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The Rotorua Geothermal Field: An experiment in environmental management

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ABSTRACT

The Rotorua Geothermal Field (RGF) is a unique example of a geothermal system that has been managed intensively to both obtain energy in a sustainable manner and to preserve the surface features and their intrinsic value. The field underwent an extensive bore closure programme in the 1980s. Exploitation today is characterised by a reduced number of shallow bores (140 consented bores and an additional 42 with down hole heat exchanges) with limits set on use by a management plan designed and monitored by the Bay of Plenty Regional Council. The RGF has a wide range of uses, values and differing significance to the Rotorua community, including cultural values, economic benefits, energy source and a tourism driver.

A collection of research and monitoring activities are presented in this paper. We summarise the current management regime, surface feature trends and results of chemical research, repeated heat flow surveys at Whakarewarewa and representative temperature-contour maps of the geothermal resource. These data and results show that the composition of the primary deep fluids have changed little over time, while marked physical changes have occurred at surface features; a mix of positive recovery signs, along with many complex exceptions to those trends are seen. The use of modern numerical modelling methodology, using bore temperature records, geology and chemical data allow for improved modelling of the system.

1. Introduction

The Rotorua Geothermal Field (RGF), New Zealand, is a unique example of a geothermal system that has been extensively exploited at shallow depth (30–200 m) under varying management regimes. Over-exploitation resulting in the decline of many and the failure of some active surface features was recognised in the 1970s and then subsequently addressed by a change of management policy (Allis and Lumb, 1992). A bore closure programme was instigated by the New Zealand government after consultation with a scientific task force (Rotorua Geothermal Monitoring Programme) as a part of a new management regime. The RGF lies within the Rotorua caldera and the Taupo Volcanic Zone (Fig. 1) juxtaposed within a modern city and hosting surface geothermal manifestations that range from geysers and hot springs to mud pools and pots and warm ground (Fig. 2). This paper summarises new research, modelling and monitoring work conducted in the last few years, post the bore closures.

In the 1960s and 1970s, withdrawal of fluid from Rotorua bores increased about twofold. As a result, the level of natural hydrothermal activity at Rotorua declined, reaching critical low levels by the mid-1980s (Lloyd, 1979; Cody and Lumb, 1992). The realisation and reluctant acceptance in the early 1980s that Rotorua's surface features were systematically waning due to extraction of geothermal fluids from local bores led to the establishment of the Rotorua Geothermal Monitoring Programme (RGMP) in 1982. This ultimately led to the Bore Closure Programme (BCP) of 1987–1988, when production was reduced by ~60%. Soon after, during 1988–1991, RGF pressures increased by about 20 KPa (0.2 bar) and recovery of some surface features was first observed.

The Rotorua Geothermal System was the subject of considerable scientific study between 1980 and 1990. The results of the RGMP were summarised by the Ministry of Energy (1985), while other aspects of the field were covered in a special issue of Geother-

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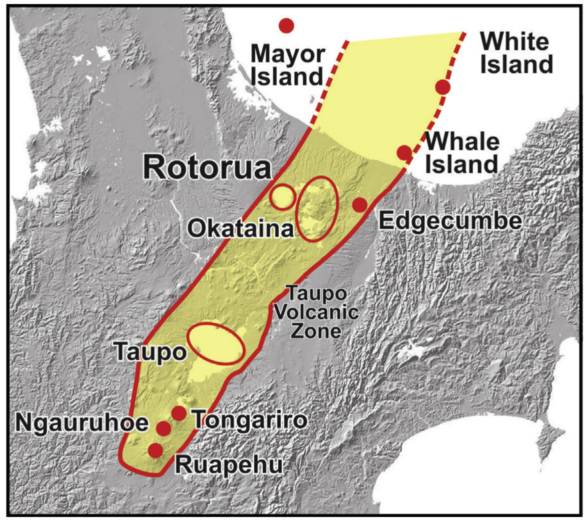

Fig. 1. Sketch map of the Taupo Volcanic Zone showing the location of the Rotorua Caldera and other major volcanoes. Calderas are shown as open circles, while cone volcanoes are shown as red dots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mics (v.21; 1992). The results of monitoring under the Rotorua Geothermal Regional Plan were presented by Grant-Taylor and O'shaughnessy (1992), and Gordon et al. (2001, 2005). Scott and Cody (2000) and Scott et al. (2005) described and discussed aspects of the recovery of surface features. This paper presents a summary of the current management regime, the results of extensive chemical sampling, and models to track reservoir recovery over the longer term since the BCP. Also presented are representative temperature-contour maps of the geothermal resource, the results of repeated heat flow surveys at Whakarewarewa and a summary of current surface feature monitoring. These data and results show a mix of positive recovery signs, along with many complex exceptions to those trends. The reservoir modelling, bore temperature records, and chemical data allow for construction of better and more consistent models of the system.

1.1. Management and legislation framework

New Zealand's geothermal resource management legislation (The Resource Management Act 1991) covers:

1. Allocation of heat and fluid abstraction,
2. Protection of the surface features from people, and
3. Protection of people from geothermal hazards.

Overarching policy and detailed rules are developed and implemented by regional councils. The RGF is managed by the Bay of Plenty Regional Council (BOPRC). Its policy framework regards Rotorua as a system with limited capacity for exploitation, to avoid further damage to the surface features. An exclusion zone (no extraction) was created for the area 1.5 km around the geyser field in the southern portion (Fig. 2), with constraints on net heat and fluid withdrawal on the remainder of the resource — all from shallow bores (<270 m).

In July 1999 the Rotorua Geothermal Regional Plan (RGRP) was approved and became operative, under the jurisdiction of BOPRC, with the purpose to promote the integrated and sustainable management of the Rotorua geothermal resource (Rotorua Geothermal Regional Plan, 1999). Aims of the RGRP include enhancement and allocation of the resource, managing and controlling adverse effects on the field and protecting surface features. The RGF holds widely varying values and significance to different sectors of the Rotorua community. It is continually identified as a major attraction for tourism in Rotorua, valued at $320M per year and contributing 18% of local jobs (Butcher et al., 2000).

A review of the planning provisions began in February 2014. This review will reassess the appropriateness of existing limits on heat and fluid withdrawal. Resource use planning is heavily science informed. It uses inputs from geophysics (e.g. MT, thermal IR and resistivity; Heise et al., 2015; Reeves et al., 2014) hydrology and geochemistry (Mroczek et al., 2005, 2011; Werner and Cardellini, 2006), feature monitoring (Scott and Cody 2000; Scott et al., 2005) and reservoir modelling (Burnell, 2005; Kissling, 2005, 2014; Ratouis et al., 2015) to determine sustainable levels of withdrawal. It also includes capability to respond and adapt to changes to the resource, as needed.

2. Monitoring

2.1. Chemistry of surface features and water bores

2.1.1. Fluid chemistry

Chemical monitoring of surface features, has provided much information about the hydrology of the RGF, and the chemistry of the hot mineralised fluids that mix with surface water, to discharge at the surface, and flow into Lake Rotorua (Figs. 2 and 3). Fluid flow within the RGF is largely constrained by geological structures like rhyolite surface morphology, and by the properties of the subsurface formations (their natural porosity and permeability) and the thermal fluids (Wood, 1992).

Fig. 3 shows a schematic representation of fluid flow paths in the RGF, which incorporate the fluid flows proposed by Giggenbach and Glover (1992), Stewart et al. (1992) and Graham (1992). This figure illustrates the two natural spring outflow areas of the field; (i) Ngapuna–Government Gardens and Whakarewarewa in the east and south respectively, and (ii) Kuirau Park–Ohinemutu in the north; and shows how these natural spring outflow areas are most likely to be connected and supplied by thermal fluids from depth. Fluid rises in the eastern part of the field, which then discharges to surface features at Whakarewarewa and Ngapuna. Lateral flow to the west also takes place where shallow mixing of the fluids can occur prior to discharge. The input of deep thermal fluids and shallow mixing adds additional complexity to the outflow model for the Kuirau Park and Ohinemutu areas.

A significant chemical characteristic of the RGF fluids is the decrease in Cl from Ngapuna (east) to Kuirau Park (west) and higher

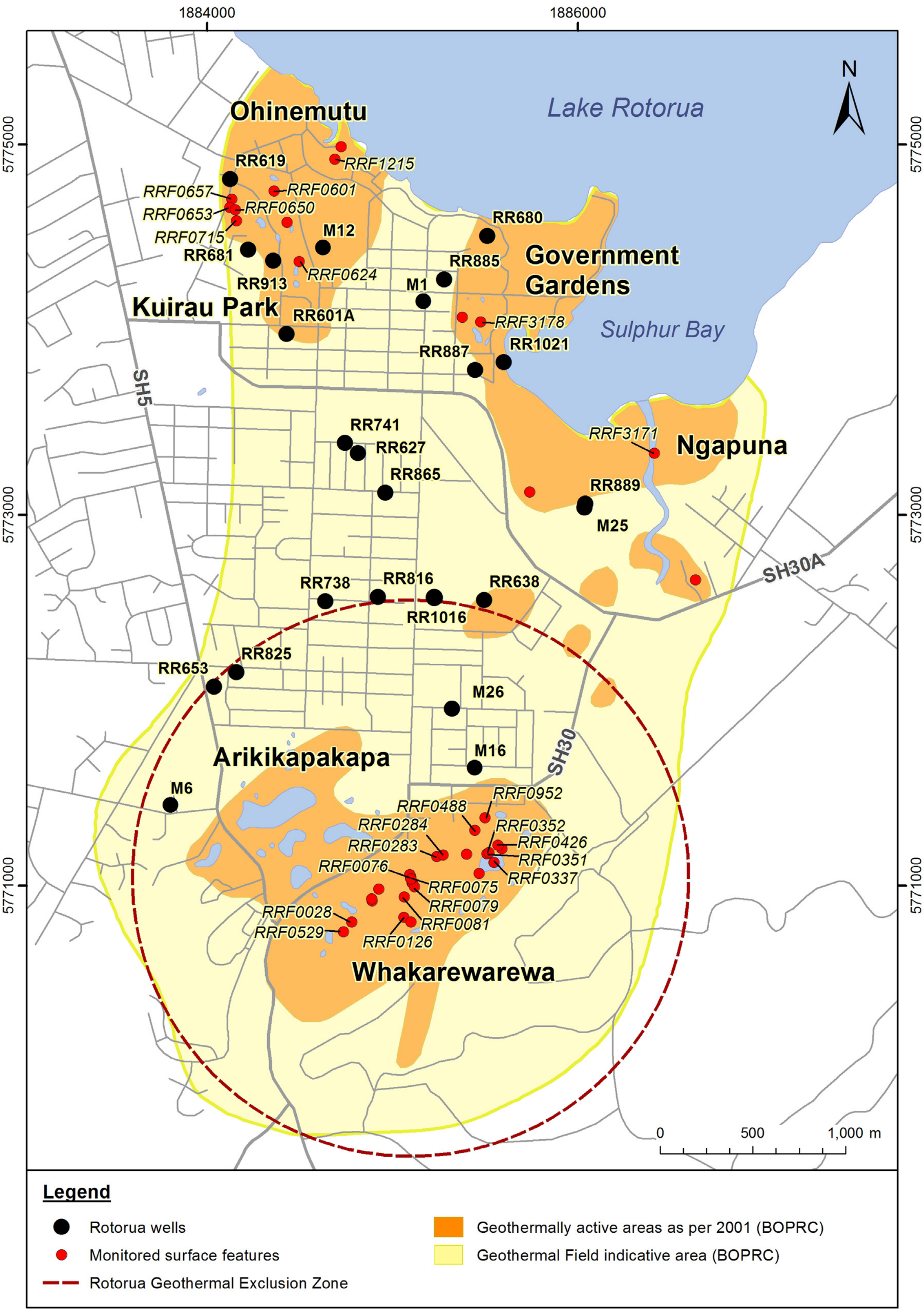

Fig. 2. Sketch map showing extent of Rotorua Geothermal Field, extent of surface features and bore exclusion zone (after Gordon et al., 2001) and locations of bores and springs mentioned in the text.

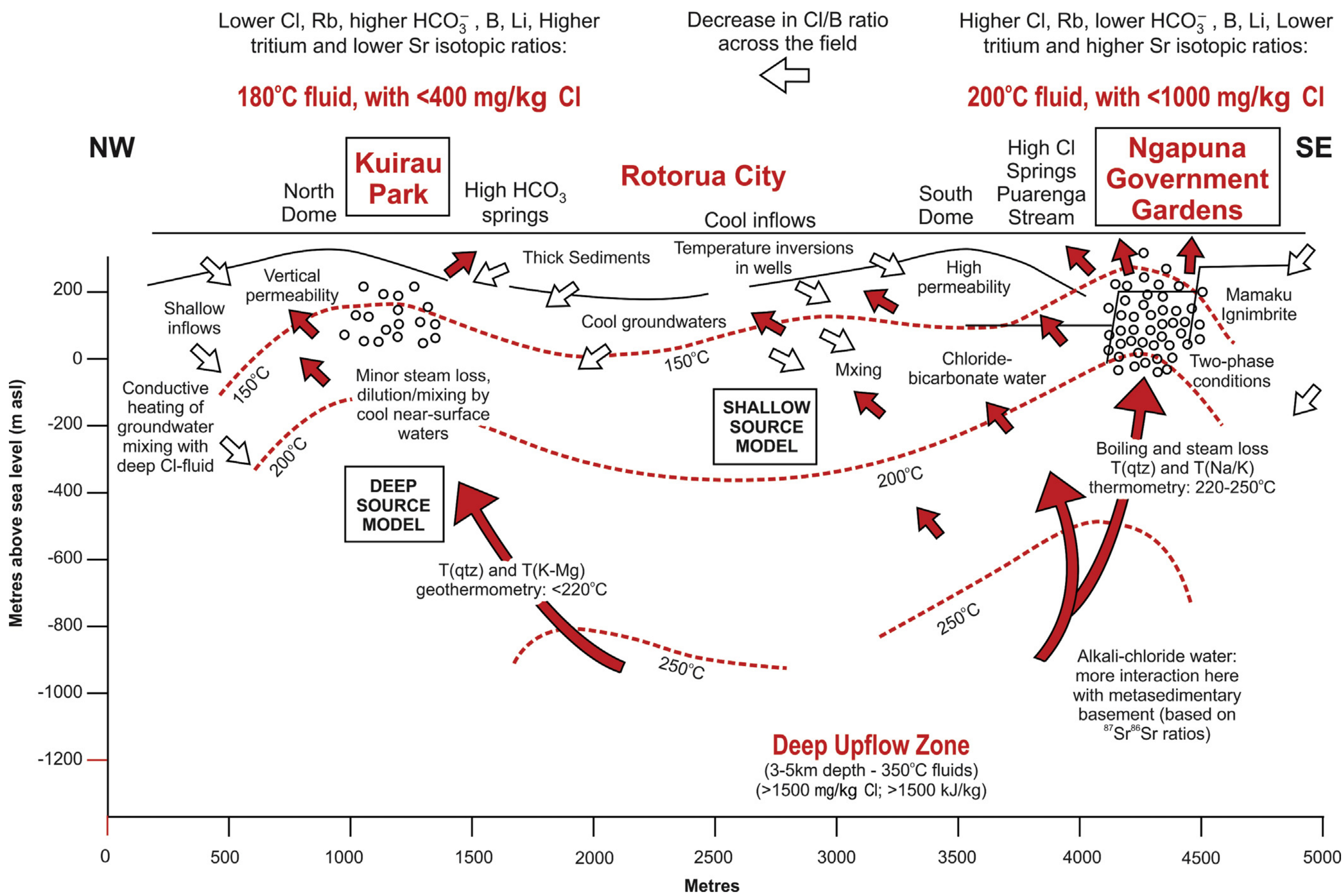

Fig. 3. Inferred hydrology of the Rotorua Geothermal Field.

HCO_3 concentrations between the two, centred broadly on the Government Gardens area and also seen in Kuirau Park (Stewart et al., 1992). The Cl and B are from the deeper sourced primary geothermal fluid while HCO_3 arises from water–rock interaction at shallower depth. Condensation of steam and oxidation of H_2S by groundwater results in elevated SO_4 and acidic fluids at very shallow levels in many parts of the field.

The change in relative concentrations between these anions gives important information on hydrological processes such as the change in proportion of the deep geothermal fluid mixing with shallow acidic high SO_4 surficial fluids.

In the last decade sampling of selected springs and bores was undertaken by GNS Science for BOPRC to support the objectives and policies of the RGRP. The purpose was to compare the results to historical data and provide an overall assessment of the recovery of the field after the bore closure programme. More recent studies have been funded by the GNS Geothermal Research Programme.

2.1.2. Spring composition

Typical alkaline spring compositions are listed in Table 1. These naturally vary within the RGF. In the Ngapuna area the Cl/HCO_3 ratio is <0.05, whereas in the Government Gardens–Ohinemutu–Kuirau Park areas the Cl/HCO_3 ratio is ~1, and in the Whakarewarewa area they are intermediate between 0.1 and 0.5. However any group of springs, within these broad geographic areas can be variably diluted with shallow groundwater and/or steam heated high sulphate rich acid water giving rise to a wide range of mixed compositions.

This can be observed in the compositional relationships presented in Fig. 4(a–c). The data in the plots are for spring samples collected after 2002. The first 4 legend markers are the geographical location in the greater RGF whereas the remaining 5 legend markers are for springs only located in the Whakarewarewa geothermal area.

The B–Cl–SO_4 plot (Fig. 4a) shows the Ngapuna features are highly enriched with respect to chloride. Similarly RRF0952 (THC Blowout) spring is also relatively low in HCO_3. This spring intercepts deep fluid that ultimately discharges at Whakarewarewa after mixing with more HCO_3 rich water and steam heated waters at shallower depths. The HCO_3–Cl–SO_4 plot (Fig. 4b) shows that the Government Gardens and Kuirau Park features are highly enriched in bicarbonate compared to the Ngapuna features, with the Whakarewarewa features lying between the two. The higher bicarbonate reflects the long residence time of the fluids in the west of the field where the CO_2 is converted to HCO_3 by water–rock interaction. The third plot is Mg–Na–K correlation (Fig. 4c). Points falling on the upper full equilibrium line, such as springs RRF0075 (Pohutu Geyser), RRF0283 (Korotiotio), RRF0284 (Parekohoru) and RRF0952 (THC Blowout), suggest fully equilibrated fluids. In contrast points plotting towards the Mg apex, such as the Kuirau Park features, suggest lower temperature partially equilibrated fluids. All the Geyser Flat features, such as RRF0075 fall on the T(Na/K) 250 °C line including other Whakarewarewa springs such as RFF0529 (Ngararatuatara), but many trend to higher Mg indicating greater mixing with shallow fluids and re-equilibration to cooler conditions given by the T(K-Mg) geothermometer.

2.1.3. Bore compositions

Bores reaching fluids from deeper aquifers are less affected by secondary processes than shallow spring waters; however since the deepest bore M25 is only 245 m, the composition and chemistry of only the shallow aquifers is known with any cer-

Table 1
Typical spring composition across the RGF, concentrations in Mg/L.

Location and spring	t/°C	pH	Li	Na	K	Ca	Mg	Rb	Cs	Cl	SO_4	B	SiO_2	Br	F	HCO_3 Total	NH_3 Total	H_2S Total
Whakarewarewa village																		
RFF0284 Parekohoru	97.3	9.26	3.8	466	52	1.6	0.01	0.53	0.51	589	70	5.1	415	0.93	6	146	0.38	17.9
RRF0488 Okianga geyser	93	8.83	3.4	520	33	4.8	0.01	0.35	0.36	688	120	6.5	197	1.4	5.4	79	0.43	17
Whakarewarewa–Te Puia																		
RRF0529 Ngararatuatara	98.4	8.42	2.3	400	50	1.5	0.01	0.5	0.64	527	67	5.6	357	1.7	7.2	146	0.6	3.1
RRF0075 Pohutu	92	9.66	3.6	452	58	1.9	0.05	0.52	0.56	560	96	5.1	444	1.5	6.6	82	<0.10	10.2
Kuirau–Ohinemutu																		
RRF0653	60.4	8.5	3.6	381	35	2	0.2	0.36	0.4	303	73	5.9	247	0.79	9.4	387	<0.10	0.02
RRF1215 Little Waikite	97.3	9.18	2.5	362	15.4	1.2	0.01	0.16	0.24	317	44	5.8	313	0.96	11.7	238	0.23	3.7
Ngapuna–Govt. Gardens																		
RRF 3171 Stopbank	84.7	2.26	1.8	781	71	11.4	1.8	0.61	0.33	1144	574	8.2	271	3.4	1.1	22	4.1	13.7
RRF3178 Rachel	67	8.35	3.4	566	34	3.2	0.07	0.25	0.37	527	120	6.1	269	1.4	3.5	542	0.3	23

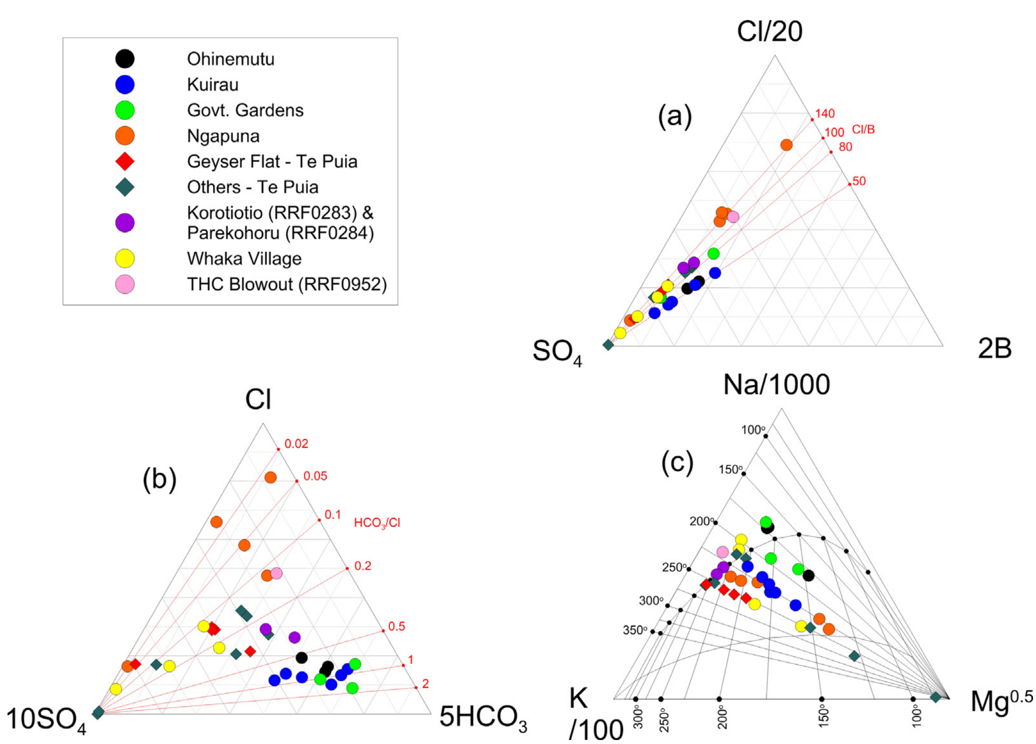

Fig. 4. Relative concentrations (by weight): (a) B–Cl–SO_4, (b) HCO_3–Cl–SO_4, (c) Mg–Na–K, with the T(Na/K) and T(K-Mg) geothermometer temperatures shown on two axes.

tainty. This decreases the confidence in the hydrological model presented in Fig. 3, such as whether there is a separate deep upflow or a shallower outflow, or both, to the east towards Kuirau Park–Ohinemutu. Although bores are not limited to areas of natural discharge, after the bore closure programme, few of the historically sampled bores were available for sampling and none within the 1.5 km exclusion zone.

Fig. 5 shows the chloride-enthalpy diagram for selected bores. The chloride Cl(res) is the reservoir concentration at reservoir enthalpy H which was calculated from the cristobalite temperature T(cris). The most recent data confirms the field wide dilution trends are essentially unchanged since before the bore closure programme. The Cl-δ^{18}O trend in Fig. 6 is for a groundwater isotopic signature which supports dilution as the principle reservoir process, rather than boiling.

On their own the Government Garden bores are variably diluted but all are of a constant enthalpy of ~650 kJ/kg (153 °C) with the cooler and more dilute western bores appearing to extrapolate to a zero-chloride end member with enthalpy 475 kJ/kg (113 °C).

Repeat sampling over the last decade shows minor changes in composition. The western and Government Garden data are trending towards less SO_4 and more HCO_3. This is what would be expected given an increase in reservoir pressure but there has been little change in the fraction of deep reservoir higher chloride fluids. Cl(res) values for Government Garden bores appear to have decreased between 1989 and 2003 by about 100 mg/L, from ~500 mg/L to 400 mg/L. These now appear to be increasing whereas

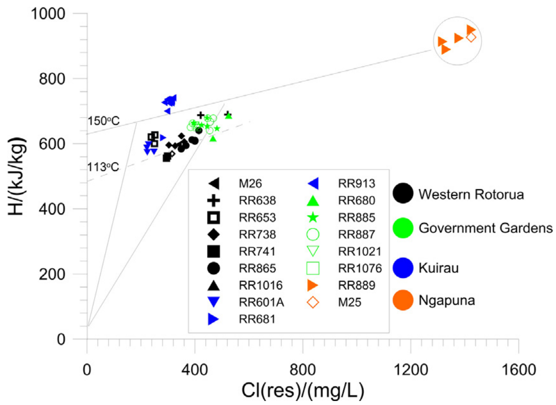

Fig. 5. Chloride-enthalpy diagram for all sampled bores; Cl(res) is at the reservoir concentration at T(cris); M25 & RR889 at T(qtz).

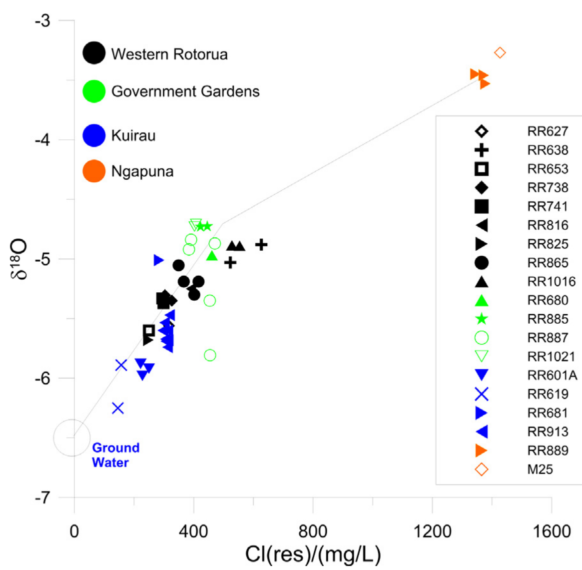

Fig. 6. $\delta^{18}O$ versus Cl(res) for all sampled and proxy bores.

in the western bores, the Cl(res) is still declining except for RR741. These changes are not great. The significance of the changes in the western and Government Garden areas is not known; given the low number of repeat samples it may just be part of the natural variability. At Kuirau Park only one bore (RR913) has been regularly sampled and both Cl(res) and T(cris) are now higher than when first sampled in 1985 and the values have been stable since 2003.

2.1.4. Summary and conclusions from chemistry monitoring

The main conclusions from the chemical and isotopic data sampling programme (Mroczek et al., 2005, 2011) are that:

1) The fluids discharged in the northern area of the field at Kuirau Park matched those discharging in the early 1960s and it is probable that this part of the field is near full recovery.
2) The shallow aquifer feeding the bores showed relatively minor changes in reservoir chloride and small increases in geothermometer temperatures (~16 °C). This indicates stability and that no deleterious processes were affecting the deeper RGF.
3) The shallow aquifer feeding the bores showed relatively minor changes in reservoir chloride and small increases in geothermometer temperatures (~16 °C). This indicates stability and that no deleterious processes were affecting the deeper RGF.
4) With only few exceptions, the compositional changes across the field appeared to be within natural variability.

There is no explanation as to why more of the Whakarewarewa springs, which became acid features prior to the bore closure programme, had not reactivated given the large increase in reservoir pressures although recent changes in discharge composition in three famous extinct geysers (currently not flowing springs) have occurred which may signal that recovery may still be possible.

1) RRF0079 (Wairoa Geyser) is a mixed acid sulphate–chloride feature; in June 2010 Cl increased from 108 mg/L to 438 mg/L, similar to the average concentration observed between 1982 and 1997. However, Cl then slowly declined to 97 mg/L by May 2012, increasing again to 310 mg/L late in 2012 and then dropped away and stabilized at less than 100 mg/L Cl for the past two years.
2) RRF0126 (Waikite Geyser) was historically the highest elevation discharging feature at Whakarewarewa and last erupted in 1968 (Bradford et al., 1987). Steam heated acid sulphate fluids with zero chloride (condensed steam) returned to the vent in 1990. In December 2011 a seep high on the geyser mound started discharging suggesting a rise in the local geothermal water table. A sample from the main vent showed the Cl had increased from near zero to 436 mg/L and SO_4 has decreased from >1200 mg/L to 300 mg/L. However pH was still an acidic 3.4. In the seep Cl was 566 mg/L and SO_4 90 mg/L although a pH was not measured at such a low SO_4 the fluid is likely to have been alkaline. By June 2012 the vent fluids returned to near zero Cl, SO_4 > 2000 mg/L and pH < 2. This subsequent change in composition has not been correlated with any other physical changes in the area.
3) RRF0028 (Papakura geyser), was historically active until March 1979 when boiling and geysering stopped. It then slowly cooled reaching a low of 37 °C in 2002. It became a stagnant feature but the pH never dropped below pH 6. The temperature was stable at ~50 °C 2012–2013 (Fig. 7a) while Cl slowly increased from 440 to over 500 mg/L, more likely due to evaporation rather than an increase in the deep water component. In September–October 2013 the spring started overflowing at 97 °C and the composition during 2014 stabilized to a pH of ~8.5, with Cl varying between 460 and 480 mg/L and SO_4 varying between 70 and 100 mg/L. The composition is now very similar to that between 1990 and 1997 but still more dilute with respect to Cl prior to cessation of overflow in 1979 (chloride ~536 mg/L average). Nevertheless the T(Na/K) geothermometer which reflects deeper reservoir temperatures, at ~259 °C is as high as for any previous sample collected.

2.2. Temperature and water level monitoring

A selection of up to 40 surface features in the three primary areas of surface activity within the RGF (Fig. 2) have been monitored on a monthly basis since 1989, with the exception of the 2003–2008 period when little monitoring was undertaken. Flowing hot springs (~70–100 °C) of near neutral to alkaline pH (~6.7 to >9) with high chloride (~500–1500 ppm) and low sulphate (~10–80 ppm) contents are preferred spring types for monitoring purposes in the RGF. Fluid discharged from these springs is more similar to the deep geothermal fluids found in production bores and is therefore a good indicator of the natural geothermal outflows from the field. Aspects of these data have been reported in Gordon et al. (2001, 2005), Scott and Cody (1997, 2000), and Scott et al. (2005).

In the southern part of the RGF surface geothermal activity occurs at Whakarewarewa (Te Puia-Whakarewarewa Village) and contains numerous geothermal features of all types, with the only presently active geysers in Rotorua. At Whakarewarewa

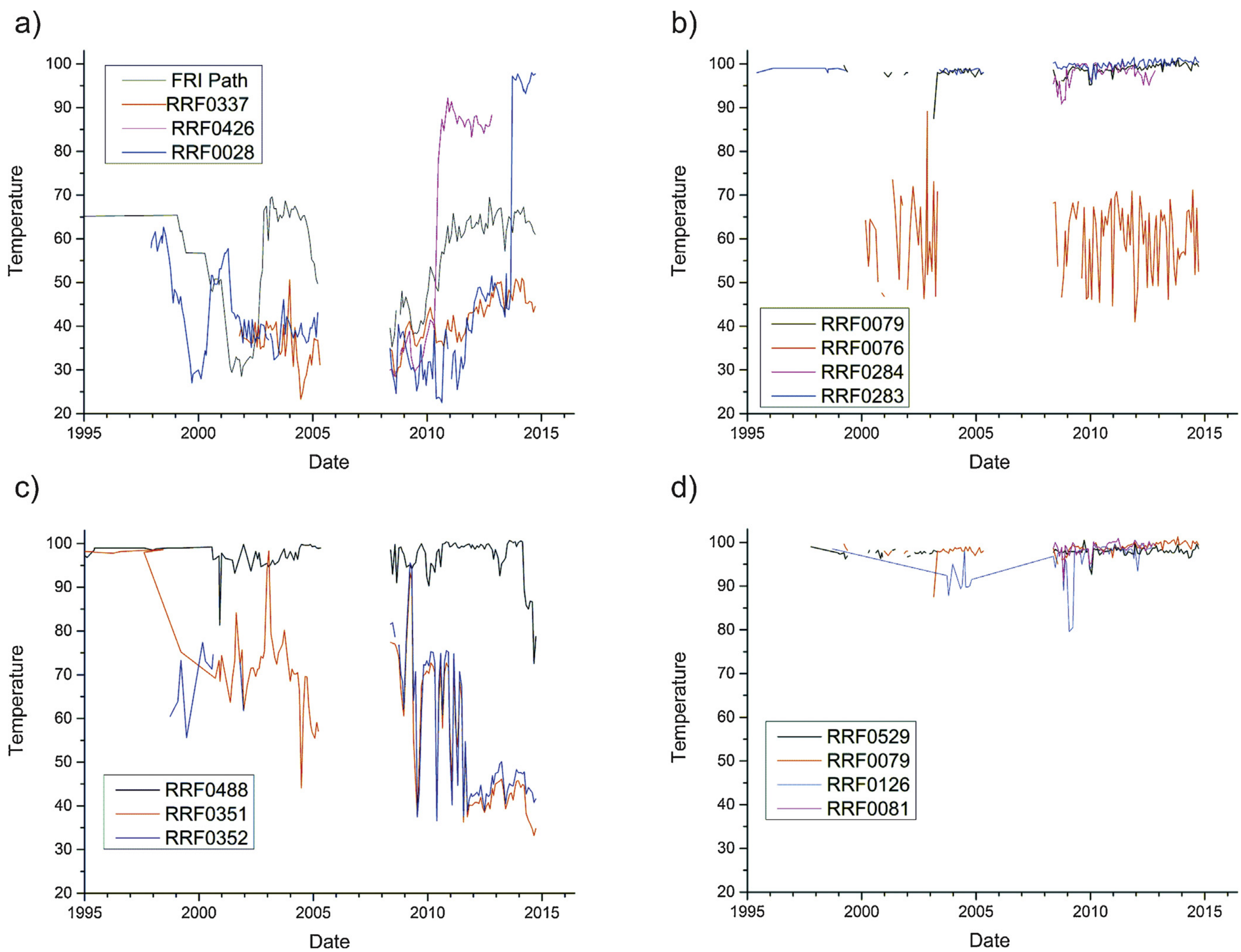

Fig. 7. Plots of the temperature of selected features in the Whakarewarewa Village–Te Puia area (southern RGF); a) features showing recovery, b) features showing a steady state, c) features that have declined, d) features showing steady state but have had water level changes.

the response of surface features to the BCP has been very mixed (Gordon et al., 2001, 2005; Scott and Cody 1997, 2000; Scott et al., 2005). These mixed trends continue today. Presented in Fig. 7 are plots of the temperature of selected features in the Whakarewarewa area (Fig. 2).

Features that have generally shown increasing trends, or have recovered and are sustained are shown in Fig. 7a and b. The two most spectacular are RRF0028 (Papakura Geyser) which started to overflow in September–October 2013 and erupting in September 2015 and spring RRF0426 which has recommenced overflowing with temperatures over 90 °C. Other features to show positive trends are Lake Roto-a-Tamaheke (RRF0337), and the temperature at the FRI Path V-Notch where the accumulated flow of several features is measured (Fig. 7a). Features like RRF0079 (Wairoa Geyser), RRF0284 (Parekohoru), RRF0283 (Korotiotio) and RRF0076 (Te Horu) (Fig. 7b) have all shown recovery but have less of a thermal signal. RRF0076 is impacted by the overflows from RRF0028 when in eruption, hence the variable signals. However features like RRF0488 (Okianga), RRF0351 (Ororea) and RRF0352 have shown marked declines (Fig. 7c). RRF0351 and RRF0352 are adjacent to Lake Roto-a-Tamaheke and have been impacted by the water level rise there and this may explain their declines. Shown in Fig. 7d are high temperature features that show little or no significant change in the Whakarewarewa Valley area e.g. RRF0081 (PuaPua). Two of the dormant geysers RRF0126 (Waikite) and RRF0079 (Wairoa) that have not erupted for decades have shown water level and chemical changes (see Section 2.1.4 above) but have not as yet overflowed. Several springs like RRF0284 (Parekohoru), RRF0283 (Korotiotio) and RRF0529 (Ngararatuatara) have shown little or no change in temperature.

Presented in Fig. 8 are plots of the temperatures of selected features at Kuirau Park in the north of RGF (Fig. 2). The temperature trends of these selected features are variable, some like springs RRF0649/RRF0650, RRF0653 and RRF0624 (Soda Spring) show increases in the 2007–2010 period, however they were as high in early 2000 before declining in the mid 2000s. Other features show declines in the early 2000s like RRF0601 (Kuirau Lake), increase in the mid-late 2000s before declining again. RRF0657 is similar while RRF0715 has declined markedly in temperature but still overflows (Fig. 7b). Cody and Scott (2005) noted an exchange of function (Scott, 1994) between RRF0657 and RRF0601 from 1999 to 2005; however this has not being so apparent in later years. It is weakly apparent in the temperature data from RRF0624 (Soda Spring) and RRF0601 (Kuirau Lake). As discussed above these features are now discharging fluids very similar to pre-exploitation times, but activity is variable. The water level of many features has attained overflow level, but few maintain a regular overflow.

It was noted in Scott and Cody (2000) that episodes of disturbances in the RGF are associated with an increased frequency of hydrothermal eruptions. In the 1970s and 1980s many such erup-

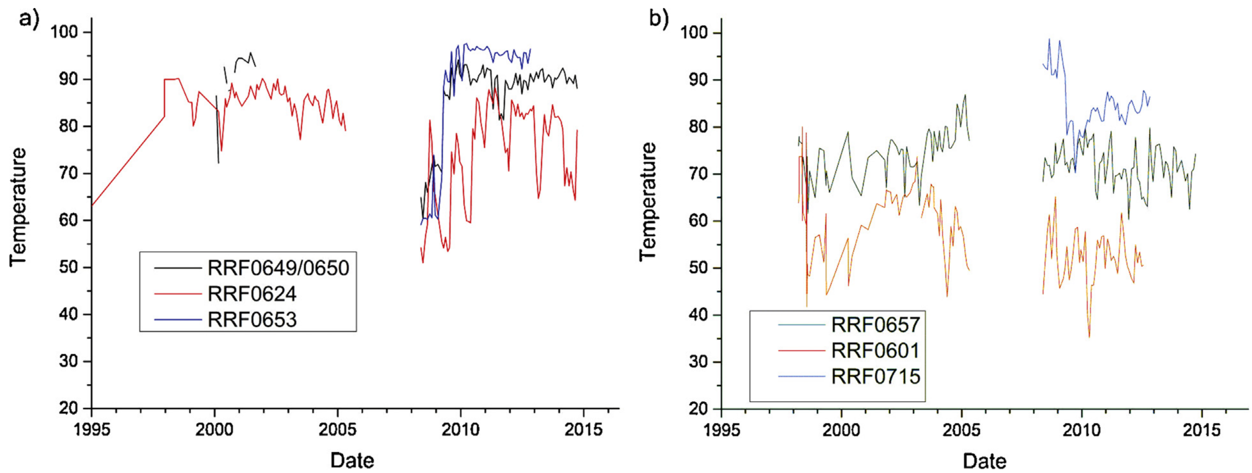

Fig. 8. Plots of the temperature of selected features in the Kuirau Park and Tarewa area (northern RGF).

tions occurred throughout the RGF, with the frequency appearing to diminish in the early 1990s. They noted a pattern where low RGF pressures correlate with more numerous hydrothermal eruptions. The activity has lessened as RGF pressures have risen. This change in the frequency of hydrothermal eruptions continued through late 1990's with the last significant events in 2000 and 2001 in Kuirau Park. In summary, the frequency of hydrothermal eruptions during the 1970–1980s was far greater than in the 1950–1960s or 1990–2000s and it is possible the accumulated drawdown in thermal water levels across the RGF of the 1970s-80s may have created widespread areas of boiling conditions and steam flows, favouring the triggering of hydrothermal eruptions.

3. Modelling

3.1. Temperature contour maps of Rotorua

Representative temperature-contour maps of the RGF are constructed using down-hole temperatures from 161 direct-use bores measured by DSIR and the BOPRC from 1953 to 2011 (82% measured in 1980s). The contour maps (Figs. 9–12) give a good idea of the subsurface temperatures beneath Rotorua City. The plots show the main up-flow zones at Whakarewarewa, Kuirau Park, and Ngapuna. These are the three main up-flow zones in Rotorua, and indicated as temperature maxima at about 100 m below the surface (Steins and Zarrouk, 2012). The out-flow zone lead from the up-flow zones at depth to Lake Rotorua and around the Sulphur Bay (Figs. 9–12).

The temperature contours at 275 masl (Fig. 9) and 250 masl (Fig. 10) are the shallow part of ground subsurface, the depth around 0–50 m below the surface, showing areas of hot spots around the thermal manifestations in Whakarewarewa, Kuirau Park–Ohinemutu and Sulphur Bay. Cooler areas are indicated by yellow to light blue colours.

Figs. 11 and 12 show the temperatures at greater depths (200–175 masl). An area of cooler conditions is apparent near the northern border of the exclusion zone. This area exhibits cooler conditions compared with the surrounding bores. This indicates bores do not self-discharge and field investigation did not show that this area is used for reinjection. Contours below 100 masl are not presented due to the limited information in the 200–250 m depth range (the average bore depth in Rotorua is around 130 m from ground surface).

Most of bores in the up-flow and out-flow zones can self-discharge with temperatures of around 150–200 °C. They show characteristics of liquid dominated reservoir with high chloride content (Fig. 3). These bores are located in the orange area in Fig. 13. The bright yellow area located in the exclusion zone also indicates self-discharging bores. However, in order to utilize the heat, down-hole heat exchanges (DHE) would be required (Steins et al., 2012).

The bores in the pale yellow area of Fig. 13 have temperatures (above 80 °C). However, these bores do not self-discharge. Similarly the blue area indicates non-self-discharging bores which have temperature below 80 °C. Consequently, in order to utilize the geothermal energy in the pale yellow and blue areas: down-hole pumps, DHE or air lifting might be required.

It is important to note that the zones of Fig. 13 were determined based on the reported and observed production history of these bores. This zoning indicates areas where geothermal fluid withdrawal verses DHE technology can potentially be used. These observations will help inform the review of the RGRP and help set policies for the different types of geothermal use from bores in the future. However, it should be noted that DHE's have a much lower heat extraction/production capacity when compared to producing bores (Steins et al., 2012). Therefore, their use should be limited to small scale applications (e.g. space heating of a house or a small motel etc.).

3.2. Numerical reservoir modelling

As part of the on-going planning for use of the RGF a 3D reservoir model was developed to assess the impact of different usage options. Industrial Research Limited (IRL) was commissioned to develop a reservoir model (Burnell and Young, 1994), based on a previous natural state model (Burnell, 1992), which was one of the first geothermal reservoir models to include chloride transport.

The monitoring programme of the 1980s together with the reservoir response to the bore closure programme provided a basic understanding of the shallow reservoir together with potential sources of calibration data. However, the available information on the reservoir was limited to the upper 300 m that had been drilled. As a consequence the model was focussed solely on the shallow upper 500 m of the reservoir.

The conceptual model of flow in the shallow reservoir was based on: 1) geology, 2) inferred natural state pressures and temperatures, 3) fluid chemistry, 4) observed changes in pressure due to withdrawal and 5) measured changes in thermal area discharges.

3.2.1. Geological model

Three main geological formations are recognised in the shallow portions of the geothermal system; the Mamaku Ignimbrite, sediments and the Rotorua Rhyolite (Wood, 1992). These formations comprise the main geothermal aquifer in which production

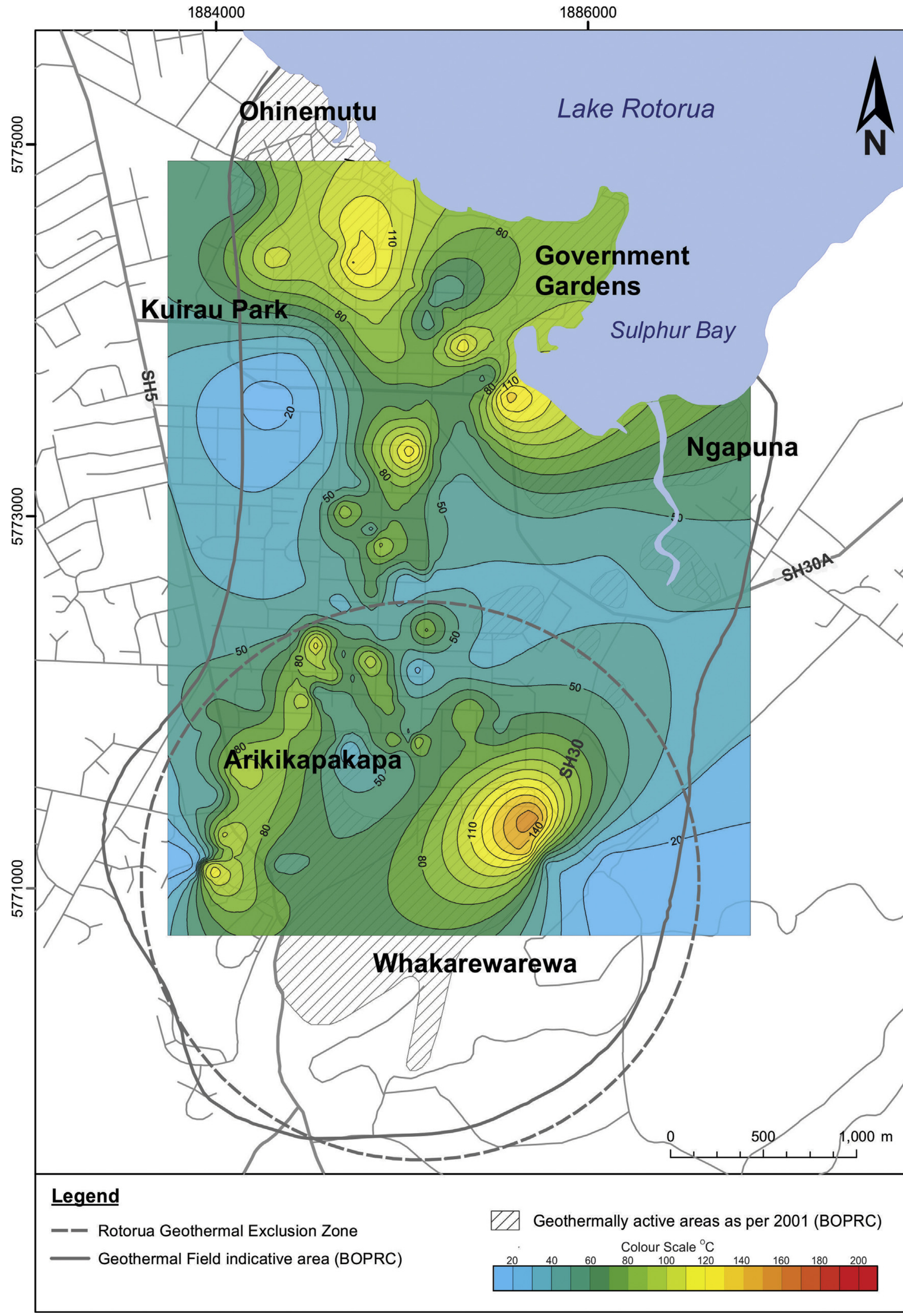

Fig. 9. Temperature contour map of the RGF at 275 masl near the ground surface. (For interpretation of the references to color mention in the text, the reader is referred to the web version of this article.)

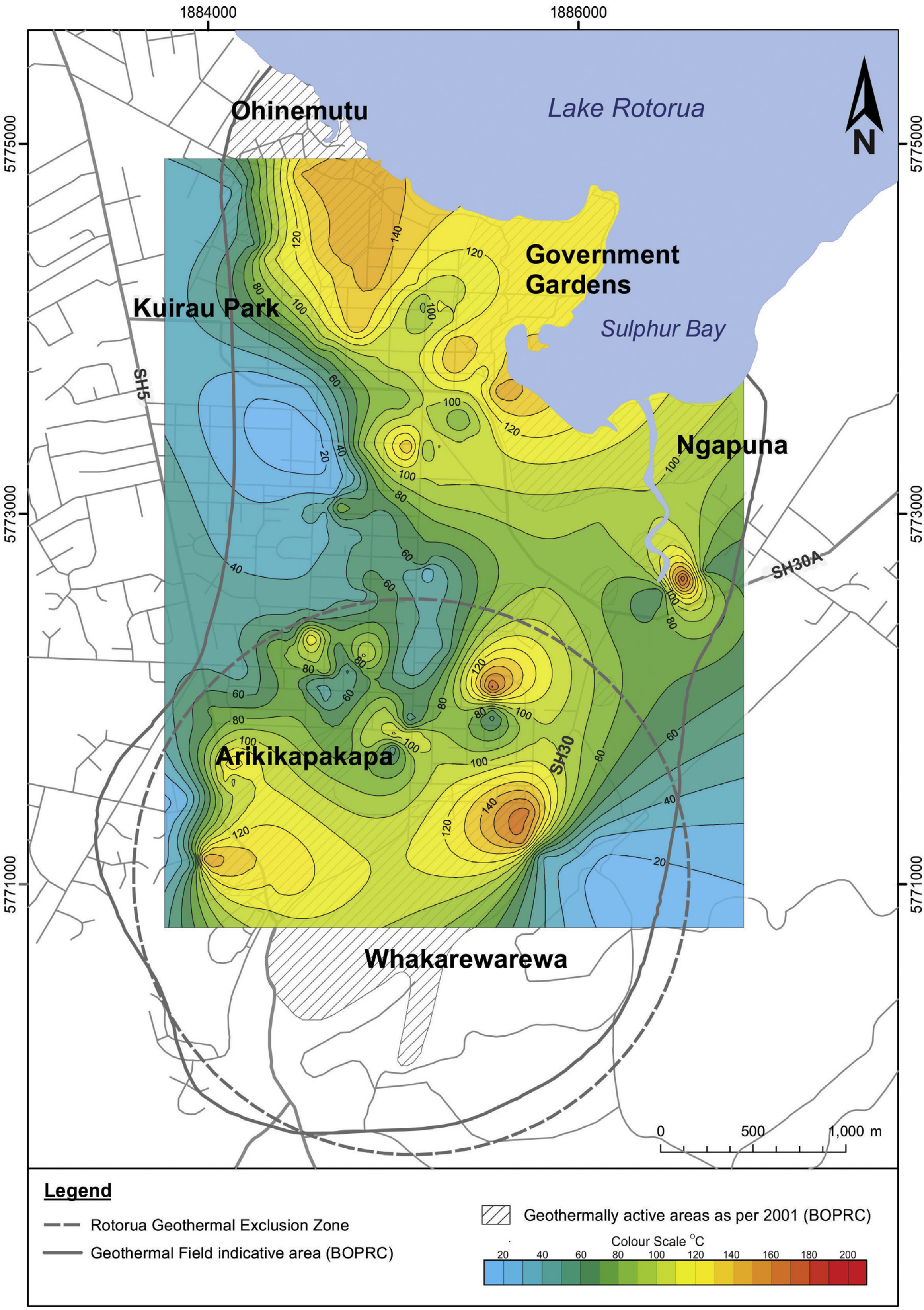

Fig. 10. Temperature contour map of the RGF at 250 masl (about 25 m depth). (For interpretation of the references to color mention in the text, the reader is referred to the web version of this article.)

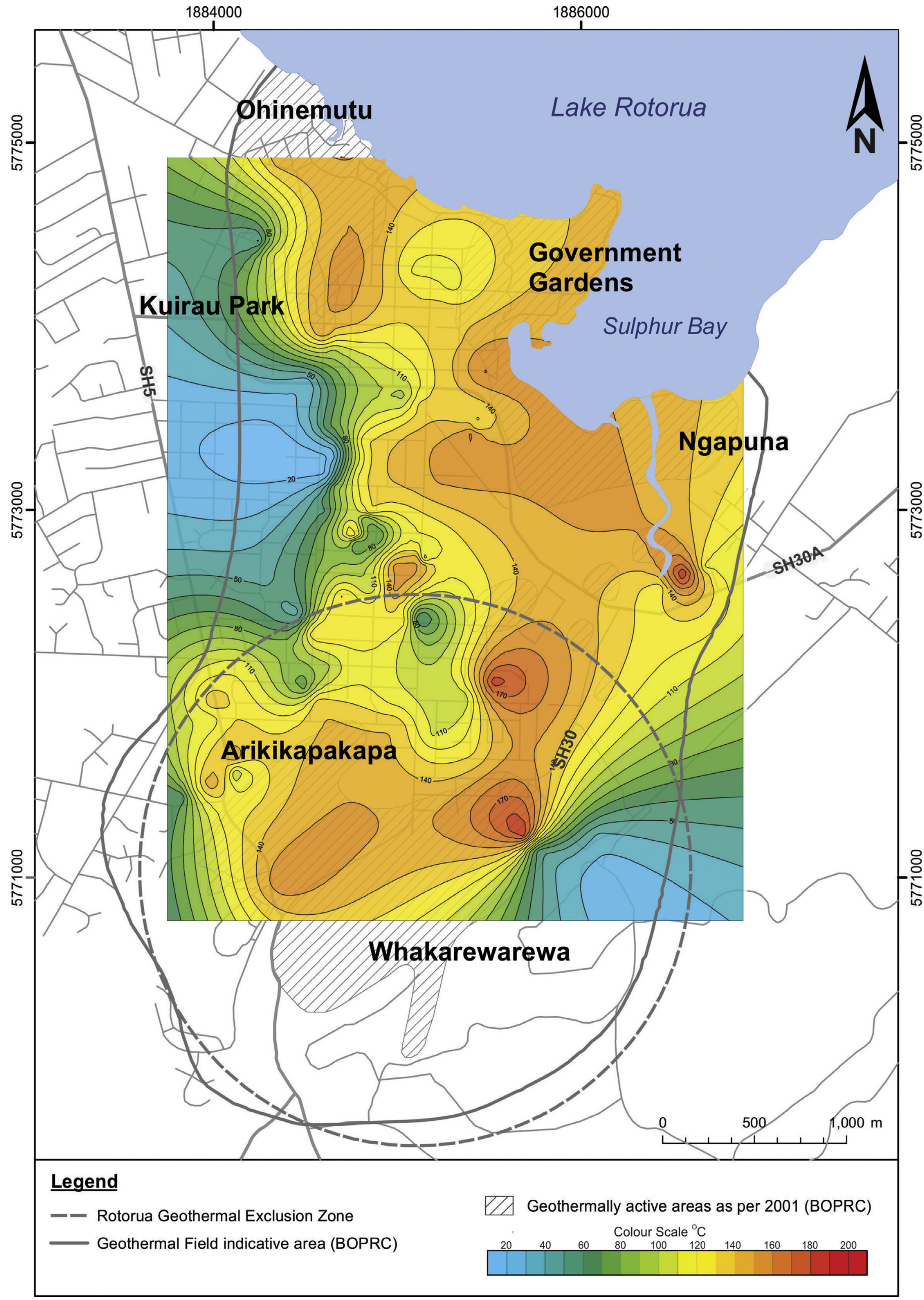

Fig. 11. Temperature contour map of the RGF at 200 masl (about 75 m depth).

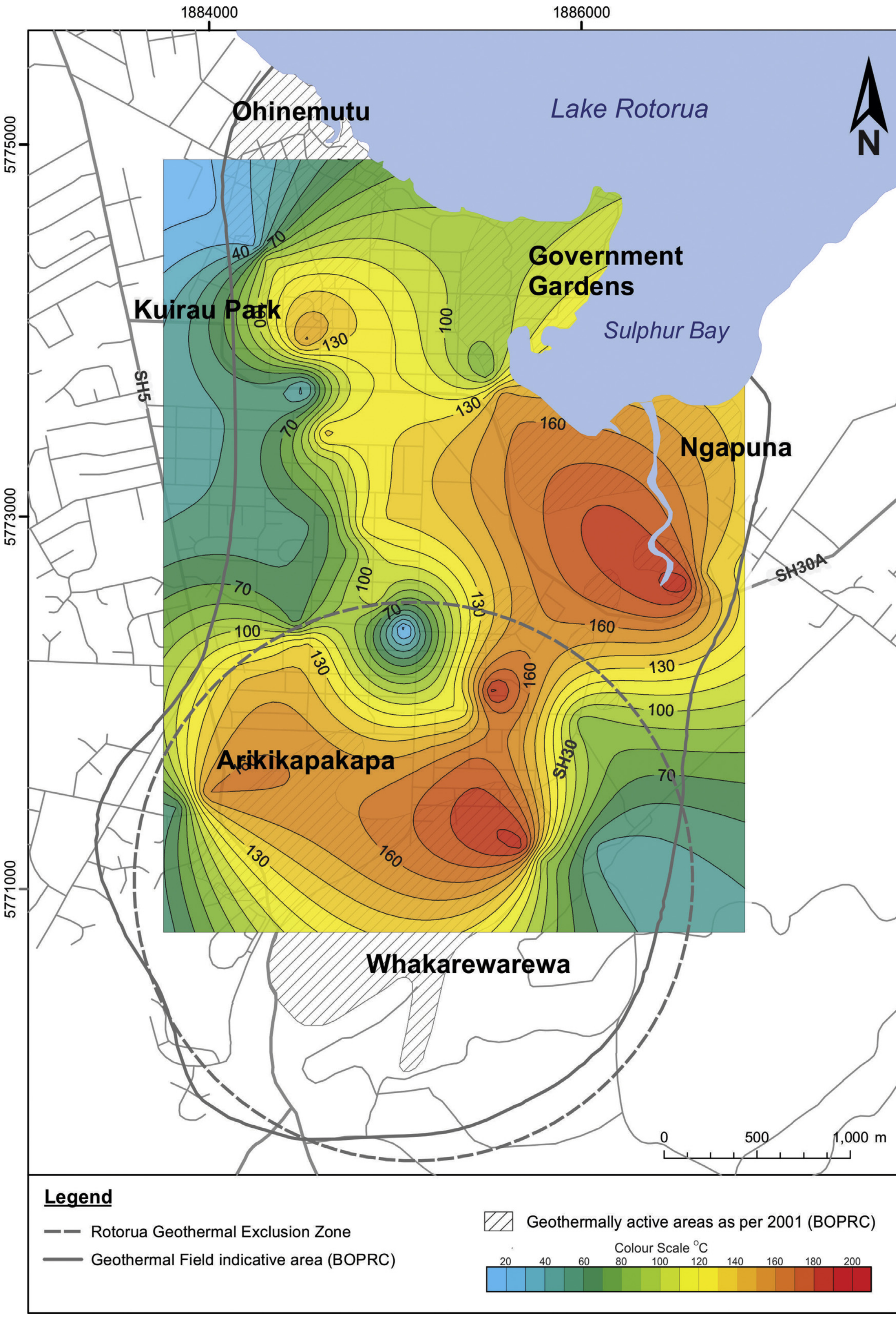

Fig. 12. Temperature contour map of the RGF at 150 masl (about 125 m depth).

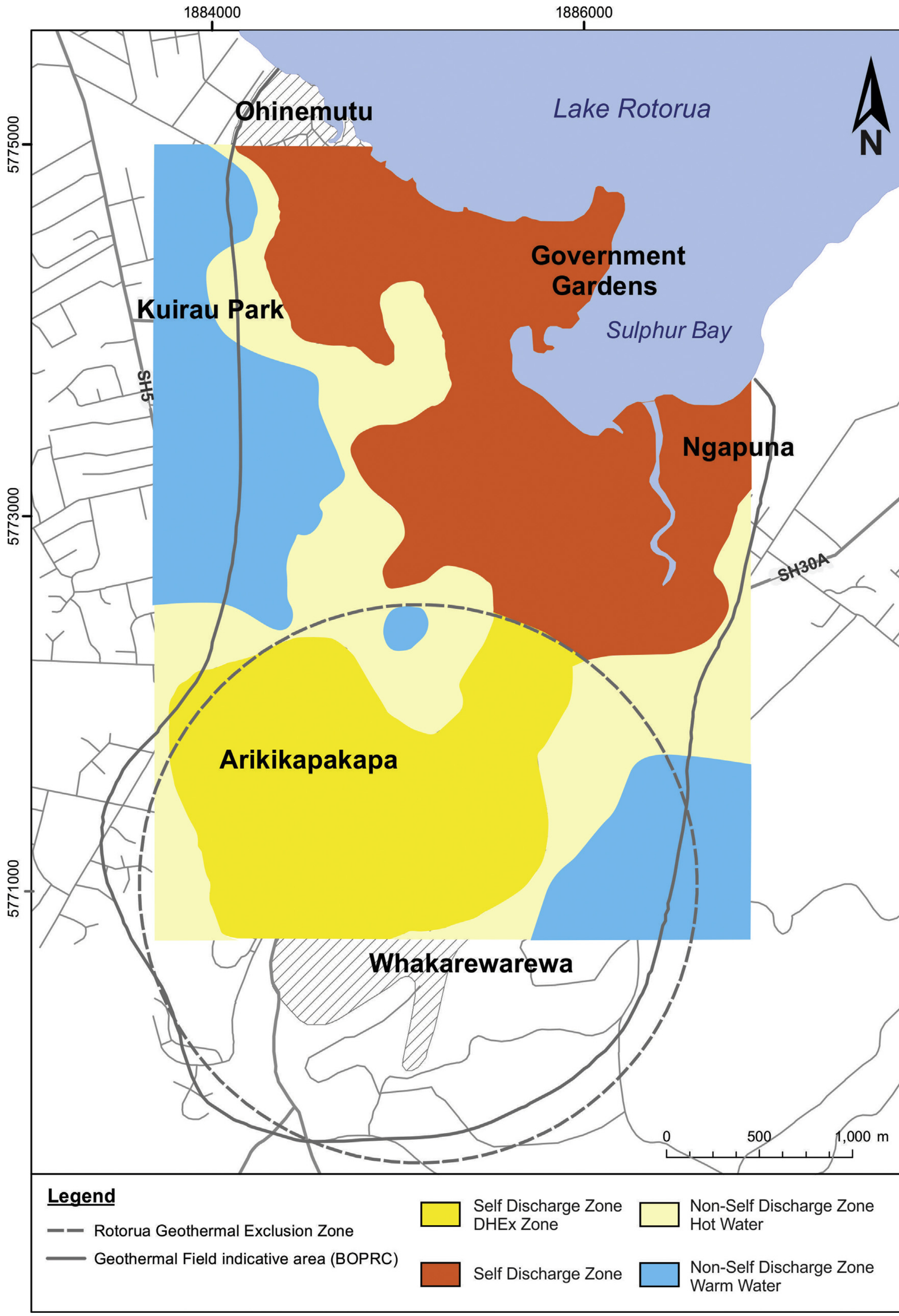

Fig. 13. Different direct use bore zones in Rotorua (after Candra and Zarrouk, 2013). (For interpretation of the references to color mention in the text, the reader is referred to the web version of this article.)

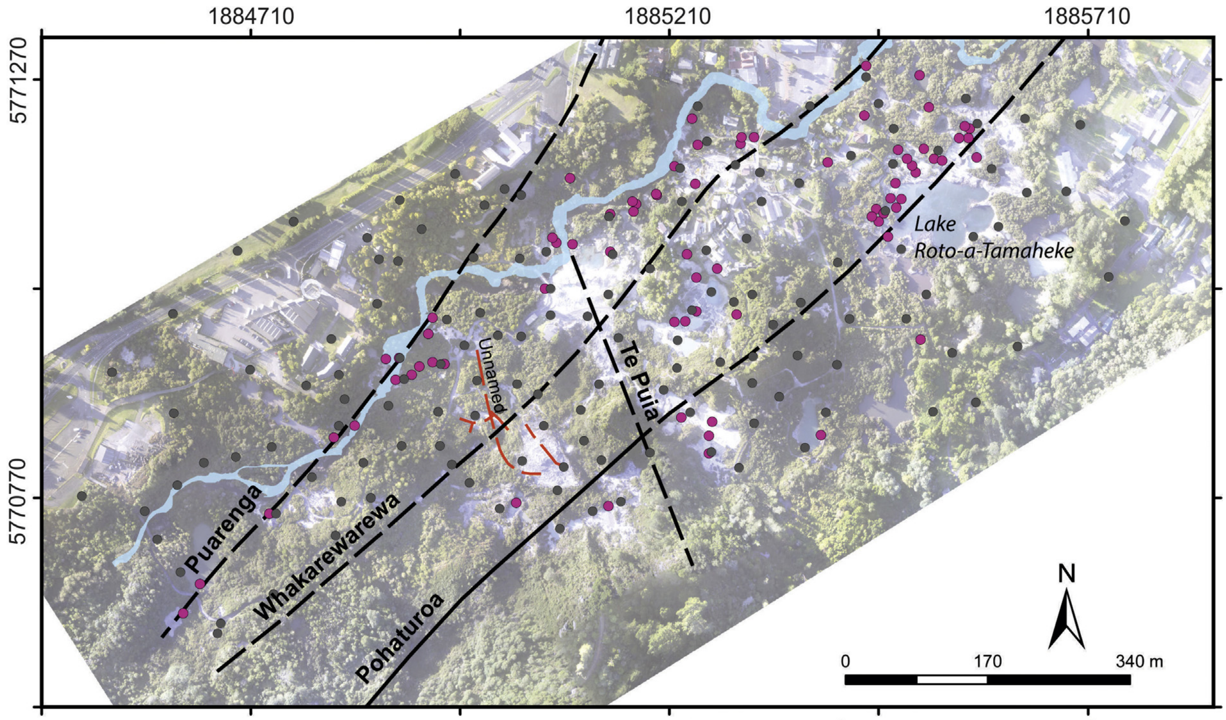

Fig. 14. Map of Whakarewarewa area. Grey dots show the locations of soil temperature measurements (2010) and pink dots the location of temperature measurements of 77 common water features. Known faults are shown in black dashed and solid lines.

bores have been drilled. The rhyolite formations are present on the western side of the field and are very permeable. The Mamaku Ignimbrite is only known at depth. These formations are overlain by sedimentary formations that confine the geothermal fluid.

A number of faults have been identified in the field, with some believed to provide permeable paths for the upflow of deep hot fluid (Simpson, 1985). One important fault is the Inner Caldera Boundary Fault (ICBF) in the south of the field. This fault coincides with a sharp drop in the measured pressures (Grant et al., 1985), such that the ICBF is postulated as a permeability barrier for north-south flow.

3.2.2. Surface heat flow

The surface heat flow from Whakarewarewa is a key indicator of impact of production from the field. The various monitoring programmes have provided measurements of mass and heat flows from many of the features at Whakarewarewa. Heat flow surveys were conducted in 1967 and 1984 and are reported in Cody and Simpson (1985). These surveys measured evaporation, radiation and surface discharge from springs and geysers, ground surface heat flux and seepage into the bed of Puarenga Stream. The 1967 survey gave a total heat flow of 229 MW. The 1984 survey reported a reduction in the total heat flow by 31% to 158 MW.

A more recent survey was undertaken in 2010 (Seward et al., 2014) and compares the heat loss from 77 common surface features with the heat loss recorded in the 1967, and 1984 surveys (Fig. 13). Heat can be lost from the surface of water features in 3 ways: evaporation, radiation and discharge (overflow). The methods for calculating heat loss are outlines in Dawson (1964) and were used in all studies. Here we recalculate heat loss from the three surveys, assuming the same atmospheric conditions (ambient temperature 12 °C; average windspeed 1 ms^{-1}). Cody and Simpson (1985) data shows a decline from 135 MW to 93 MW between 1969 and 1985 for 283 common surface features. This suggests a total decline of 31% in surface heat flow over this time. The heat loss from the 77 features common over the three surveys (Table 2; Fig. 14), show a decline of 37% over this same time period and account for approximately 72% of the total heat flow given by Cody and Simpson (1985). The results of the 2010 survey show a further 24% decline in heat loss from the surface features in the area. This decline is mirrored in the heat loss through the soils (Table 2).

Table 2
Comparison of heat loss from soils and 77 surface features common between 1969, 1985 and 2010 surveys at Whakarewarewa.

Type of heat flow	1969 survey	1985 survey	2010 survey
Evaporation and radiation from pools and springs	78 MW	58 MW	40 MW
Out flow	23 MW	5 MW	8 MW
Total from water features	101 MW	63 MW	48 MW
Through soil	10 MW	8 MW	6.4 MW

This suggests that although the geothermal reservoir is showing signs of recovery through the RGF as reflected in the monitor bores, chemistry and especially the springs in the northern portion. This is not the case at Whakarewarewa as these results indicate it is not reaching the surface at Whakarewarewa. This is in contrast to the recovery seen in some surface features.

Grant et al. (1985) inferred a heat flow of 300 MW in the natural state, which corresponds to a discharge of 400 kg/s of aquifer water. This calculation relies on the change in pressure from the natural state, which is only an estimate. So, the actual value of the heat flow from Whakarewarewa in the natural state cannot be determined with certainty.

3.2.3. Monitoring and changes in production

To assess the effect of production on the reservoir, a network of monitoring bores was established in 1982 to record reservoir pressures and temperatures. BOPRC has continued monitoring conditions in the reservoir with a programme that includes replacement of monitoring bores. Reservoir pressures, reported as water levels, are collected from the M-series monitoring bores drilled

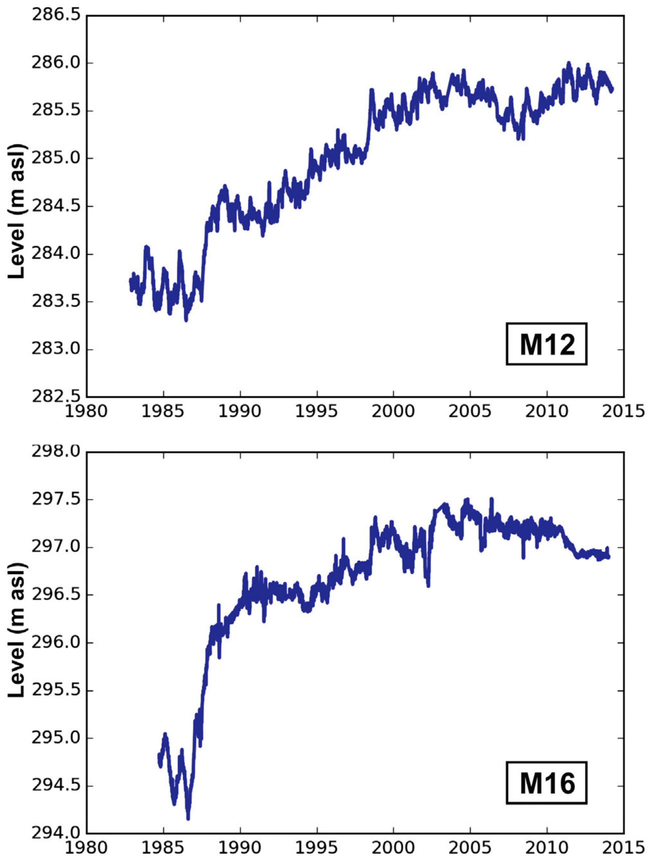

Fig. 15. Water levels from monitor bores M12 and M16 corrected for barometric affects.

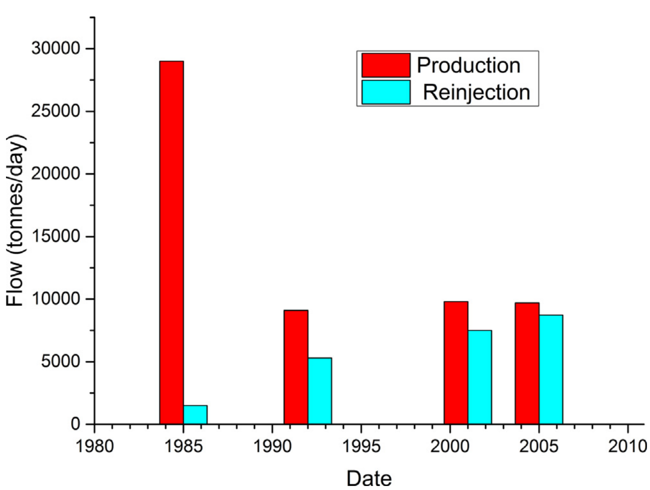

Fig. 16. Estimates of production and reinjection rates from the Rotorua system.

between 200 to 300 m in depth. Long term records have been collected from M1 and M12 in the northern part of the city and M6 and M16 near Whakarewarewa in the south. Shorter records also exist for other monitor bores in the field. Much of the data has been summarised in various BOPRC publications (Gordon et al., 2005; Kissling, 2005).

Water levels from two of the monitor bores, M12 and M16, are shown in Fig. 15. Data shows a decline in reservoir pressure in the early 1980s (see M16, Fig. 15), prior to the BCP, followed by a clear increase in water level, approximately 2 m, between the mid 1980s and 2000.

Bradford (1992) evaluated correlations between reservoir pressures, groundwater and rainfall. It has been noticed that reservoir pressures show cyclical behaviour with a yearly period. Before the BCP, the pressure low occurred in winter when extraction rates were highest. After the BCP the phase of the cycle changed with the pressure low occurring in summer in correlation with a minimum in rainfall indicating some correlations with groundwater changes are also present.

Estimates of production and reinjection rates from the RGF have been made by the RGMP and BOPRC. Fig. 16 shows the estimates of production and reinjection for the period 1985–2005. The effect of the 1987 BCP can be seen immediately and over following years net production gradually reduced, reaching a level of 1000 tonnes/day in 2005.

3.2.4. *Final model and calibration*

A reservoir model was developed using the EOS7 module (water, air and NACL) from TOUGH2 simulator (Pruess, 1991). The model covers the upper 500 m of the geothermal reservoir. Undoubtedly the reservoir extends below this, but due to the lack of knowledge of the structure and properties below 500 m, the influence of the deeper parts of the aquifer are included as upflows to the base of the model. Since the primary focus of the model is predicting changes to the shallow aquifer, this approximation should suffice.

The model is open along the north and south sides, allowing fluid to flow between the modelled area and the surrounding groundwater. The boundary at the north represents the lake and groundwater, accepting outflow from the field, and providing recharge from the lake.

The spring and geyser outflows were modelled as TOUGH2 wells on deliverability, with flow rates being proportional to the difference between the reservoir pressure and a prescribed pressure. Fixed heat and mass inflows were added at the bottom of the model. The inflows were adjusted until the model outflows and temperatures matched those of the natural state. These flow rates were then allowed to increase as pressures in the reservoir declined. The main inflows were sited under Whakarewarewa in the south and southeast. A further inflow was placed under Kuirau Park in the northwest as the chemistry indicates there is a separate flow in this region (Figs. 2, 3 and 11).

The model was mainly calibrated against data collected before 1992; primarily because the greatest changes were seen in the system over that period. Specifically, the model results were compared to 1) Inferred and measured pressures from the natural state; 2) Measured temperatures in 1985; 3) Inferred outflows at Whakarewarewa in the natural state and measurements from 1985; 4) Pressure changes from 1985 to 1992; and 5) Chloride concentrations in 1989.

Examples of the match of the model to the data are shown in Figs. 17 and 18. Overall the model reproduces characteristics seen in the reservoir, in particular pressure changes due to the bore closures. It is these pressure changes that are important in driving the changes in flow from Whakarewarewa that are the primary interest.

4. Discussion and conclusions

The RGF continues to be exploited with shallow bores, but under the control of the 1999 RGRP to which no subsequent changes have been made. The effect of the 1987 bore closure programme resulted in a substantial decline in production with an increase in reinjection of fluids. In 2005, net production was estimated at 1000 tonnes per day and is estimated to be unchanged. This has allowed the reservoir to recover in a relatively stable environment since about 2005. The declining pressures before the bore closure programme

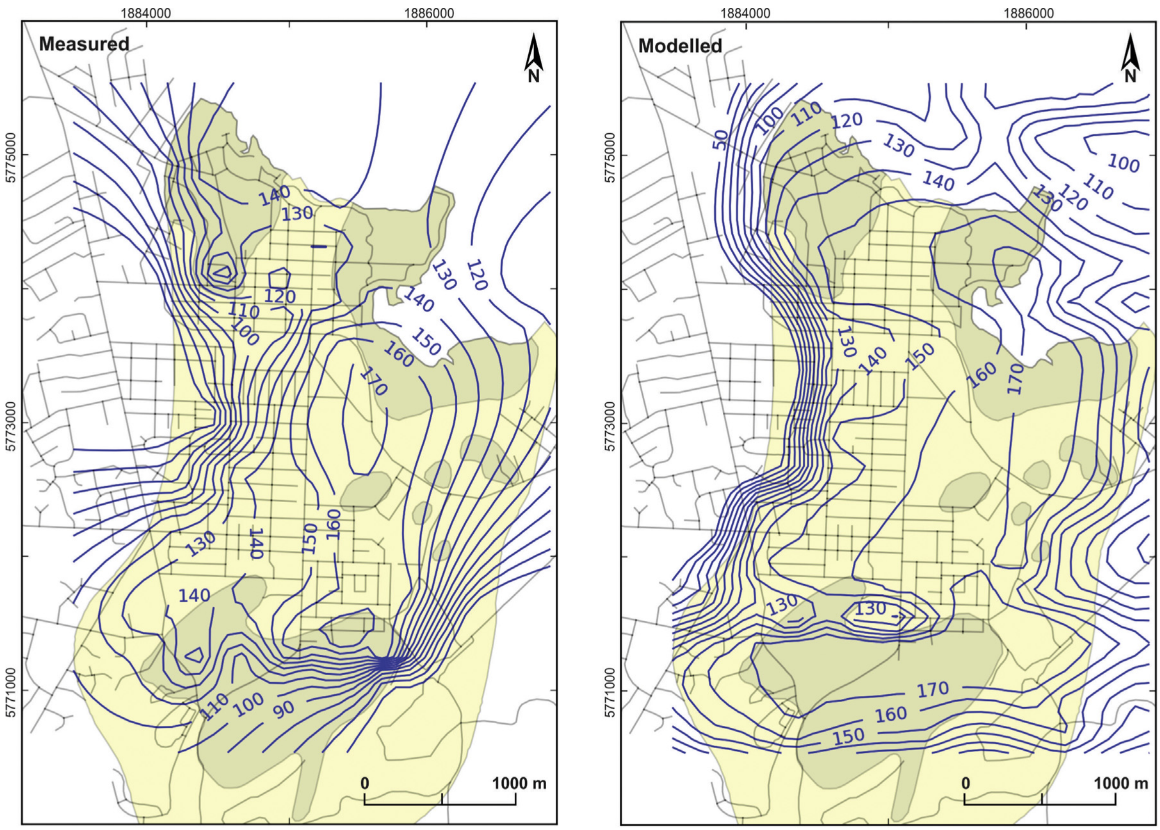

Fig. 17. Measured and Modelled temperature (°C) contours at 180 masl.

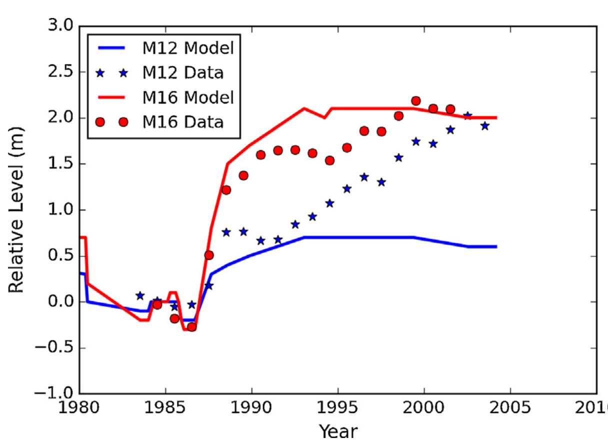

Fig. 18. Comparison of average measured and model water levels at M12, and M16.

were reversed in the 1986–1988 period of bore closures. Post-1990 further increases in reservoir pressure have been recorded in monitor bores and are now reflected as a 2–3 m increase in water level (Figs. 15 and 18).

The extensive surface feature monitoring programme has recorded several significant recoveries of surface features, but this has also been equivocal in many ways. In the northern area as represented by Kuirau Park the recovery has been very clear. Sinter lined basins that were dry in the early 1980s are now discharging fluids that are chemically similar to those observed prior to spring failure (Mroczek et al., 2005, 2011). At Whakarewarewa the recovery has been mixed. Though some features show increases in aquifer (geothermometer) temperatures they have not recovered to be overflowing features. However there are promising trends but the speed of the recovery is puzzling. The shallow aquifer feeding the bores has shown small changes and a slight geothermometry temperature increase. Indicating stability of the deeper system that feeds into the shallow exploited portion of the RGF.

A re-evaluation of past heatflow surveys and resurvey of surface features in Whakarewarewa in 2010 has shown a continual decline, but the rate of decline is decreasing. A similar trend is also seen in the soil heat flow. This is in contrast to the recovery seen in some surface features (Fig. 7). It is also now very apparent there was a significant decline in the number of hydrothermal eruptions in the RGF, after the bore closures. It would appear the draw-down of the reservoir leading to the 1970–1980s was the primary contributing factor in triggering eruptions. Other geothermal hazards like collapse holes remain a factor in the RGF.

Overall the management of the RGF has been a very successful experiment in environmental management. A useful and robust management plan, supported by monitoring of surface features and the reservoir has enabled the recovery of the RGF to be documented. Under-pinning research of the RGF has established a robust model of the system, with support by studies of chemistry, geology, geophysics and thermal structure. There have been impacts on the society, with the loss of access to the resource or damages during recovery. As well there has being large gains with the preservation and recovery of surface features supporting many of the intrinsic values of the geothermal resource.

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