 1992: "Changes in thermal activity in the Rotorua geothermal field". Geothermics (Special Issue: Rotorua Geothermal Field, New Zealand), 21: (1/2), pp.215-230. February/April 1992.

Cody, A.D.; Simpson, B.M. 1985: "Natural hydrothermal activity in Rotorua". pp.227-273 in Mahon (Editor), "The Rotorua Geothermal Field - Technical Report of the Geothermal Monitoring Programme 1982-1985". Published by Department of Scientific and Industrial Research, Wellington; for Oil and Gas Division, Ministry of Energy. 522pp.

Glover, R.B.; Heinz, H. 1985: "Chemistry of Rotorua waters". pp.295-393 in Mahon (Editor), "The Rotorua Geothermal Field - Technical Report of the Geothermal Monitoring Programme 1982-1985". Published by Department of Scientific and Industrial Research, Wellington; for Oil and Gas Division, Ministry of Energy. 522pp.

Glover, R.B. 1991: "Rotorua chemical monitoring to June 1991" in Grant-Taylor, D.F. (Editor) "Rotorua geothermal monitoring programme - Appendices to the report June 1990 to June 1991". Published by Department of Scientific and Industrial Research, Wellington.

Glover, R.B. 1992: "Integrated heat and mass discharges from the Rotorua geothermal system". Geothermics (Special Issue: Rotorua Geothermal Field, New Zealand), 21: (1/2), pp.89-96. February/April 1992.

Grant, M.A.; Lloyd, E.F. 1980: "Measurements at Papakura geyser, Whakarewarewa". Report No.92, Applied Mathematics Division, DSIR Wellington. 19pp.

Ingle, R.H. 1914: "Monthly Report to Tourist Department, Rotorua". Report from Caretaker at Whakarewarewa Thermal Reserve dated 1st January 1914. IGNS File U16/466 General, vol. 1.

Lloyd, E.F. 1975: "Geology of Whakarewarewa hot springs". Department of Scientific and Industrial Research Information Series No.111, 24pp. Wellington.

Luketina, K.M. 1996: "Determination of flow rates, volumes and temperatures in Okianga geyser, Rotorua". in Proceedings of 18th Geothermal Workshop, pp.85-88.

Mahon, W.A. J. 1985: "(Editor), "The Rotorua Geothermal Field - Technical Report of the Geothermal Monitoring Programme 1982-1985". Published by Department of Scientific and Industrial Research, Wellington; for Oil and Gas Division, Ministry of Energy. 522pp.

Malfroy, C.J. 1891: "Geyser action at Rotorua". Transactions of the New Zealand Institute, vol. 24 pp.579-590. Government Printer, Wellington.

Modriniak, N. 1945: "Thermal resources of Rotorua". NZ Journal of Science and Technology 26B: 277-289.

O'Shaughnessy, B.W. 2000: "Use of economic instruments in management of Rotorua geothermal field, New Zealand". Geothermics (Special Issue: Environmental Aspects of Geothermal Development"), 29: (4/5), 539-555. August/October 2000.

RMP 11/12/40: Rotorua Morning Post, Friday 11 December 1940.

Scott, B.J.; Cody, A.D. 1997: "Effect of bore closure at Rotorua, New Zealand". pp.270-276 in "Proceedings of NEDO International Geothermal Symposium". 11-12 March 1997, Sendai, Japan. Sponsored by New Energy and Industrial Technology Development Organisation, Japan.

Scott, B.J.; Cody, A.D. 2000: "Response of the Rotorua geothermal system to exploitation and varying management regimes". Geothermics (Special Issue: Environmental Aspects of Geothermal Development"), 29: (4/5), 573-592. August/October 2000.

Thomas, A.P.W. 1886: p.106 in Fieldbook. Held in Geology Library, University of Auckland, New Zealand.

Wood, C.P. 1992: "Geology of the Rotorua geothermal system". Geothermics (Special Issue: Rotorua Geothermal Field, New Zealand), 21: (1/2), pp.215-230. February/April 1992.

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.

Solafatara: 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-productsttack 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 sohat 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.

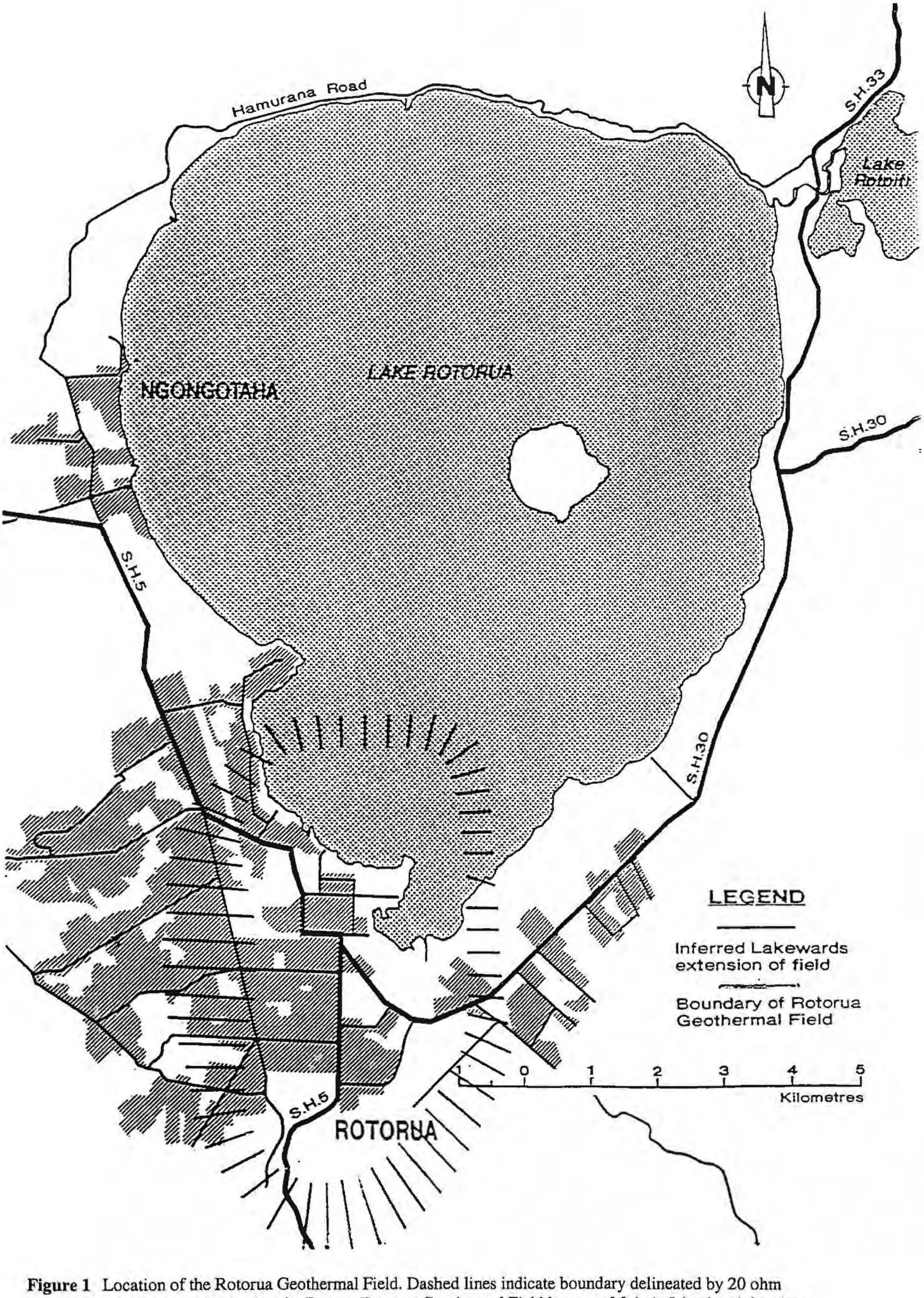


Figure 1 Location of the Rotorua Geothermal Field. Dashed lines indicate boundary delineated by 20 ohm metre contour. Note that the Eastern Rotorua Geothermal Field between Mokoia Island and the airport and Rotokawa is not shown.

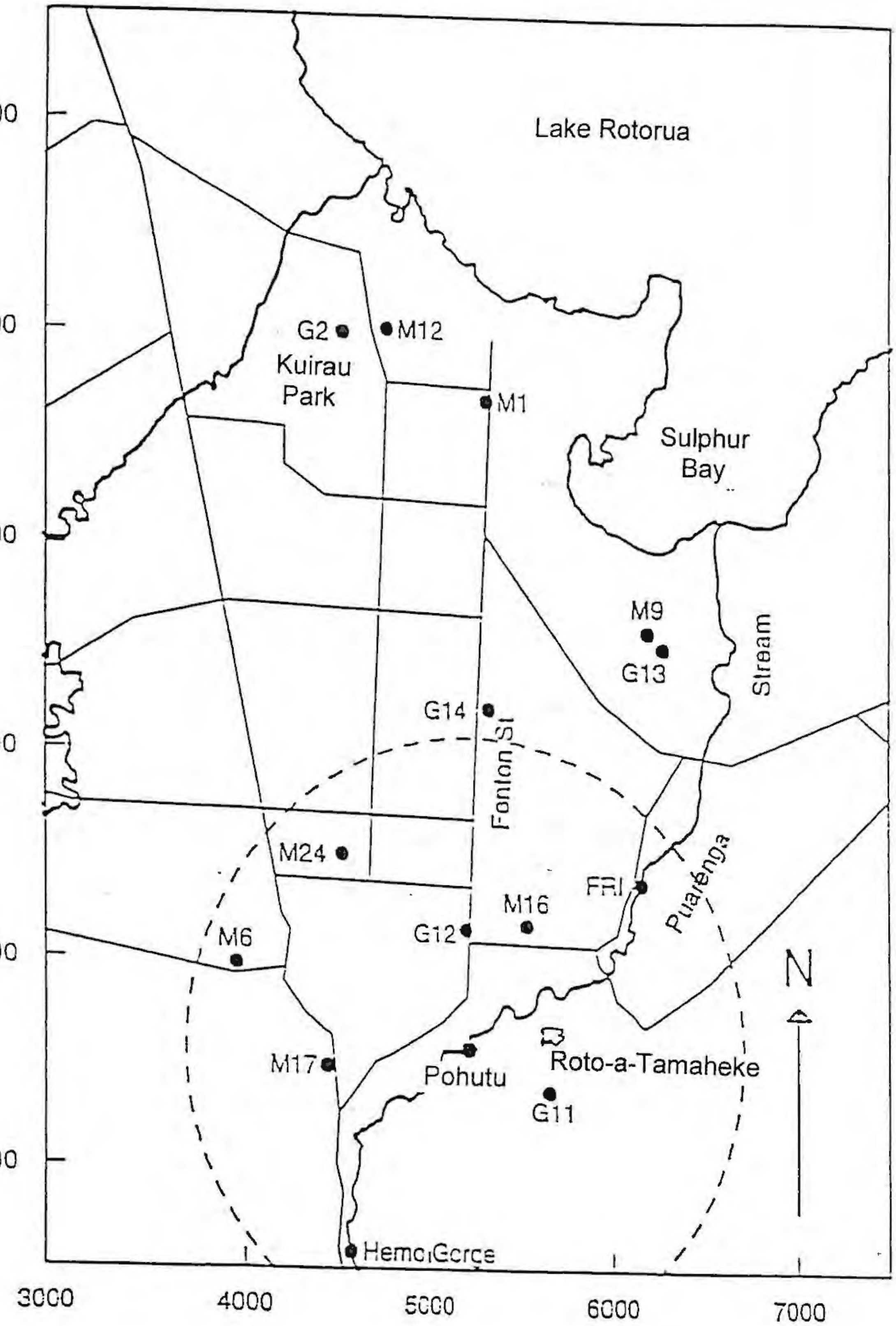


Figure 2 Geothermal monitor wells (M-series) and shallow groundwater wells (G-series). Pohutu geyser and Puarenga Stream gauging sites at Forest Research Institute (FRI) and Hemo Gorge are also shown. Dashed circle is 1.5 km radius exclusion zone about Pohutu geyser.

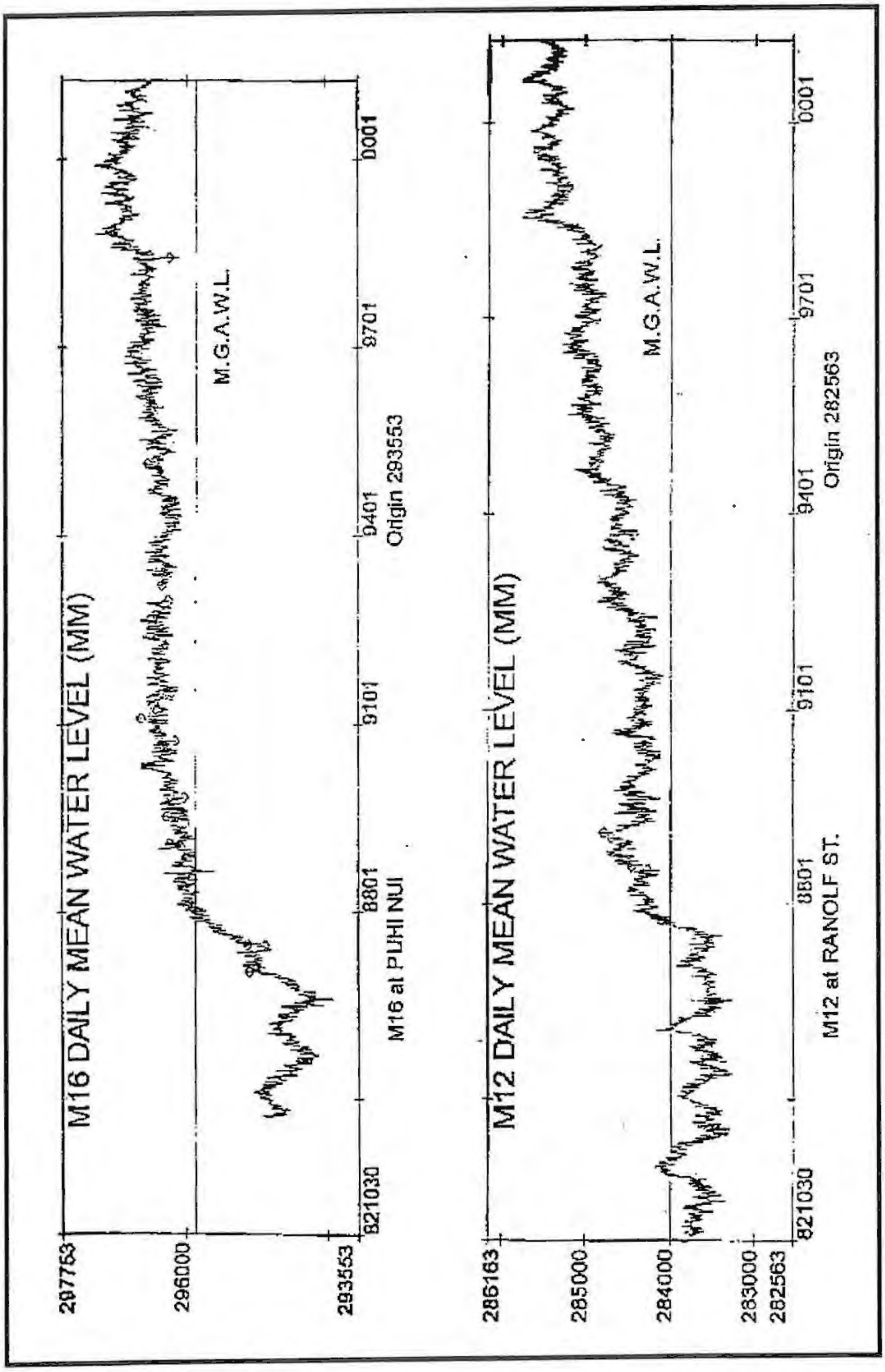


Figure 3 Water levels in two monitor wells M16 (ignimbrite aquifer, Sala Street), and M12 (rhyolite lava aquifer, Hospital Hill). Levels are in millimeters above mean sea level, corrected for atmospheric pressure effects. MGAWL is the minimum geothermal aquifer water level in each well. The management plan provides for drastic immediate well closures should levels fall to these values! See Figure 2 for well locations.

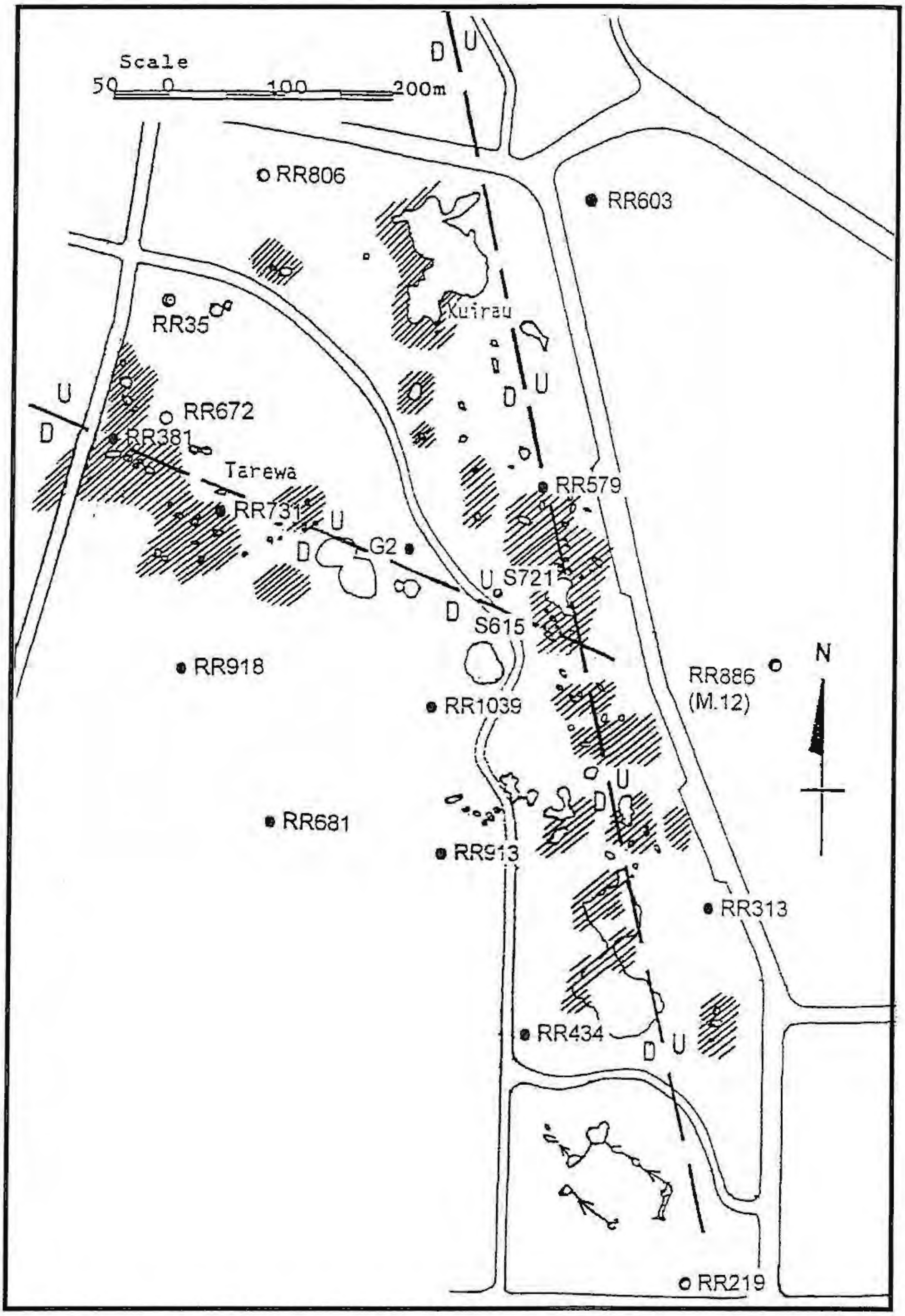


Figure 4 Kuirau Park showing some of the larger surface pools and thermal features and previous or existing wells (RR series). Hachures show areas of silica sinter, indicating areas of previous or current spring overflow sites. S271 is the site of the 26/01/2001 hydrothermal eruption. S615 is approximate site of August 1966 eruption crater. Fault lines are inferred only.