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Recovery of Rotorua geothermal field, New Zealand: Progress, issues and consequences

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Abstract

Recovery of most surface features in many parts of the Rotorua geothermal field (RGF) has continued as water levels rose and pressures increased following bore closures that began in 1986. However, the pattern of recovery of features is very variable, even within a relatively small area, with no apparent consistency as to location or type of feature. Most features in the Whakarewarewa Thermal Area that were affected by the pre-1986 pressure drawdown have recovered, but some have not. More puzzling is the behaviour of a few features (such as Waikorohihi and Mahanga geysers) that initially showed recovery, but later ceased activity. Chemical data indicate that for some features there has been an increase in the amounts of deep fluid reaching the surface, but in others there has been no change. Examination of seismic records suggests that the unusual behaviour is not related to local seismic activity. The recovery of many thermal features has been beneficial from a tourist and environmental viewpoint. However, there have been some detrimental occurrences. Following the decline and disappearance of thermal features before the bore closures, the vents of some features were inadvertently filled in and the land around them reclaimed and used for buildings or services. As water levels recovered after the closures, discharge to the surface recommenced, causing damage to buildings and associated services, resulting in several houses being damaged or forced to be relocated. In all cases, however, the discharges were from historically active vents. The data suggest that while most natural

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thermal features may recover from the effects of geothermal exploitation some may not, and in the case of Rotorua there does not appear to be any pattern or explanation for such non-recovery.

Keywords: Thermal features; Discharges; Hydrothermal eruptions; Field management

1. Introduction

The Rotorua Geothermal Field (RGF) is recognised internationally as an example of a geothermal system that has been extensively exploited at shallow depth (30–200 m), but not at greater depths (500–1500 m). It is unique in that over-exploitation was recognised and then subsequently addressed by a change of management policy. The RGF lies within the Rotorua Caldera and the Taupo Volcanic Zone and is renowned for its local geothermal manifestations including the geysers and hot springs at Whakarewarewa and Ohinemutu–Kuirau (Fig. 1). In the 1960s and 1970s, mass flows from Rotorua wells increased about twofold. During these times the level of natural hydrothermal activity in Rotorua declined to reach what was becoming critically low levels by the mid-1980s (Lloyd, 1979; Cody and Lumb, 1992). Ironically, during the early 1980s public sensitivity to the intrinsic and tourism values of New Zealand's few remaining geysers increased dramatically, even as the geysers and hot springs in Rotorua progressively failed due to extraction of geothermal fluids via well drawoff. A realisation that these geysers and hot springs might soon be lost led to establishment of the Rotorua Geothermal Monitoring Programme (RGMP) in 1982. This ultimately led to an enforced bore closure programme that began in 1986 (O'Shaughnessy, 2000), and resulted in well drawoff being reduced by ~60% during 1987–1988. Soon after, during 1988–1991, pressures increased by about 10–20 kPa (0.1–0.2 bar) and recovery of some surface features was observed.

Considerable work has been done on the Rotorua Geothermal System. The results of the RGMP are summarised in Ministry of Energy (1985), while other aspects of the field are covered in a special issue of *Geothermics* (volume 21, no. 1/2, 1992). The results of monitoring under the Rotorua Geothermal Regional Plan (RGRP) are reported by Grant-Taylor and O'Shaughnessy (1992), and Gordon et al. (2001). Scott and Cody (2000) described and discussed recovery of surface features following aquifer water level and pressure rises that followed the bore closures of 1987–1988. This paper reviews the resultant recovery of surface features and discusses the associated impacts, together with the success and extent of this recovery, and also its social consequences. Some as yet unexplained changes, which are exceptions to the general trends, are also recorded.

2. Field management

2.1. Rotorua Geothermal Regional Plan

In July 1999 the Rotorua Geothermal Regional Plan was approved and became operative, under the jurisdiction of Environment Bay of Plenty (Environment B.O.P.), with the

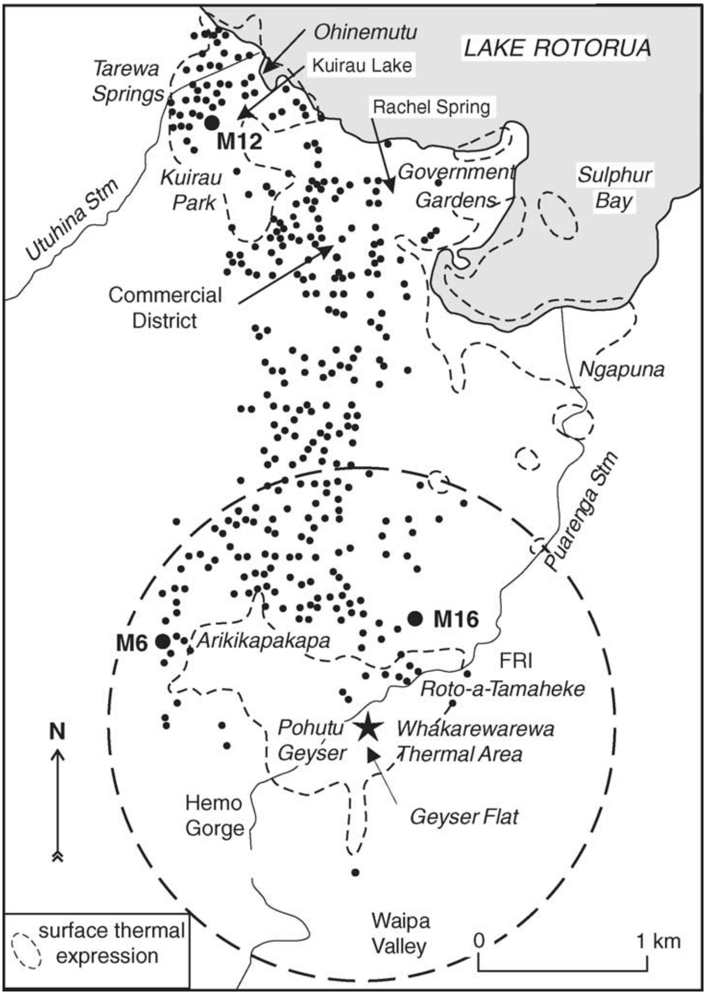

Fig. 1. Map showing the 1985 distribution of wells (small solid circles) in Rotorua, monitor wells (M; larger solid circles), and main areas of surface hot springs. The circle denotes 1.5 km about Pohutu Geyser (indicated by the solid star). FRI indicates position of the Forest Research Institute.

purpose of promoting the integrated and sustainable management of the Rotorua geothermal resource. The aims of the RGRP include enhancement and allocation of the resource, managing and controlling adverse effects on the field, and protecting surface features. The Rotorua Geothermal System has a wide range of values and a differing significance to sectors of the Rotorua community (Becker and Johnston, 2001). It is frequently identified as a major attraction for tourism in Rotorua, and has been valued at bringing NZ$ 320 million per year into Rotorua and both directly and indirectly provides about 18% of employment (Butcher et al., 2000). The natural surface geothermal activity has a tangible economic value that may be readily compared with potential electricity production and other possible uses.

Some of the key policies of the RGRP are:

- Retention of the 1.5 km radius mass abstraction exclusion zone around Pohutu Geyser (Fig. 1) to protect the outstanding geothermal features at Whakarewarewa.
- No net increase in fluid abstraction from the field. The maximum fluid abstraction permitted for the field has been set at 4400 t/d (the mass extraction level for 1992).
- Reinjection of all abstracted fluid. As a result of this reinjection policy it has been possible to allocate additional amounts of extraction, while still allowing a recovery in water level.
- Setting of strategic water levels in the geothermal aquifer to sustain geothermal surface features and protect these resources into the future.
- Protection of surface features from physical destruction, restoration of outflows and the avoidance or mitigation of natural geothermal hazards.

2.2. *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. 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; this is, however, not a useful concept because a number of sites have back-up wells and a number of wells may actually be replacements for failed wells. It is more useful to record the number of production sites. Records suggest that in 2001 there were 144 production sites, 68 reinjection sites and 41 downhole heat exchangers. Unlicensed wells in use were investigated during 2001–2002, and the results indicated there may be an additional 20 production sites and 10 downhole heat exchangers. The number of licensed user sites has remained relatively static since 1992 (Gordon et al., 2001). Since 1985, domestic bore ownership has risen from 50 to 54%, while commercial ownership has decreased to 46%. If only bores extracting fluids are considered (i.e. excluding downhole exchangers), the commercial users represent 65%.

The monitoring programme established that the average daily withdrawal from bores was 29,000 t in 1986, but there has been a substantial decline since then. In 1992 this was assessed at 9100 t/d, and in 2001 it was 9800 t/d. As the volume of geothermal fluid being reinjected has increased from 1500 t/d in 1985, 5300 t/d in 1992, to about 7500 t/d in 2001 (Gordon et al., 2001), the net withdrawal is now estimated at only 1900 t/d, a total decrease of 27,100 t/d. By contrast, the total natural outflow of the entire RGF has been estimated at about 80,000 t/d (Glover, 1992).

3. Monitoring programme

A central government-funded monitoring programme began in 1982 but this was taken over by the regional government (Environment B.O.P.) in 1991 and continues to date, with local funding. The initial monitoring programme included establishment of monitoring wells for both the geothermal and shallow groundwater aquifers. It also included intensive observations of the natural surface features and ongoing geochemical investigations of both hot springs and geothermal wells. Between 1982 and 1985, the RGMP developed an understanding of the hydrology and geology in the RGF, monitored changes in the field and developed a numerical model of the system to aid management decisions (Grant et al., 1985; Ministry of Energy, 1985).

During the period of enforced closures from April 1987 to July 1988 and in the period that followed up until 1990, intensive monitoring continued, funded largely by the Ministry of Energy, with contributions from Rotorua District Council and the Bay of Plenty Catchment Board. From 1987 to 1990, the targets set for the RGMP were to monitor the recovery and performance of geothermal features and to determine the nature and extent to which increased use could be made of the resource while still ensuring its conservation. Towards the end of this period the measurements indicated that the field appeared to have reached a stable state.

During the 1990–1991 period, legislative changes and government restructuring had their impact on the RGMP. Reduced funding following closure of the Ministry of Energy, and the adoption of some of its functions by the Ministry of Commerce, resulted in a significant reduction in the amount of data collected. Monitoring of water levels in the geothermal and groundwater aquifers continued, but surface feature monitoring was reduced to periodic "snap-shot" surveys. In 1991, the Resource Management Act shifted responsibility for field management to Environment B.O.P. This required the development of a regional plan to effectively manage the field. Consequently, the Rotorua Geothermal Regional Plan was developed between 1991 and 1994, and became operative in July 1999. The collection of well data has continued and has recently been augmented by an extensive set of surveys of natural features and mapping of properties with potential geothermal hazards (Cody, 2003); recently a chemical survey has also been made of 31 selected surface features and 10 wells (Mroczek et al., 2002, 2003a).

3.1. Field pressures and water levels

In 1982, geothermal monitor (M) wells (80–180 m deep) were established throughout Rotorua City and have been continuously monitored. They either stand open to atmosphere, or, if under pressure, are shut in so that no discharge occurs.

3.2. M-well responses

Prior to mid-1986 there were very strong seasonal cycles in geothermal aquifer water levels and pressures, with lows during the winter months (May–July) and highs during the summer months (December–February). There was remarkable consistency between monitoring bores across the whole of the RGF in the timing of these extremes. For all monitoring bores, the water level consistently showed a seasonal variation (low in winter, high in summer) superposed on a decreasing trend, i.e. exploitation.

During 1987–1988 all the M-wells showed a rapid water level or pressure rise of 1–2 m (0.1–0.2 bars pressure or 10–20 kPa), concurrent with the bore closure programme (Fig. 2). The same general trends are present in all M-wells, although relatively cool waters entering

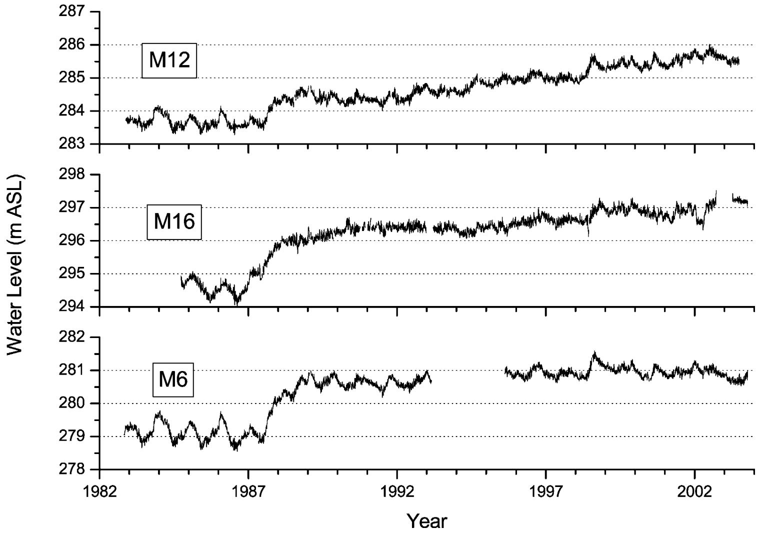

Fig. 2. Time series plot for three of the monitor wells (M12, M16 and M6), the locations of which are shown in Fig. 1. M16 is typical of wells into ignimbrite aquifers, and M6 and M12 typical of wells into rhyolite aquifers. Note the rapid rise in water level following the bore closures in 1986.

the ignimbrite from the west and proximity to Lake Rotorua at the north caused some wells to show additional short-term responses. From then through to 1990–1991 little change was observed. After 1990–1991, the long-term behaviour of the geothermal aquifer changed, with a consistent long-term water level rise becoming apparent. However, the onset of this rise was variable in both timing and amplitude across the field. The long-term rise is about 20–30% of the increase recorded during the 1987–1988 closure period. Kissling (2000) has shown that rainfall has an effect on the levels in the monitor wells, but neither this nor changes in borefield use (such as reinjection) can fully explain the significant water level rises across the field after 1990–1991. This long-term response is more apparent in the northern part of the field than in the southern (cf. M6, in Fig. 2).

4. Natural activity

The principal areas of surface activity in Rotorua include Ohinemutu–Kuirau (clear flowing springs, lakes, mud pots and steaming ground), Government Gardens (alkaline and acid pools), Ngapuna (flowing springs and hot ground), Arikikapapa (acid lakes and steaming ground) and Whakarewarewa (mud pots, near boiling and boiling springs and geysers) (Fig. 1). Thermal features discharging naturally to the surface are generally neutral to alkaline, high chloride–low sulfate waters typical of geothermal waters found in neighbouring shallow wells. Many springs and geysers have up to about 150 years of intermittent recorded information, but only a few large springs and geysers have substantial amounts of quantitative data spanning many decades. The discussion below is restricted to features with relatively good records of behaviour, or those not influenced by human activities such as drainage and modification for other uses.

4.1. Revised mapping

In 1967–1969, Lloyd mapped the active springs in Whakarewarewa, Scott mapped Kuirau Park in 1981 and Cody mapped Ohinemutu in 1985 and Arikikapakapa in 1989. The Ngapuna–Sulphur Bay area was never mapped in detail. Beginning in 1998, Environment B.O.P. employed contractors to begin compiling a database of thermal features in the RGF as a GIS layer to show these features relative to property boundaries. Over subsequent years this database was progressively added to and corrected, so that by April 2002 it contained 1525 entries. An important aspect of this mapping project was that it included sites for which there was any historical or geological evidence to prove that some geothermal feature had been present. This has significance with respect to the rejuvenation of long dormant, dry and cold hot spring vents, which, in many instances, have also been in-filled and covered by lawns, gardens, or buildings. As well as providing a better understanding of the spatial extent of these features throughout time, the database has importance for planning purposes within the city.

5. Government Gardens, Sulphur Bay and Ngapuna areas

The shoreline of Government Gardens and Sulphur Bay contain many outcrops of silicified sediments that represent hot spring activity when Lake Rotorua stood at higher levels (Kennedy et al., 1978). Few alkali–chloride flowing springs have existed in this area in historical times. Upflows of geothermal waters do occur, but generally they undergo mixing with lake waters to produce turbid acidic waters. Rachel (Whangapipiro) Spring (Fig. 1) is one of the larger alkali–chloride hot springs in Rotorua and is now the only remaining spring of its type in Government Gardens. Rachel Spring has had many periods of flowing and non-flowing, boiling and non-boiling activity through historic times. Since the early 1920s, water has been pumped from the spring to supplement nearby public baths, and this was increased in the 1990s. Oruawhata Spring (also known as Malfroy's Geyser), located about 100 m west of Rachel Spring, was dug open and the boiling alkaline water levels were recorded for several years, in the 1990s and to date. Boiling occurs at 1–2 m depth, but no surface overflow or geysering has occurred since the early 1950s. Around Sulphur Bay and Ngapuna, increased outflows of hot water were noticeable in the 1990s but these areas have limited safe access. The accessible Ngapuna Springs have heated and outflows have substantially increased since 1987–1988. The larger outputs, higher water levels and hotter outflows have killed manuka shrubs (*Leptospermum scoparium*) in adjoining areas (Gordon et al., 2001).

6. Kuirau Park and Ohinemutu Hot Springs

Since 1989, there has been a marked resumption of thermal activity in Kuirau Park–Ohinemutu and Tarewa areas (Fig. 1). Historical and post-bore closure changes in this area have been described by Cody and Lumb (1992), Cody (1998a), Scott (2000a, 2000b), and Scott and Cody (2000). Typical of this recovery is Kuirau Lake that rarely overflowed during the 1970–1980s, allowing kanuka scrub (*Kunzea ericoides*; tea tree) to develop about the lake shore. In 1989, Kuirau Lake resumed continuous hot (70–80 °C) alkali–chloride outflows of 7–20 l/s, with an ongoing pattern of old vents refilling with hot water, flooding the lake shore area and killing vegetation up to 25 years old.

On the western side of Kuirau Park are the Tarewa Springs. These are a series of large sinter-lined basins, 5–8 m diameter, that form a chain of vents extending from central Kuirau Park westward to Tarewa Road. These springs were known to boil and overflow at irregular intervals from the 1890s, but during the 1950–1970s activity became dormant in this area. Through the late 1970s and early 1980s many of these vents were in-filled with soil and debris, which camouflaged the fact that they were dry spring vents. In the 1970s, building development also commenced in this area.

In early 1998, there was a resumption of hot spring activity beneath and between residential housing at 14–24 Tarewa Road. In March 1998, springs S657 and S649 were boiling and overflowing onto the street (Figs. 3 and 4); this was the first such boiling or overflow from either of these two springs for over a decade. However, during subsequent months these two boiling and flowing springs and others nearby became more troublesome. On 8 May 1998, the adjacent (5 m) spring S657/1 re-opened its vent with hydrothermal eruptions 7–8 m high that continued for several days. In July 1998, geysering occurred in S657 and also from underneath the garage at 20 Tarewa Road. In May 1999, spring S657 resumed

Fig. 3. Spring 657 overflowing strongly in March 1998. Originally the spring was contained behind the wooden fence (photo: A.D. Cody). This figure, and others in this article, can be viewed in colour online at the ScienceDirect website: http://www.sciencedirect.com/.

Fig. 4. View looking south along Tarewa Road, Rotorua, showing spring overflow onto the roadway as a result of spring recovery in March 1998 (photo: A.D. Cody).

overflowing and S649 boiled and flooded its surrounding area. During 1–14 May 1999, the nearby spring S715 geysered 3–5 m high every 40–50 min. In November 1999, the large western-most pool at 22 Tarewa Road (S653) briefly erupted, killing a dog kennelled alongside; prior to that date this had been a calm, cool pool without overflow for many years. On 19 January 2000, hydrothermal eruptions occurred from a long-dormant, cold and in-filled dry spring vent (S652) (Fig. 5), which had been described and mapped by Thompson (1953) as an active spring. Between 24 and 26 January 2000, nearby S649 erupted in spectacular style at least six times and caused large overflows of boiling waters across the land at 20 Tarewa Road (Cody, 1998a; Scott, 2000a, 2000b). Intermittent vigorous boiling and over-

Fig. 5. Spring 652 after the hydrothermal eruption on 19 January 2000. Note the section of fence destroyed and the debris surrounding the feature (photo: B.J. Scott, GNS).

Fig. 6. Spring 653 after a vigorous boiling and overflow event in April 2000. Note the water and debris covering the surrounding area and the bund constructed in front of the fence to prevent water flowing onto Tarewa Road (photo: B.J. Scott, GNS).

flow events continue to date (Figs. 6–9). The resumption of activity in the Tarewa Road area resulted in several houses being damaged or forced to be relocated.

Along the eastern side of Kuirau Park, parallel to Ranolf Street, hot spring and hot pool water levels have shown increases since 1987. The Jaycee Monument and Lobster Pool (Papatangi–Waiparu) area has refilled and heated, with the result that many shrubs have been killed by returning hot waters. Ground heating has progressively killed shrubs and trees in the park, including large oak trees (45 years old) and several well-established large rhododendrons and camellia trees.

The recent resumption and increase of geothermal activity at Kuirau Park have been progressive and ongoing. Hot waters are heating, rising and beginning to boil after many decades without hot waters at such shallow levels. A dramatic hydrothermal eruption from an unnamed turbid acid pool (S721) occurred on the afternoon of Friday 26 January 2001. This pool is about 100 m west of the Jaycees Fountain and Monument. The eruption lasted for about 4 min, reaching an estimated column height of about 100 m and throwing out a carpet of ejected boulders and muddy rubble, which dispersed mostly in an easterly direction. Approximately 1200 m^3 of debris were ejected during this 4-min interval, with blocks up to 1 m diameter being thrown up to 70 m away (Fig. 10). A crater of about 15 m diameter remains, and the ejecta have been left on site as a tourist feature (Slako, 2002; Cody, 2003).

Ongoing changes to surface activity are not restricted to Kuirau Park, but are also progressively occurring throughout Ohinemutu to the north.

Fig. 7. Vent area of Spring 653 following a vigorous boiling and overflow event in April 2000. Note the ejecta from previous eruptions and flooding around the spring (photo: B.J. Scott, GNS).

Fig. 8. Springs 653 (left) and 649/650 (right). These springs were the sources of several hydrothermal eruptions and strong overflow events in 1999 and 2000. Photograph taken on 13 April 2000 (photo: B.J. Scott, GNS).

Fig. 9. View of a small scale overflowing event on 18 September 2000 in Tarewa Road. This event followed removal of the shallow concrete foundations of a rotary clothesline (photo: B.J. Scott, GNS).

Fig. 10. Aerial view taken shortly after the 26 January 2001 eruption of Spring 721 in Kuirau Park, Rotorua (photo courtesy of the Daily Post newspaper).

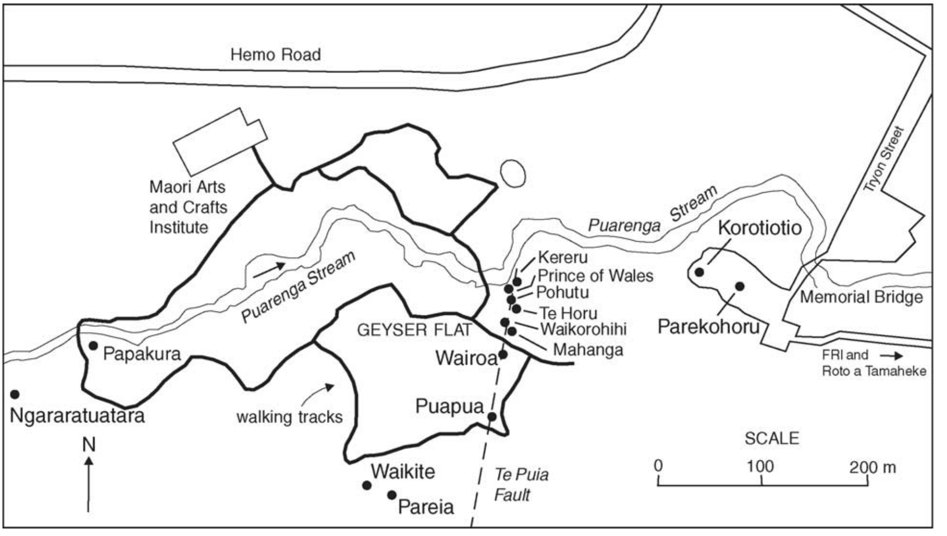

Fig. 11. Map of Geyser Flat, Whakarewarewa Thermal Area, showing locations of some of the geysers. FRI: Forest Research Institute.

7. Southern springs and geysers

In the southern part of the Rotorua Field, natural geothermal activity is concentrated in the Whakarewarewa Thermal Area and the Arikikapakapa Reserve (Fig. 1). Features include geysers and flowing hot-to-boiling alkaline and acid springs, mud cones, mud pools, turbid acidic pools and solfataras. Natural changes are continually occurring to the geysers and springs as a result of silica deposition changing the dimensions of conduits and channels, rupturing flow channels and causing total closure of conduits (Lloyd, 1975; Scott and Cody, 2000; Gordon et al., 2001). These types of natural changes compound the problems with interpreting geyser and hot spring changes through time.

Since the 1950s, nine geysers have been active at Whakarewarewa, six of which were active in the 1990s. Seven of the geysers are intimately connected over the north–south lineation of the Te Puia Fault (Fig. 11). Lloyd (1975) showed the existence of shallow and rapid (<24 h) connections between all these geysers with a series of dye-tracing experiments during the 1950s and 1960s. As a consequence of these interconnections, reliable assessments of individual geyser outputs or changes require that the overall patterns for this group of geysers also be considered. North to south along this fault, the seven features are given below.

7.1. Kereru Geyser

Kereru Geyser is at the northern end of Geyser Flat, on a sinter terrace immediately above the Puarenga Stream (Fig. 11). In the late 1800s and early part of the 20th century, Kereru had irregular eruptions that were weeks or months apart and were generally very short-lived

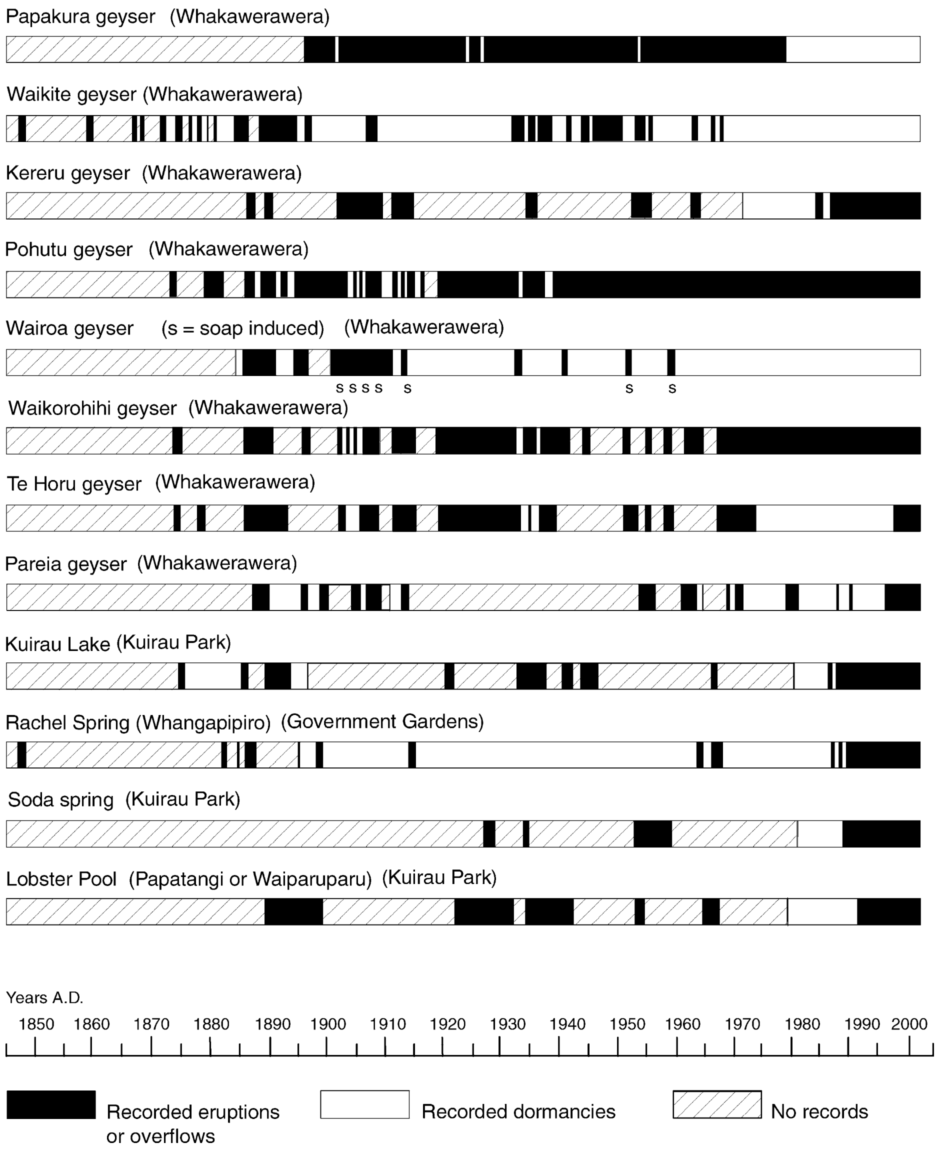

Fig. 12. Time series histogram illustrating the major changes in spring–geyser activity in Rotorua from 1845 to 2003.

(typically only 15–25 s duration) but 7–20 m high, with large overflows flooding the lower sinter terraces. Between geyser eruptions, Kereru was typically continuously boiling and splashing with sporadic weak overflows. From about 1972 until January 1988 no natural eruptions were observed (Fig. 12), although a few soap-induced eruptions were made for photographic purposes. This period of dormancy coincided with the general decrease of spring and geyser activity elsewhere at Whakarewarewa. After 1988, natural eruptions of Kereru recommenced, but they remain rare. Typically today it boils continuously, with splashes 1–3 m high and weak overflows, but on one occasion it was observed to erupt seven times in less than 9 h. Eruptions of Kereru have no apparent relationship to any other geyser activity. This might be explained by its water chemistry, which is different from the rest of Geyser Flat vents. Kereru has about 10% less chloride than other geysers, indicating that it has some fresh water inputs (Bradford et al., 1987). It continues this sporadic eruption activity to date.

7.2. Prince of Wales Feathers Geyser

When in eruption, Prince of Wales Feathers (Fig. 11) plays 8–12 m high during its strongest phase, with a weaker splashing play of 1–3 m height also being common. From 1886 to 1901 it was known as “The Indicator” because it always commenced geyser activity several hours before Pohutu geyser erupted. Throughout the 20th century, it continued to commence eruptions just before Pohutu and Waikorohihi geysers played. During the 1950–1970s it erupted about 25–35% of each 24 h day and invariably played throughout each eruption of Pohutu Geyser. During 1992, however, this changed to almost continuous eruptions lasting more than 95% of each day. Increased outflows of hot water killed surrounding algal growths and increased silica deposition about the geyser. It also played nearly continuously from March 2000 to April 2001 while Pohutu was in constant eruption. In April 2001, discrete eruption cycles developed, with long dormancies that generally accompanied those of Pohutu. However, since late 2001, it has had nearly continuous eruptions with very few dormancy periods.

7.3. Pohutu Geyser

Pohutu Geyser (Fig. 11) is the largest of the geysers and a symbol of Rotorua. Significantly, it was used as the centre point of the 1.5 km bore-closure zone in 1986 (Cody and Lumb, 1992). Historically, eruptions occur 10–60 times a day, averaging 10–30% of a day in activity, with a “typical” full column eruption height of about 21 m (Scott and Cody, 2000). The pattern of activity has changed through time (Fig. 12). From 1845 (earliest records) until the 10 June 1886 volcanic eruption of Mount Tarawera, Pohutu seldom erupted. After this volcanic eruption, however, activity was monitored more frequently and increases in play frequency were observed between 1886 and 1891, although experiments were conducted with the aim of controlling and stimulating the geyser’s eruptions (Malfroy, 1891). From the 1900s until the 1940s, Pohutu had irregular activity, with eruptions about 5–8% of a day (although periods of many days and weeks without eruptions were common), as were a number of events lasting over an hour (Cody and Lumb, 1992). This bi-modal distribution of plays remained until the 1970s, with the duration in eruption increasing to over 30% of a day. In the 1970s, Pohutu showed a pronounced shift to more frequent eruptions but of shorter duration. Longer eruptions became very rare, although the percentage of a day in play remained at around 30%. In July 1986, about 17% of the eruptions lasted less than 5 min with almost half lasting less than 10 min (Cody and Lumb, 1992). Eruptions would degenerate into a continuously steaming phase, with droplets of water and no overflows

(Cody, 1986). In 1988, Pohutu resumed longer duration full-column eruptions, although these were typically only a few minutes long. Observations of eruptions in 1996–1997 showed a change to numerous short-duration eruptions of 2–5 min occurring up to 60 or 80 times over a 24 h day (still around 30% in eruption). During 1997–1998 longer plays occurred and by 1999 some of these short-duration eruptions began to blend into longer plays. From 17 March 2000 until 17 April 2001, the geyser played continuously, mostly at full column (~20 m). During April–May 2001, it rarely had any full column eruptions. From early June 2001, however, it resumed longer and more frequent full-column eruptions, with events lasting 5–10 min and complete dormancies between eruptions. This pattern is similar to that observed in 1997–1998. Since late 2001, it has had almost continuous eruptions with very few dormancies in any week.

7.4. Te Horu Geyser

Te Horu Geyser, a large (about 5 m diameter) open pool immediately south of Pohutu Geyser (Fig. 11), has demonstrated interconnections to Pohutu and Waikorohihi geysers (Lloyd, 1975). Historically, it has erupted 10–15 times a day (5–7 m high) with large overflows, but this style of activity stopped in 1972. By 1987 the water level had fallen several metres below overflow. In the late 1990s, the water level began rising progressively and in January 2000 it resumed overflow. These overflows are at temperatures below boiling (approximately 76 °C) and are coincident with eruptions from Pohutu; it is therefore difficult to assess how much fluid is received from Pohutu Geyser versus that generated by its own activity. However, whenever Pohutu is dormant for several hours, the water level in Te Horu will fall 0.3–0.5 m below overflow level, suggesting that a substantial portion of the overflow is from Pohutu activity.

7.5. Mahanga (Boxing Glove) Geyser

Eruption activity at Mahanga Geyser (Fig. 11) has been known only since October 1961 (Lloyd, 1975), although its name was established well before then. Records of activity from the 1980s indicate that eruptions occurred for 20–23% of each 24 h period. Eruptions usually lasted for 13–20 s every 60–80 s and typically were 3–5 m high, with weak overflows of less than 1 l/s. Mahanga Geyser eruptions would often become shorter and further apart when Pohutu or Waikorohihi geysers were erupting and occasionally it would “miss” an eruption. Plays were still regular during 1999 but since then geyser activity has progressively decreased and eruptions have become erratic. During 1999–2000 several days would sometimes pass without eruptions and by early 2001 they had become rare, with days or weeks of inactivity. It was observed in eruption in May and December 2001 but has remained dormant since then, except for two days of eruptions in late March 2002. It remains inactive to date.

7.6. Waikorohihi Geyser

Located between Pohutu and Mahanga geysers (Fig. 11), Waikorohihi Geyser has been active throughout historical times (Lloyd, 1975; Cody and Simpson, 1985; Cody and Lumb, 1992). A variety of activity has been observed, from unusually high (about 13 m) sporadic eruptions to dormancies of several weeks' duration. In the 1960s and 1970s, it typically played 12–20 times per day, with long periods (25–40 min) of overflow. During the early 1980s, instrumental recordings showed Waikorohihi typically erupted for 55–65% of the day (12–15 eruptions per day). Typically these events were 5–8 m high, generating overflows of 5–10 l/s. In 1986, its eruption style changed to long dormancies of 20–35 h (Cody and Lumb, 1992). During the 1990s eruption activity from Waikorohihi decreased, with fewer eruptions and typically shorter durations. During 2000 no eruptions were observed when Pohutu Geyser was continuously erupting; since April 2001 it has not been observed to erupt except for 10 days in November 2002 (up to 13 eruptions per day), and on a few days in May 2003. No eruptions have been observed since.

7.7. Wairoa Geyser

Wairoa Geyser is situated about 15 m south of Mahanga (Fig. 11), also lying on the Te Puia Fault. It has not erupted naturally since 10 December 1940, although many large (40–50 m high), soap-induced eruptions occurred during 1958–1959. By 1981, it contained an acidic (high sulfate–low chloride), continuously boiling pool, with the water level about 4.5 m below overflow. In 1996, the water level rose to about 3.2 m below overflow, and remains so at the time of writing (August 2004).

7.8. Other Whakarewarewa geysers and hot springs

There are four primary concentrations of springs in the Whakarewarewa Thermal Area apart from Geyser Flat. One located to the west around Papakura Geyser, two groups to the east focused around Parekohoru and Lake Roto-a-Tamaheke, and another around Waikite to the south (Figs. 1 and 11).

To the west are Papakura Geyser and Ngararatuatara (Fig. 11), a continuously discharging feature that has shown very little hydrological or chemical change in the last 20 years. Papakura Geyser was historically active until March 1979, when all geysering ceased (Grant and Lloyd, 1980). Until 1979, it had been known to stop playing on only three occasions: twice in the 1920s and once in the 1950s, with each stoppage lasting only a few days or weeks (Cody and Lumb, 1992). Since the 1990s, it has contained a weakly-acidic, low-chloride warm pool, with no indications of recovering its previous water chemistry and activity.

Parekohoru (Champagne Pool) is a large spring located about 200 m east of the active geysers on Geyser Flat (Fig. 11). Historical activity included the occasional fizzy ebullition, boiling surges and continuous overflows of boiling fluid. This type of activity ceased by late 1979, and overflow stopped for several days during July and August 1986. Throughout the 1990s, Parekohoru showed increasing signs of recovery. Recent chemistry data show higher chloride concentrations, indicating that deeper aquifer fluids are now present. Since 2001, it has had powerful boiling surges, at approximately hourly intervals.

Korotiotio (Oil Bath Spring), situated west of Parekohoru (Fig. 11), is a series of seven small vents. Originally it was the source of water for the Oil Baths from the 1890s until about 1978, when it ceased reliable overflows (Parekohoru was channelled to supply the Oil

Baths after 1978). In 1980, all surface overflows ceased and have not resumed. Frequent, small-scale hydrothermal eruptions during the 1970s and 1980s occurred from Korotiotio's vents, and these eruptions may have affected fluid inflow–outflow. Since about 1996 water levels have gradually risen so that today the water level is about 0.1–0.3 m below surface overflow level. Recent chemistry data suggest that less deep geothermal fluid is now present (Mroczek et al., 2002).

East of Whakarewarewa Village is the large hot lake Roto-a-Tamaheke, which occupies a broad shallow valley impounded by silica sinters deposited from the numerous boiling springs that surround the lake (Fig. 1). In historical times, outflows from the lake and surrounding springs have been altered by human intervention on many occasions, and the neighbouring springs have ceased boiling for several years at a time. Historic changes, summarised by Gordon et al. (2001), show a complex series of changes with time. Since early 2001, many features have ceased boiling and flowing, including the western lakeside springs (S377 area). By late May 2001 the Hirere Bath (Down Bath) could only be filled once a day instead of being constantly replenished with hot water, and in November 2001 the water supply abruptly stopped. By June 2001, the water levels in many pools around the northern and western margins of Roto-a-Tamaheke had fallen to 1.2–2 m below overflow and had cooled, with no outflow at the eastern outlet and no boiling around the entire lake. There are no signs of recovery to date (August 2004). Changes of this scale are unprecedented since 1981 and are similar to the widespread collapse of boiling and flowing in 1938–1944 (Modriniak, 1944). The cause of this cessation of hot spring activity is as yet unknown, but it is contrary to the general field-wide trend of improved spring flows and rising water levels.

During recent decades, several episodes of sporadic and brief geysering have occurred from other known geysers. For example, at the eastern end of Roto-a-Tamaheke, spring S435 geysered many times daily (3–5 m high) in March–April 1983, but its vent has been physically damaged by human intervention and it has not geysered since. Eruptions of Okianga Geyser (about 300 m east of Geyser Flat, near Roto-a-Tamaheke) started in 1960, and in 1969 they occurred every 12 min, up to 5 m high; by 1972 eruptions had, however, ceased (Lloyd, 1975). In the early 1980s it rarely erupted, except during periods of low atmospheric pressure. Throughout most of the late 1980s to the late 1990s it played up to 4 m high every 35–60 min (Luketina, 1996; Cody, 1998b). By 1999, the ground surrounding it had opened several small fissures, which have developed as new boiling flowing vents. Geysering activity has now ceased. Waikite Geyser vent is atop a prominent sinter mound (Fig. 11), having been the highest discharging feature in the area (315 m above sea level). Historic eruptions have always been erratic and it last erupted in 1967 (Fig. 12). This vent filled to within 3.2–3.5 m of overflow with clear, constantly boiling water several times in the 1990s but each time the water has contained less than 5 ppm chloride and very high sulfate, indicating that it is only steam- and gas-heated meteoric water, not deep geothermal water. Pareia Geyser is located on the southeast end of Waikite mound (Fig. 11), and historically it erupted in conjunction with Waikite geyser. Pareia erupted during February–May 1981, then remained dry until several eruptions were observed on 27–29 December 1987. It then became dry again until August 1997, when it resumed erratic eruptive activity and remained active until December 2001. When active it typically erupts 2–4 m high for about 1 min every hour, totalling <3% of a day in eruption.

8. Summary of surface activity changes

Observations of surface thermal features have shown that activity is extremely variable across Rotorua. Since the bore closures, there has been considerable reactivation of springs in some areas of the field, in particular in the northern part around Kuirau Park–Ohinemutu, but dormancy of springs and features in other parts of the field (e.g. Roto-a-Tamaheke) has continued.

Within the Whakarewarewa Thermal Area, in the southern part of the field, there is wide variance in the changes observed since the bore closures. Some of the geysers are erupting more, while others have ceased activity. There has clearly been a decline to the east around the Roto-a-Tamaheke area since early 2001. Gordon et al. (2001) record a decrease in the flow of the Puarenga Stream between Memorial Bridge (Fig. 11) and the Forest Research Institute (FRI). If this fluid is draining down into the shallow geothermal aquifer, it could account for the collapse of the surface activity near Roto-a-Tamaheke.

9. Earthquake activity

Shallow seismicity for the 1987–1995 period in the Taupo Volcanic Zone (TVZ) was reviewed by Bryan et al. (1999), who demonstrated that most earthquakes were distributed in a narrow band through the central and eastern parts of the Taupo Volcanic Zone. Within this distribution they observed several well-defined clusters, one of which lay beneath Rotorua, while a smaller one occurred in the Okataina Volcanic Centre 20 km east, and larger ones in the Waiotapu–Waimangu area 20 km southeast and in the Taupo Fault Belt.

The New Zealand Earthquake Catalogue was searched for earthquakes within 10 km of Rotorua and shallower than 12 km. The spatial distribution of these events (Fig. 13) shows a prominent cluster under the Rotorua geothermal field, especially the northern part. Focal depths range from 1 to 12 km, with most in the 2–6 km range. Bryan et al. (1999) observed that the Rotorua and Waimangu–Waiotapu geothermal fields are characterised by a concentration of swarm seismicity and a density of earthquakes greater than in the surrounding areas. To determine whether there is any relationship between the changes in thermal activity and seismicity, the water levels of two monitor bores and the magnitude of earthquakes under the Rotorua geothermal system given in the catalogue were plotted (Fig. 14). The earthquake catalogue is, however, only reasonably complete after the early 1990s when a volcano–seismic network was established about the Rotorua–Okataina volcanic centres (Scott and Sherburn, 1994; Scott et al., 1995). For the more complete data set relative to post-1992, two observations can be made: seismic activity is near-continuous under the Rotorua field; however, when swarms occur there is a decline in the number of events immediately following a swarm. This suggests that over a long period of time there is relatively uniform stress release in this area.

Unfortunately, the earthquake catalogue is not complete enough through the 1980s to draw any definite conclusions on changes during or following the bore closures. It appears, however, that the number of recorded events is also regular for the 1980–1992 period and it is concluded that there has been little change in seismic activity associated with the bore closures.

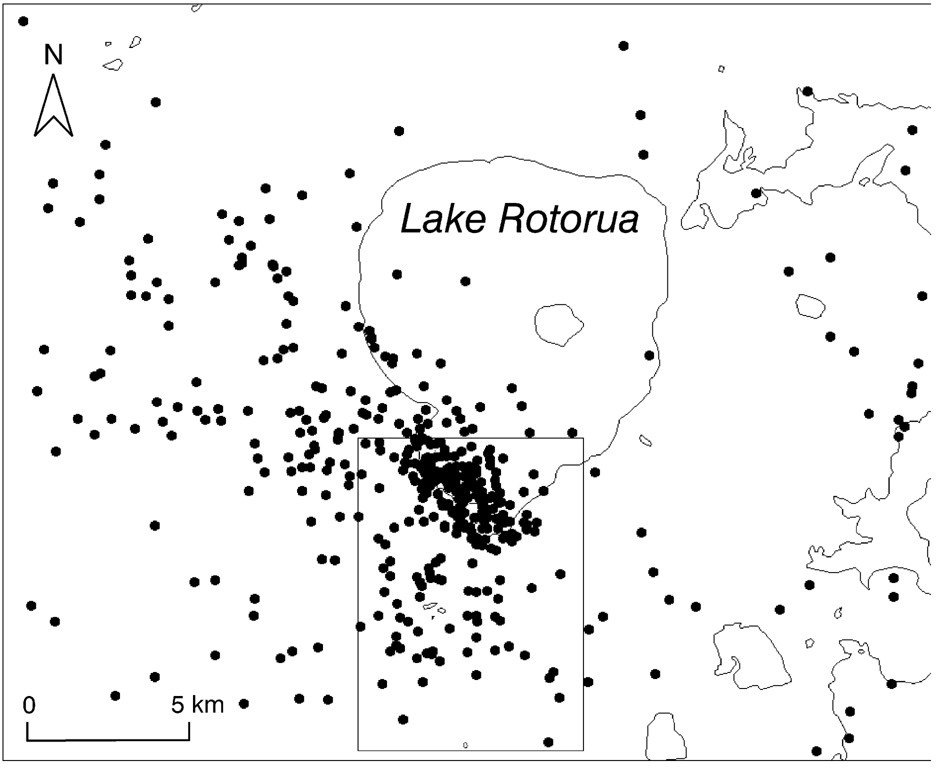

Fig. 13. Epicentres of shallow (<12 km) earthquakes detected near Rotorua (1980–2003). Note that the events are primarily distributed under the northern part of the geothermal field.

10. Social impacts of geothermal activity

Rotorua City has always lived with the consequences of being built over a geothermal system. Engineering solutions have been developed to accommodate the gas flux and elevated heat flow, and higher maintenance for properties within the geothermal area is accepted. Durand and Scott (2003) examined some aspects of soil gas emission and indoor pollution, indicating that engineering solutions have only a finite life.

Since the closures of wells and the imposition of royalties in 1987, a significant reduction in well draw-off has been accomplished, and, as anticipated and desired, the geothermal aquifer water levels and pressures have risen (Cody and Lumb, 1992; Scott and Cody, 2000; Gordon et al., 2001). Coincident with this recovery there have also been several incidences of property damage and adverse effects upon buildings and other infrastructures, such as roads and underground services. These effects appear to be of a nature and frequency that are not typical of the historical natural fluctuations of geothermal activity. Investigations of some of the more significantly damaged properties have shown that these buildings had been constructed near, or even over, geothermal features that had failed as a consequence of the earlier drawdown. Land had been filled or re-landscaped as a result of a loss of knowledge

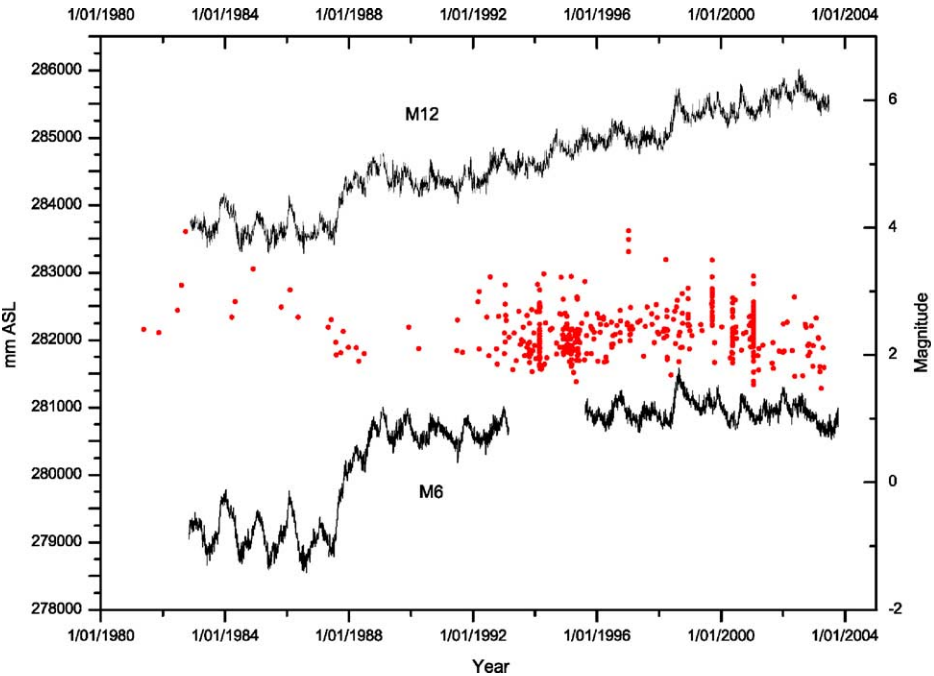

Fig. 14. Time series plot showing the water level in two monitor wells (lines) and the distribution of earthquakes (solid dots) in Fig. 13 by time and magnitude. Note that the apparent increase in numbers of earthquakes after 1992 is due to an increase in the ability to detect earthquakes as a result of emplacement of a local seismograph network.

about the former features. With recovery of this geothermal aquifer as a consequence of bore closures and other management policies, fluids have re-established paths to the surface, often beneath or amongst residential housing. This is most apparent in the north-western part of the field. This situation, which has posed some unusual dilemmas and resulted in evacuation (and in some cases permanent abandonment) of houses due to the resurgence in activity, is unprecedented in Rotorua and, possibly, in the world. The Earthquake Commission (EQC) has paid out compensation for the total loss of some houses, and potential damage to others, and negotiations continue between EQC, insurers and the local council for other affected properties.

11. Discussion

One of the fundamental tenets of the bore closure programme in the late 1980s was that it would both prevent the decline in natural geothermal activity and return it to some state with natural output at a higher level, as pressures in the aquifers increased. Subsequent monitoring recorded a rapid response of the aquifer pressure over approximately 2 years following the closure. The response of the natural features was much more equivocal, and slower. The response of features such as geysers and hot pools is difficult to assess on an individual basis. There are certainly some areas that have shown considerable increase in geothermal fluid output, almost (in the case of Kuirau Park) to the point of alarm. For other areas the responses have been more varied. Gordon et al. (2001) reviewed heat flow surveys at Whakarewarewa, but found that discrepancies and incompleteness of the data sets made interpretation difficult; nevertheless, a trend of increasing outflow was apparent.

In the northern, and especially north-western, part of the field there has been consistent recovery of surface features. Sinter-lined basins that were dry in the early 1980s are now discharging fluids that are chemically similar to those observed in the 1960s (Mroczek et al., 2002), indicating recovery to near pre-closure status. In the northeast there have been increases in heat flow and discharge (Gordon et al., 2001), but the chemistry suggests a decline in the proportion of deep fluid in these discharges (Mroczek et al., 2002); this apparent contradiction is not understood.

Using qualitative data from the 1890s and instrumental recordings from the 1950s onwards, records of geyser activity have been compiled that present a clear trend of declines in outflows and failing geysers during the 1950–1980s (Fig. 12). Soon after the bore closures in 1986 there has been recovery of spring flow and geyser eruption activity in many of these features. Not all the features that have recovered did so immediately after the closures: it was not until 1995 that Parekohoru recommenced boiling surges and overflowing; in August 1997 Pareia Geyser resumed frequent geyser eruptions; and in January 2000 Te Horu Geyser resumed hot overflows (Scott and Cody, 2000).

At Whakarewarewa there has been a wide range of changes, with no apparent consistency with respect to geographic location or style of feature. Features such as Parekohoru, Pohutu, Okianga, and Ngararatuatara show signs, including chemical signatures (Mroczek et al., 2003b), indicating that increased amounts of deeper fluids are reaching the surface. Whereas features such as Kereru, Korotiotio, Prince of Wales Feathers, Te Horu and Puapua appear to have undergone no chemical changes, their surface activity has changed. All of the large failed geyser features (Papakura, Wairoa, Waikite and Ororea) show no signs of recovery, with acid chloride waters continuing to dominate the vents.

The surface discharges, heat flow and chemical parameters for the southern part of the field all show some signs of recovery, but also highlight areas of little or no recovery. Since early 2001 there has, however, been a significant decline of features in the eastern (Roto-a-Tamaheke) area. This decline has not been investigated in detail, but the large loss of water from the Puarenga Stream in this area could be a contributor if the lost water is draining down into the shallow geothermal system.

The recovery of features in Rotorua has had an impact on the society. As springs declined and failed to flow they were encroached upon, and land around them was utilised. With time, knowledge of the features was lost. In some places, the encroachment has included reclamation of land and subsequent erection of buildings on it. As water levels have recovered in the geothermal aquifer, discharge to the surface has also recommenced. In all cases of significant outflows or hydrothermal explosions, they have occurred from historically existing vents. There have been only minor exceptions, where increases in heat flow at Kuirau Park have resulted in new locations. In the worst cases, properties have been evacuated, while others have had the houses relocated to non-geothermal properties. In terms of the total number of dwellings in Rotorua (approximately 35,000), less than 20 have been affected by the recovery of surface features. Although the impact is high, the percentage of the city affected is very low. Fortunately, significant portions of the geothermal area are undeveloped, thus minimizing the overall impact.

12. Conclusions

1. Shallow water levels have risen and pressures have increased, initially rapidly then more slowly, since implementation of bore closures in Rotorua geothermal field in 1986.
2. Most natural geothermal surface features in the field have shown some recovery since the bore closures.
3. The pattern of recovery of features is very variable, even within a relatively small area, with no apparent consistency as to location or type of feature. This variability is difficult to explain.
4. A few features have shown no sign of recovery or initially showed recovery but later ceased activity. Such behaviour is not fully understood.
5. Examination of seismic records suggests that the recovery or its variability is not related to changes in local seismic activity.
6. In some places, discharges to the surface have recommenced, causing damage to buildings and associated services, such cases are, however, largely confined to the vicinity of pre-existing vents, especially vents that had been in-filled.

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