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CHANGES IN THERMAL ACTIVITY IN THE ROTORUA GEOTHERMAL FIELD

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Abstract—During a period when geothermal fluid was being withdrawn for energy use at an increasing rate, the level of natural hydrothermal activity in the Rotorua geothermal field declined to an all-time low in the mid 1980s.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

INTRODUCTION

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

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 Reference to unpublished papers has been avoided as much as possible, but, if proper credit is to be accorded to the original observers, such reference must be made in some cases.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

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

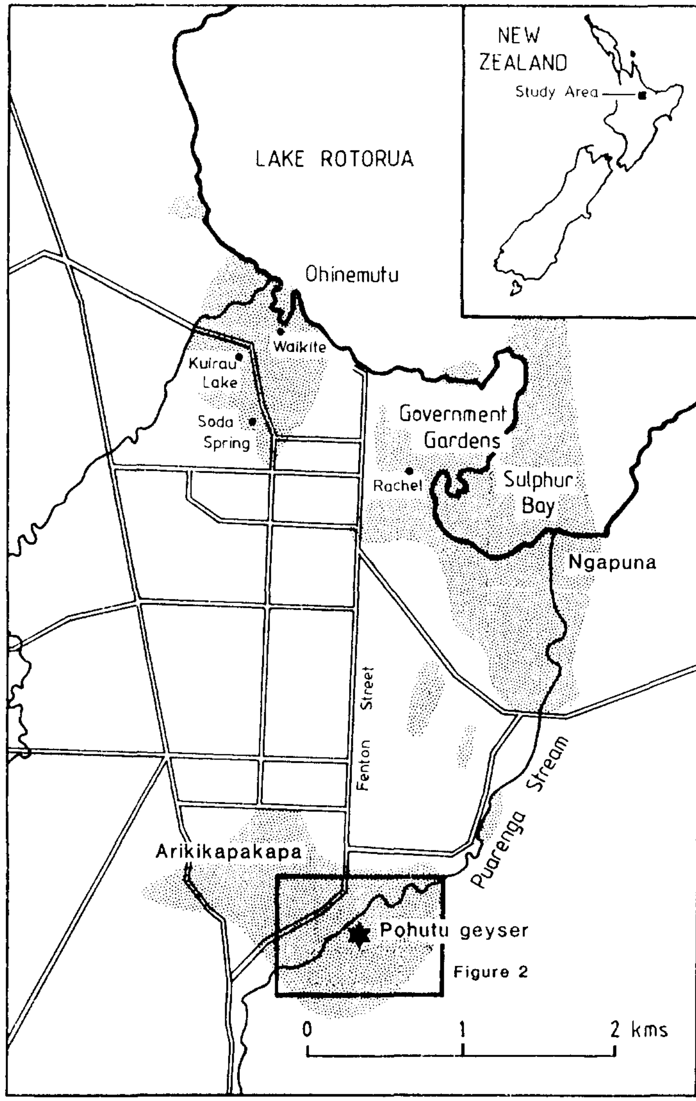

Fig. 1. Map of Rotorua City showing the location of the principal areas of hydrothermal activity and locations named in the text. The inset shows the location of Rotorua in the North Island, New Zealand and the area covered by Fig. 2 is shown.

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

The natural thermal activity is very important for the local tourist industry, providing both spectacular visual amenities and a source of heat for the very popular spa pools, offered as an attraction by many motels and hotels in the city. The "energy" use of the geothermal activity was just part of a growing application of the resource by the local populace to a variety of industrial and domestic uses, and since the late 1970s concern has been widely expressed that drawoff of thermal water was affecting the natural thermal features. Any substantial change in the natural activity would be of great significance to the tourist industry. When the Government decided in 1986 to close all of the bores within 1500 m of Pohutu, the best known and today the most spectacular geyser at Whakarewarewa, the reason given for this action was the protection of the natural activity from the changes that were occurring and were perceived to be placing in jeopardy the very existence of several great tourist attractions.

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

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

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

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

THE "NATURAL" STATE OF THE SURFACE MANIFESTATIONS AT ROTORUA

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

A natural event which had a significant and lasting effect on the surface activity at Rotorua, was the eruption of Mt Tarawera, some 25 km distant, on 10 June 1886. Many contemporary accounts, including newspaper reports, refer to increased thermal activity in Rotorua immediately after the eruption. While many of these reports may have been made by untrained observers, those referring to some of the natural features are so consistent and persuasive that they leave little doubt that several features were affected, and that new features formed at this time. Among the new features, one of particular interest is the Prince of Wales Feathers, a geyser at Whakarewarewa. This geyser, called, by Malfroy (1891), "The Indicator" because its playing generally indicated an imminent eruption of Pohutu, has no Maori name, suggesting that it did not exist before Europeans lived in the area. It was not included in a detailed map of Whakarewarewa based on fieldwork completed by the surveyor E.C. Goldsmith in April 1885, but the fieldbook of a geologist, A.P.W. Thomas, now held by the University of Auckland, records a visit on 18 July 1886 when a "new hole", close to Pohutu, was playing. The 23 June 1886 issue of the New Zealand Herald describes an artist as having "taken a series of views ... of the new geyser at Whakarewarewa."

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

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

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

CHANGES IN THE NATURAL ACTIVITY DURING EXPLOITATION UNTIL 1986

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

The winter drawoff in 1985 was almost double the natural flow from Whakareawrewa of approximately 17 000 tonnes per day (Ministry of Energy, 1985). Based on measurements of chloride flux out of Lake Rotorua (Glover, 1992), and Glover's assumption that some 27 000 tonnes per day of "shallow soakage" from soak bores discharges through the lake bed, it can be concluded that the total natural outflow from the entire Rotorua field may be at large as 78 000 tonnes per day. Part of this discharge may be derived from a separate geothermal upflow indicated by high conductive heat flow through the lake floor between Mokoia Island and Rotokawa (Whiteford, 1992). Thus the winter drawoff from Rotorua bores represented a significant fraction of the natural mass flow from the Rotorua field. Although the pressure decline in the geothermal aquifer at Rotorua (0.5 - 0.7 bar) is small compared to that in other exploited fields in New Zealand with larger drawoffs (Bradford, 1992a) it is difficult to avoid the conclusion that bore drawoff has affected the natural surface features at Rotorua. Major effects of exploitation on hot spring discharge are documented for the Wairakei geothermal field (Glover, 1963 and 1965; Allis, 1981).

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

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

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

Whakarewarewa

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

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

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

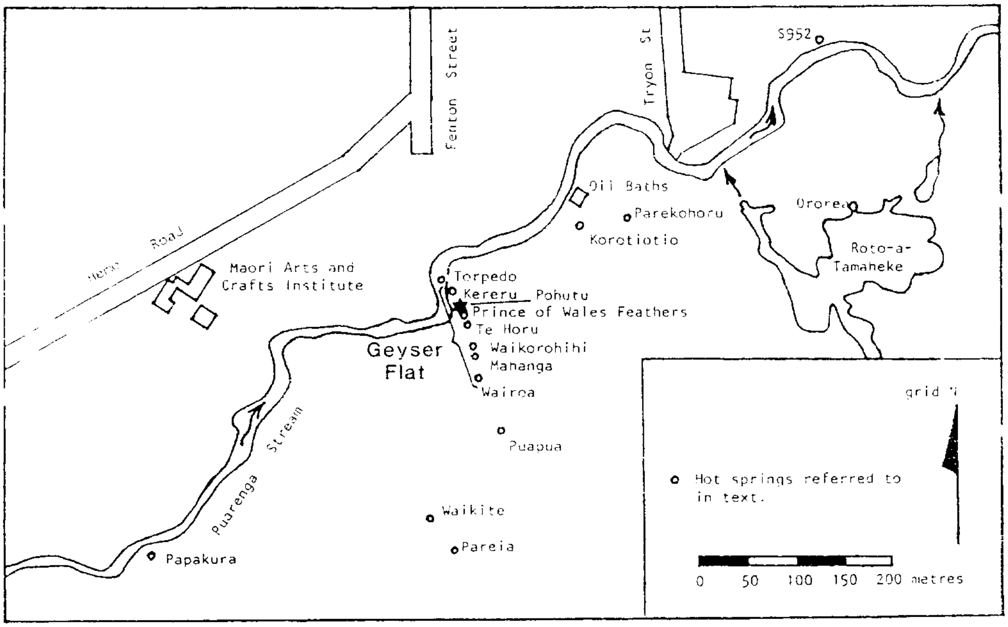

Fig. 2. Location of springs and geysers in the Whakarewarewa area.

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

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

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

Whakarewarewa is drained by the cold Puarenga Stream which typically flows at about 1.2 m^3/s and is heated as it passes the thermal area from about 12°C to 20°C, predominantly by outflows of water from the surface features and a few springs and seepages in the stream bed. Heat and chloride flow into this stream along with chloride/sulphate ratio were monitored from late 1982, in the hope that any changes observed would reflect changes in overall thermal flow from all of the surface features of Whakarewarewa. Unfortunately, up to the time that bore closures began in 1986, no unequivocal trend in any of these parameters was seen. In 1985 there had been an unexpected increase in chloride flow, but this was later shown to be related to discharge from spring S952 (Fig. 2) which formed abruptly following a hydrothermal explosion after a nearby well casing had fractured (Glover, 1989).

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

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

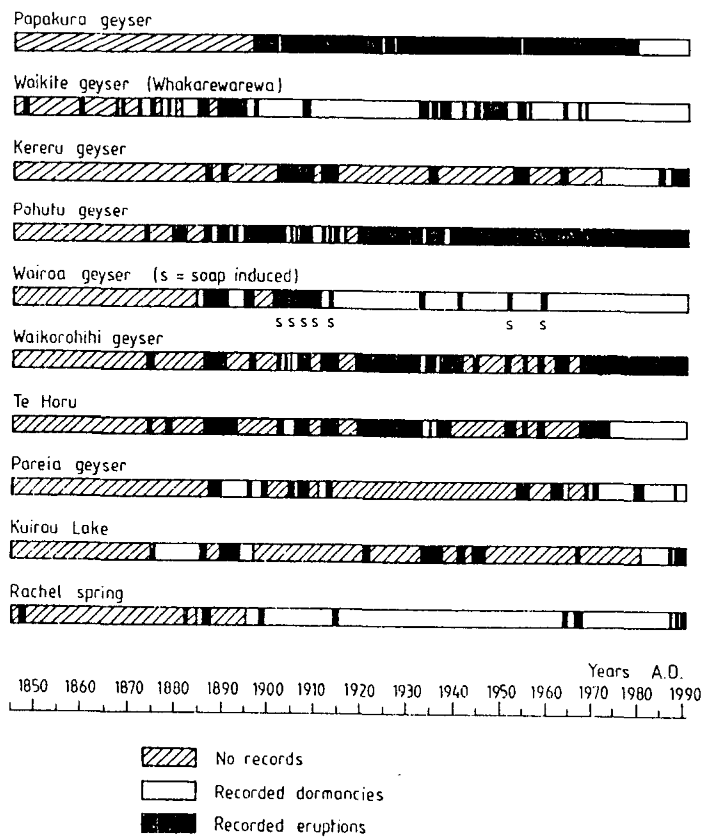

Fig. 3. Time logs of the activity of some major geysers and hot springs in Rotorua. For Kuirau lake and Rachel spring active episodes are those with boiling and surface overflow, whereas all other features are eruption geysers.

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

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

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

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

(Bradford *et al.*, 1987).

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

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

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

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

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

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

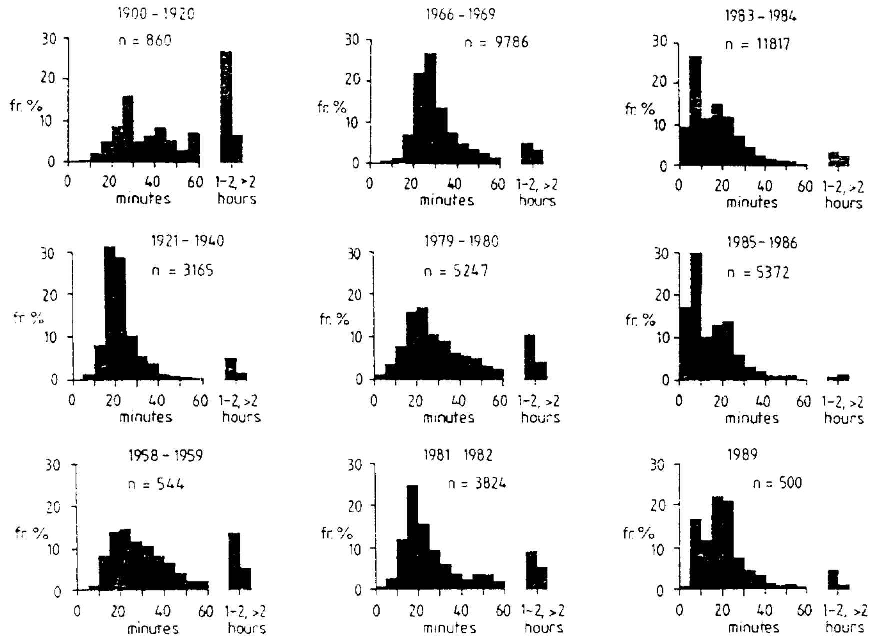

Fig. 4. Histograms of Pohutu geyser eruption durations showing the percentage of eruptions whose duration fell within the time limits shown on the x-axis. Groupings are five-minute intervals up to one hour, then 1-2 hours and more than 2 hours. Each histogram is for the range of years shown, and the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

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

Roto-a-Tamaheke is the largest thermal feature in the Rotorua geothermal field. Although the outflow from this lakelet varies greatly because of artificial drawoff to a nearby bath-house, its heatflow was estimated, in 1984, by Cody and Simpson (1985) to be approximately 33 MW, compared with 60 MW in the 1967/69 survey. This fall in heatflow is attributable to both a drop in temperature (from 64 to 49°C) and a reduction in flow (from 15 to 2 l/s at one of the outlets). Taking the 1967/69 and 1984 heatflow figures at their face value (perhaps questionable, because of the great fluctuation in the outflow from the lakelet), suggests that the fall in heat flow from Roto-a-Tamaheke alone may account for some 60 percent of the total decline from the whole of Whakarewarewa. This change appears to be disproportionately large, as the feature provides only about 40 percent of the total heatflow from Whakarewarewa, according to Cody and Simpson (1985).

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

Features outside the Whakarewarewa area

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

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

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

Since the mid-1940s, Rachel Spring has been the only remaining alkaline spring in the Government Gardens. In a report from 1847 (Johnson, 1847) it is described as erupting in a roaring jet 1-2 m high, and occasionally to 5 m. For many years water has been pumped from this spring to supplement thermal bore water that supplies the nearby public baths, the "Polynesian Pools". Rachel spring has a circular vent, some 10 m in diameter, and in prehistoric time overflowed to establish an extensive surrounding apron of sinter. Most of this sinter has long since been destroyed, following modifications to the spring outlet designed to increase and divert its flow to provide a supply to the baths in the 1880s. During periods when the spring was not pumped, its water level varied between about 600 and 1300 mm below the former outlet, but both water-level and temperature would rise during pumping. Although during the present century the spring has typically been calm, below overflow and below boiling temperature, it has occasionally erupted explosively with strong overflows; the most recent events, prior to the bore closures, were in 1964 and 1966-67. Up to the time of the compulsory bore closures the spring was described by Bradford *et al.* (1987) as having shown neither seasonal nor progressive changes that might be associated with a gradually increasing bore drawoff in the city. However, its flow may have been affected by 12 bores within about 100 metres of the spring, drilled before 1964. It is by no means in its natural state and, even in 1991, continues to be pumped several days a week to supply the baths.

CHANGES FOLLOWING THE BORE CLOSURES

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

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

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

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

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

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

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

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

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

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

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

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

For many decades, Kuirau Lake had an erratic, weak discharge of acidic water, but by 1988 this state had changed to one of strong (45-60 l/s), alkaline (pH 7.0-8.1) outflow which has remained throughout 1991. Its present outflow is higher than observed at any time since the 1940s. The nearby Soda Spring abruptly resumed hot (70°C) alkaline discharge in January 1989, the first natural flow from this feature for about 30 years.

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

CONCLUSIONS

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

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

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

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

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

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