Chemistry of the Rotorua Geothermal Field Part 3: Hydrology

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Chemistry of the Rotorua Geothermal Field
Part 3: Hydrology

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ENVIRONMENT BAY OF PLENTY

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LIST OF CONTENTS

Page

Page

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

Page

APPENDIX A. DISCHARGING WELLS – CHEMICAL AND ISOTOPIC COMPOSITIONS

APPENDIX B. NATURAL FEATURES – CHEMICAL AND ISOTOPIC COMPOSITIONS

APPENDIX C. ELECTRONIC COPY OF THIS REPORT (BACK POCKET ON CD-ROM)

EXECUTIVE SUMMARY

In Parts 1 and 2 of this study a geochemical survey of 31 selected Rotorua natural features and 10 wells was undertaken for comparison with historical data and to provide an overall assessment of the recovery of the springs following the enforced bore closure programme undertaken since 1986. In this report we conduct further interpretation of existing and new survey data to provide insight into shallow aquifer relationships between east to south (Ngapuna-Whakarewarewa) and north-western (Kuirau Park) parts of the field and examine the possibility of second deep upflow in the northwest.

The chemical and isotopic evidence incorporating the historical and recent well and spring results supports previous work that indicates that at least two separate plumes make up the overall Rotorua system. The primary upflow is to the east of the Rhyolite Domes, and then subsequently flows Southeast to Whakarewarewa. The smaller separate upflow to the Kuirau area is chemically distinct, although the geological evidence suggests that they are hydrologically connected. Excessive exploitation of one is likely to cause significant changes in the primary upflow that supplies Whakarewarewa.

The Wakarewarewa springs do not appear to be fed directly by a primary upflow and consequently the recovery has been mixed as the hydrology between the upflow and the surface outlets are influencing conditions. However recovery has been particularly notable at Parekohoru and Pohutu, but also evident for Okianga Geyser, Ngararatuatara and THC Blowout, with increases in aquifer (geothermometer) temperatures and a greater proportion of deep geothermal fluid being discharged. However in the northern area of the field at Kuirau Park the chemical evidence shows that the fluids discharged now match those discharging in the early 1960s and it is probable that this part of the field is near full recovery.

The shallow aquifer feeding the wells over the last decade shows relatively minor changes in reservoir chloride and small increases in heat (~16°C). This indicates stability and no deleterious processes are affecting the Rotorua Geothermal Field.

The initial bore closure programme and the subsequent Environment Bay of Plenty Regional Council's operative resource management plan for the field appear to have achieved the key objective of reversing the deleterious changes to the geothermal reservoir and ensuring the continued recovery of the springs and geysers.

1.0 INTRODUCTION

The geysers and other geothermal manifestations of the Rotorua area have long been valued as one of New Zealand's major tourist attractions. Prior to European settlement, Maori used the thermal waters for bathing, cooking, heating and processing natural products. Geothermal drilling began in Rotorua City in the 1920s, with local residents taking advantage of the thermal waters for domestic and commercial heating, and hot water supply. The early direct use developments were characterised by poor field management. From the 1960's through to the 1980's borehole numbers increased dramatically and the extraction of subsurface fluid started to reach a level where there was a demonstrated affect on the geysers and hot springs (Allis and Lumb, 1992; Gordon *et al*., 2001). In 1985 only about 5% of well discharge fluids were re-injected to the production aquifer with most waste waters being discharged into shallow soak holes (<20 m depth) with little incentive for efficient use of the resource. Fears that the remaining geysers and hot spring features would be lost if exploitation of the field continued at the same rate, prompted the government to fund a monitoring programme. This led to enforced closure, mostly in 1987-1988, of all wells within 1.5 km of Pohutu geyser and a punitive royalty charging regime for all remaining wells (O'Shaughnessy, 2000). This regulatory programme was met with much animosity and opposition from the local community.

Management of the field was then transferred to Environment Bay of Plenty (Bay of Plenty Regional Council), in 1991 with passing of the Resource Management Act. A regional resource management plan for the field was then developed which included some of the key components of government policy continuing the 1.5 km ban on abstraction from Pohutu Geyser at Whakarewarewa. The key objective of the management plan was to bring about recovery of surface features while providing for some limited use (Gordon *et al.*, 2001). Conserving field mass was considered to be a key requirement of bringing about recovery of the geothermal aquifer and Environment Bay of Plenty implemented the reinjection policy to help achieved this. Polices, methods and rules in the plan were vigorously tested in the Environment Court and the plan became operative in July 1999.

It is now 10 years since the closure programme and 5 years since the management for the field was first implemented. Water levels have recovered, flows of hot springs have increased and fluid flow to many previously dormant springs and geysers resumed (Scott and Cody, 2000). Although some failed geysers have shown no signs of recovery to date, it appears that the 1986 closure programme together with the field management plan has delivered significant success in the recovery of the geothermal reservoir (Gordon et al., 2001).

The greatest period of recovery of the Rotorua natural surface features was from 1992-2000. Over that time water levels and natural activity has been monitored by Environment Bay of Plenty, however chemical analysis of the discharging fluids was essentially discontinued in 1993 when central government funding for field monitoring was withdrawn. From 1993 only sporadic sampling and analysis of a few wells and springs has occurred, usually during significant events such as well failures or spring outbreaks. Nevertheless chemical monitoring of the thermal features, during the early days of exploitation and in recent times, has provided much information about the hydrology of the Rotorua Geothermal Field, and the chemistry of the hot mineralised fluids that mix with surface groundwaters, discharge at the surface, and flow into Lake Rotorua. In conjunction with physical monitoring this enables a comprehensive understanding of the current state and "health" of the field with respect to exploitation and recovery. The chemistry data also provides constraints for the complex mathematical models being developed of the field.

The chemical and isotopic studies summarized in this report are a component of a continuing field management monitoring and research programme undertaken by Environment Bay of Plenty to support the objectives and polices of the resource management plan for the Rotorua Geothermal Field (Rotorua Geothermal Regional Plan, 1999). This study had been divided into three parts. In Parts 1 and 2 a chemical and isotopic survey of selected Rotorua natural features and wells was undertaken to compare the results to historical data and provide an overall assessment to highlight any changes (Mroczek et al., 2002; 2003).

In this, the third part, we conduct further interpretation of existing and new survey data collected 2002-2003 to provide insight into shallow aquifer relationships between east to south (Ngapuna-Whakarewarewa) and north-western (Kuirau Park) parts of the field and examine the possibility of second deep upflow in the northwest.

For completeness the recent chemical and isotopic analyses for wells and springs together with relevant historical data collected and collated in Parts 1 and 2 are summarized in Appendices A and B.

2.0 RECENT WORK

2.1 Part 1

In Part 1 of this study a chemical and isotopic survey of 31 selected natural features in the Rotorua Geothermal Field was undertaken to asses the recovery of springs across the geothermal field following the enforced bore closure programme which began in 1986 (Mroczek et al., 2002). The results of the spring survey indicated that the key objective in Environment Bay of Plenty's operative resource management plan (regional) for the field, of protection and restoration of natural outflows, was being achieved. The recovery is particularly apparent in the northern area of the field where the composition of fluids discharged at Kuirau Park now match those discharging in the early 1960s and it is probable that this part of the field is near full recovery. While in the Whakarewarewa area features show a range of chemical and isotopic changes with apparently no consistency to geographical location. These changes ranged from continuing decline or no recovery to stable or recovery with aquifer re-heating. Of particular note is the recovery of Pohutu Geyser which now discharges a fluid with composition comparable to that recorded by Grange in 1937 (as reported by Glover, 1967).

The main conclusions of Part 1 were that the relative changes in composition of non-reactive and reactive species indicated a greater proportion of deeper aquifer, and hence hotter, fluids were now being discharged at the surface. However, the chemistry of the deep source fluids feeding the shallow aquifers of the geothermal systems was essentially unchanged.

A possibility of fundamental change in the underlying fluid compositions as a consequence of an input of heat at depth was suggested by mathematical modelling of the water level rises across the geothermal field (Kissling, 2000).

2.2 Part 2

We continued the study in Part 2 with a chemical and isotopic survey of selected Rotorua wells. Wells tap fluids from deeper aquifers that are less affected by secondary processes than spring waters where the determination of aquifer relationships and reservoir characteristics can be problematic.

Unfortunately many of the previously sampled wells have been closed and are now not available for sampling, hence the wells sampled were not always the ideal choices, but a compromise between availability, geographic distribution, temperature and depth.

The principle conclusion of Part 2 was the shallow aquifer feeding the wells over the last decade showed relatively minor changes in heat and reservoir chloride. This indicates stability and no deleterious processes are affecting the deeper Rotorua Geothermal Field. Na/K Geothermometer temperatures of the deeper source waters appear to have increased typically by 16^{o}C. Nevertheless three wells, two in Western Rotorua and one in Government Gardens showed small decreases in derived aquifer enthalpy (i.e. lower heat content) and reservoir chloride (i.e. more dilution). Whether this is part of natural fluctuations could not be fully assessed in this study and may be better determined in future sampling.

Gas compositions of steam were broadly similar to those previously determined except that helium enrichment relative to argon and nitrogen appears to be present over a wider area of the Western part of the field. This suggested that the “upflow” zones may now cover a wider and more diffuse geographic area than previously thought or degassing is delayed because of increased pressures in the reservoir.

3.0 TREATMENT OF CHEMICAL DATA

3.1 Introduction

The fluid and gas chemistry provides information on the deep conditions and processes not obtainable by geological and geophysical techniques. Temporal changes and spatial relationships in chemical and isotopic composition enable a hydrological model of the field to be developed which complements other observations. As the chemical and isotopic compositions reflect subsurface aquifer processes, like the mixing of different source fluids (hot and cold), which may result in cooling and dilution of deep aquifer fluid and boiling and water rock interaction, hence a picture of the subsurface processes can be obtained. The geothermal fluids equilibrate with aquifer rocks through dissolving and precipitating minerals, changing the concentrations of certain dissolved constituents in proportions dependant on temperature. These reactions form the basis of the chemical geothermometers providing data on reservoir temperature and heat.

3.2 Triangular diagrams

The comparison of the recent results with historical data presents two major difficulties. The first is the sheer volume of data to compare and the second is the need to compare samples over 40 years, where the changes in absolute concentrations may appear to be erratic particularly in springs where the absolute compositions could be influenced by local effects such as high rainfall episodes and other transitory disturbances to the shallow aquifers. The technique used here is to compare the changes in the relative concentration of both chemically inert non-reactive species and chemically reactive species using triangular diagrams as described by Giggenbach (1991). Comparison of the relative, rather than absolute concentrations has many advantages. In the absence of mineral dissolution/precipitation the relative proportions of constituents remains constant during steam loss or dilution. Furthermore, mixing between end-members are always straight lines so that trends and relationships between different groupings of features are more easily discerned. All relative concentrations have been calculated by weight% from the analysed fluid composition.

Following the techniques developed by Giggenbach (1991), we use five different triangular plots in this study and these are discussed in detail below;

i) Relative Boron (B) – Chloride (Cl) – Sulphate (SO_4)

Boron (B) and chloride (Cl) are chemically inert and so allow differentiation of the source fluids. High sulphate (SO_4) results from the oxidation of hydrogen sulphide (H_2S) in steam heated waters to sulphuric acid. Thus a group of related (same source aquifer) alkaline chloride springs will all lie along a line of constant Cl/B which will trend to the SO_4 apex of the diagram if progressively mixed with steam heated waters.

ii) Relative Bicarbonate (HCO_3) – Chloride (Cl) – Sulphate (SO_4)

This diagram is useful for classification of the springs at Rotorua. In the south and east waters cooled by boiling are greatly depleted in CO_2 and consequently contain less bicarbonate (HCO_3). Thus Cl/HCO_3 ratios are low in the north-western part of the field and high the south and east. Intermediate values of Cl/HCO_3 may be due to a smaller degree of boiling before dilution or to a smaller degree of dilution and reaction of CO_2 with rock (Giggenbach and Glover, 1992; Glover and Mroczek, 1998). High HCO_3 results from prolonged contact of fluids containing carbon dioxide (CO_2) reacting with rock at lower temperatures. The process requires a considerable residence time and is of particular significance for Rotorua where fluids in the north-western part of the field have highly elevated HCO_3 concentrations. Again trends to the SO_4 apex of the diagram imply progressive mixing with steam heated waters.

iii) Relative Sodium (Na) – Potassium (K) – Magnesium (Mg)

This correlation is based on two geothermometers, the sodium (Na) – potassium (K) and potassium (K) – magnesium (Mg); see Section 3.3.

iv) Relative Argon (Ar) – Nitrogen (N_2) - Helium (He)

Relative proportions of the inert and reactive gases are also useful for interpreting reservoir processes. The argon (Ar) – nitrogen (N_2) - helium (He) diagram is useful for classification of gas samples in terms of their likely source and for identifying samples affected by air contamination (Giggenbach , 1991).

v) Relative Carbon dioxide (CO_2) – Hydrogen sulphide (H_2S) - Methane (CH_4)

The carbon dioxide (CO_2) – hydrogen sulphide (H_2S) - methane (CH_4) diagram reveals boiling processes as there is a marked difference in solubility between methane and the other two, so with progressive boiling the residual fluid becomes enriched with the more soluble gases (Giggenbach and Glover, 1992). Bores on the western sector of the field discharge steam which is depleted in methane, suggesting boiling of the deep geothermal fluids as they ascend to the surface, compared to wells on the east (Kuirau) where boiling at depth is suppressed by dilution and cooling.

3.3 Geothermometers

Three geothermometers, silica (quartz and cristobalite), sodium/potassium (Na-K) and potassium/magnesium (K-Mg) are used to determine subsurface fluid temperatures and are used for evaluating water-rock equilibration temperatures. The silica geothermometer equilibrates rather quickly so that the corresponding temperatures reflect those at or near the feed points of the wells. The mineral reactions that are the basis of the Na-K geothermometer proceed only very slowly at temperatures below 300°C. So this geothermometer reflects the aquifer temperatures in the deeper parts of the system and the temperatures may therefore indicate equilibrium conditions at some distance from the producing wells where waters may reside for very long periods of time. In contrast the K-Mg geothermometer is based on mineral reactions which respond faster so that the calculated temperatures are lower than for Na-K and reflect the most recent equilibration of the fluids in the shallow aquifer. The correct application of geothermometers, especially to spring fluids, is not trivial and subject to many uncertainties (Fournier, 1991, Arnosson, 2000)[1].

3.4 Chloride-enthalpy diagram

Changes due to aquifer boiling, mixing (dilution) and conductive heat gain or loss may be identified on a Chloride-Enthalpy diagram. Both components are essentially conservative. The aquifer enthalpy (H) is derived from the inferred aquifer temperature, which is calculated using either the quartz or cristobalite silica geothermometer. In the absence of recent physical well enthalpy or down-hole temperature measurements, the silica geothermometer temperature has been assumed to best represent the temperature in the reservoir in the immediate vicinity of the well. It has also been assumed there is no excess steam in the reservoir, so that the aquifer chloride (Cl_{res}) is the same as the total discharge (TD) composition; i.e. combined steam and water discharged at the wellhead. Renormalising concentrations to total discharge is a convenient method for comparing samples collected at different separation pressures.

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[1] Many equations have been proposed for the same geothermometer, which gives rise to varying calculated temperatures. Also the reaction controlling the apparent ratio may not be the one on which the geothermometer is based. The Na-K geothermometer is based on exchange reactions between feldspars and water, but at lower temperatures as occurs in hot-springs, the Na/K ratio may be controlled by reactions involving clays (Fournier, 1991). In this report the cation relationships are used empirically to show temporal changes in composition between hot springs across the field.

Quartz typically controls the silica concentration in reservoir fluids in the Taupo Volcanic Zone and the silica solubility in wells RR889 and M25 appears to be controlled by this silica polymorph. However cristobalite appears to be the controlling silica mineral in the reservoir for the remainder of the Rotorua wells sampled in this study. Figure 14 was constructed by assuming quartz geothermometer for M25 and RR889 and the cristobalite geothermometer for all other wells sampled. This choice of geothermometer was based on the best matches with previously measured down-hole well temperatures (Table A1).

The features of the Chloride-Enthalpy diagram are that H and Cl_{res} both decrease with dilution while H decreases and $Cl_{res,}$ increases with adiabatic cooling (boiling), see Figure 14 The composition of the parent water may be obtained from an intersection of the dilution and boiling lines. There are two dilution lines drawn in Figure 14, dilution of the "parent" type fluids (represented by M25) by a "hot" low chloride fluid and then a dilution of the cooler reservoir fluids by cold groundwater (Glover and Mroczek, 1998).

4.0 GEOLOGICAL SETTING

The Rotorua Geothermal Field is one of about a dozen large active hydrothermal systems located within the central part of the Taupo Volcanic Zone (TVZ), in a region characterised by catastrophic caldera-forming Quaternary rhyolitic volcanism. The Rotorua Geothermal Field, as defined by surface activity, shallow drillholes, geophysical (electrical resistivity) and geochemical surveys covers an area of 18-28 km^2 and occupies the southern margin of the 25 km diameter Rotorua basin, which was formed from caldera collapse associated with the eruption of the 220,000 year-old Mamaku Ignimbrite (Wilson *et al*., 1995). The area of 18 km^2 is that on land; 28 km^2 covers the area on land plus the area within Lake Rotorua.

Fluid flow within the Rotorua Geothermal Field is largely constrained by geological structures (e.g. the Kuirau Fault was identified on the basis of surface thermal activity, high downhole bore temperatures, and rhyolite surface morphology), and by the properties of the subsurface formations (their natural porosity and permeability) and the thermal fluids. Wood (1992) describes the geology of the Rotorua geothermal area, which comprises syn-caldera pyroclastic materials (Mamaku Ignimbrite), lava flows and domes (Rotorua Rhyolite), and lake sediments. Shallow drilling of geothermal bores, for abstraction of thermal fluids for heating and direct uses, has provided stratigraphic information about the shallow geology and hydrology of the area, although little is known about the geology, structure and hydrology of the geothermal system deeper than about 300m below ground level.

5.0 PREVIOUS WORK

Glover (1974) compiled data for all chemical surveys undertaken in the Rotorua field up to the mid 1970s, and provided a general outline of the field hydrology, and upflow of hot chloride-type thermal fluids near Whakarewarewa. Glover inferred that the deep thermal waters mixed with a secondary flow near the Pukeroa Dome, with both being diluted with low-chloride groundwaters as they flowed northwards. By 1985, additional information had been obtained from the field, including further chemical and isotopic analyses of the bore and spring waters, which led to recognition of the structural control on fluid flow. This led to a general model of the Rotorua Geothermal Field, whereby springs at Whakarewarewa were considered to be directly fed by a 230°C deep aquifer, with other upflow zones identified at Ngapuna, and lateral flows extending north and west beneath Rotorua City.

Giggenbach and Glover (1992) suggested that the main upflow zone of deep geothermal fluid at Rotorua occurred in the eastern part of the field where alkali chloride fluids are found at depth and in a few springs. A closely related plume supplied the Whakarewarewa area (characterised by slightly altered alkali-chloride, near boiling/boiling springs and geysers, which show increasing dilution by meteoric waters towards the south). A second upflow of bicarbonate-rich fluid, cooled by dilution with deeply penetrating meteoric water and altered by long contact time between water and rocks, fed wells and surface features in the northwestern part of the system. Glover (1992) indicated, from chloride budgets, that about 60% of the total output from the field discharged through the lake bottom, which implied excellent hydraulic connection between the lake floor and the geothermal aquifer.

In contrast, Stewart *et al.* (1992) proposed a model of the Rotorua Geothermal Field, based on water/gas isotopic and chemical data, which pointed to deep aquifer fluids rising in the east, and boiling as they approached Ngapuna (where the hottest bore fluids are encountered). Waters discharging at the surface at Whakarewarewa (and Arikikapakapa, where acidic cold lakes and steaming ground are encountered, contain minor amounts of bicarbonate and were diluted by groundwater before boiling. Stewart *et al.* (1992) suggested that a component of this fluid flows below shallow lake sediments that underlie Rotorua City, where they are diluted with bicarbonate-chloride waters, before mixing with cool, near surface groundwater (and steam-heated fluids) and discharging in the Kuirau/Ohinemutu area.

Graham (1992) suggested a deep origin for the primary thermal waters and interaction with metasedimentary basement (greywacke) at >2 km depth, with direct upwelling in the east, plus fluid flow to the west, which undergoes dilution by old groundwater. Subsequently, Glover and Mroczek (1998) examined changes in silica chemistry and hydrological connections across the Rotorua Geothermal Field, and their work pointed to two diluting fluids in the system – one at 15°C and another at 150°C, supporting the shallow mixing model of Stewart *et al*. (1992).

Horwell et al., (2005) mapped H_2S emissions across the Rotorua Geothermal Field in 1997 and not surprisingly found high emissions along a corridor in the Mamaku Ignimbrite to the east of the Rhyolite Domes following the general NE-SW trending Ngapuna and Roto-a-tamaheke Faults. Wood (1992) speculated that these structures allowed fluids to rise from depth and considered that the northeast Mamaku Ignimbrite was closer to the main upflow than any another drilled area. This area as the source of the main upflow was supported by Giggenbach and Glover's (1992) geochemical evidence but is inclusive of subsequent dilution with cooler less mineralized fluids flowing laterally as proposed by other authors. Horwell et al. (2005) found significantly less emission in the Kuirau area which they ascribed to smaller upflow in this area. This is likely to be correct but in addition less permeability at depth in the Rhyolite, cooling and suppression of boiling, which enables the removal of the H_2S by water-rock reaction, would also result in reduced degassing in the Kuirau area.

Figure 1 is a schematic representation of fluid flow paths in the Rotorua Geothermal Field, which incorporate the fluid flows proposed by Giggenbach and Glover (1992), Stewart *et al*, (1992) and Graham (1992). The figure highlights two natural spring areas; (i) Ngapuna, Whakarewarewa, and (ii) Kuirau, Ohinemutu; and how these two parts of the Rotorua field may be connected and supplied by thermal fluids. Fluid rises in the eastern part of the field, with its outflow comprising discharge to thermal features at Whakarewarewa and Ngapuna, lateral flow to the western thermal areas and extraction of fluid from geothermal wells. For features in western areas, shallow mixing can supply fluid to thermal features in Kuirau and Ohinemutu areas, whilst there is also likely to be an input of deep thermal fluids that have a pressure effect on the system.

Horwell et al. say that it is not known whether the downflows between the Rhyolite Domes are natural or caused by pressure reduction due to the extensive exploitation of the field. This no doubt came from Wood (1992) who references Grant et al., (1985) that a drawdown of 0.5 bar was caused by withdraw of fluid in the downtown area. However Wood (1992) goes on to say that historical well temperature data suggests the thermal/pressure low extended to areas with low geothermal exploitation suggesting it is a natural phenomenon. Future temperature and pressure monitoring will enable the issue to be resolved.

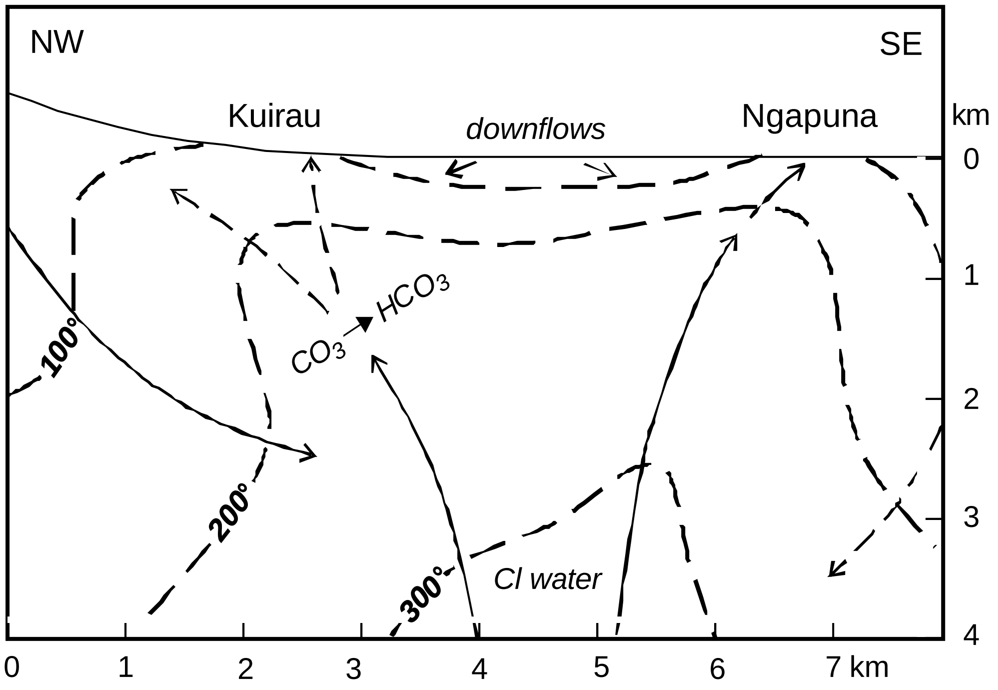


Figure 1. Schematic of the inferred hydrology of the Rotorua Geothermal Field (after Giggenbach & Glover, 1992).

6.0 RESULTS FOR SAMPLES COLLECTED IN 2002 AND 2003

Results for samples collected in 2003 (geothermal wells) 2002 (hot springs) and are given in the Appendices, Tables A1 to A10 and Tables B1 to B3 respectively.

6.1 Ngapuna – Government Gardens

Figures 2 and 3 show Cl-HCO_3 and Cl-HCO_3-SO_4 plots for samples from Ngapuna and Government Gardens. Clearly the HCO_3/Cl ratios are very different for waters in these two areas; those at Ngapuna have low HCO_3 and high Cl concentrations (with HCO_3/Cl ratios mostly <0.05), whereas those at Government Gardens have moderate HCO_3 and Cl concentrations (and HCO_3/Cl ratios of about 1). The wells at Ngapuna and Government Gardens show the same differences as the springs (Figures 11-13). Government Gardens waters can be produced from Ngapuna-type water by groundwater dilution and rock-water alteration, but cannot be produced from Kuirau-type water, because the former have higher HCO_3 (particularly) and Cl concentrations. Hamiora Baths water is intermediate between Ngapuna and Government Gardens waters, suggesting that it is a mixture of the two. The Cl-B-SO_4 plot (Figure 4) also shows a clear distinction between the Ngapuna and Government Gardens springs, again indicating that the latter have interacted extensively with rock. The Cl/B ratios are about 140 and 78 respectively for these groups.

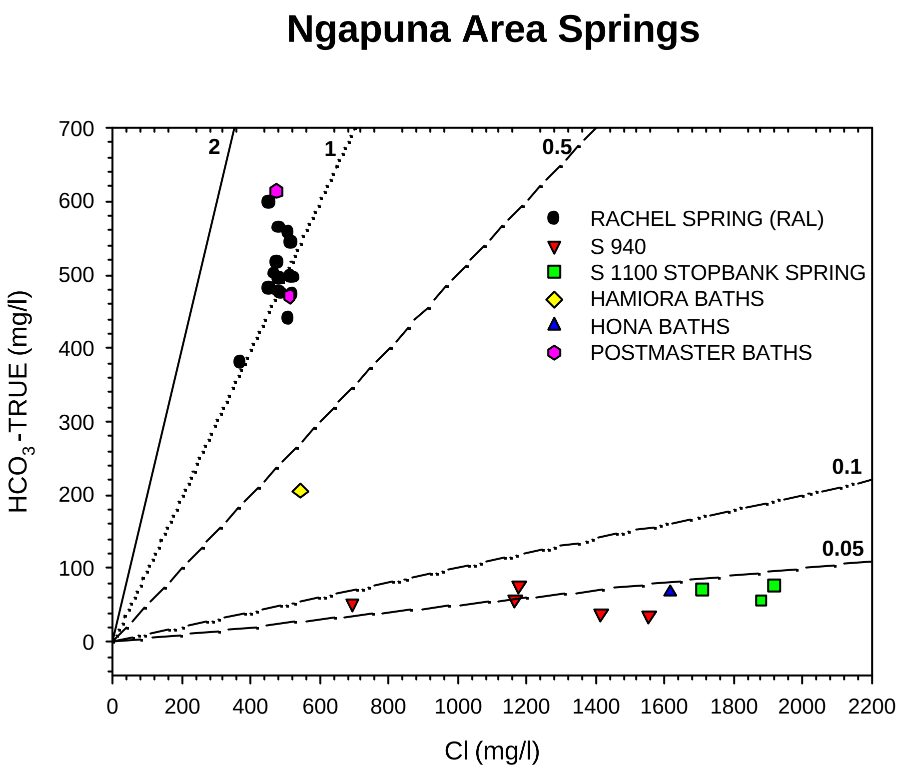


Figure 2. HCO_3 (true) versus Chloride – Ngapuna Springs Area.

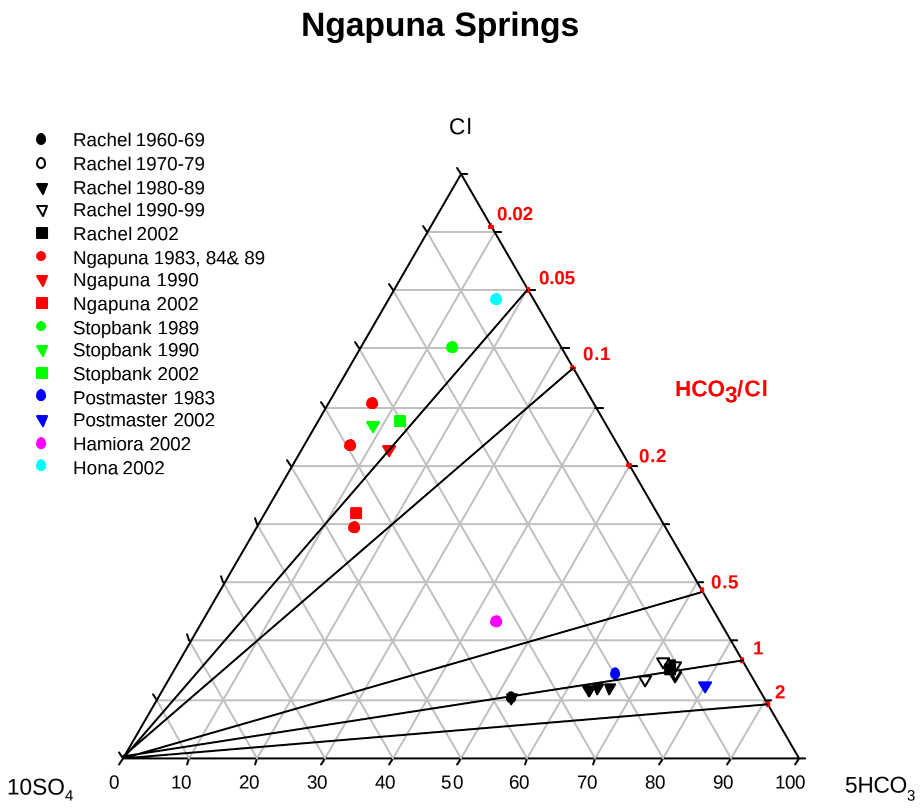


Figure 3. Relative HCO_3-Cl-SO_4 – Ngapuna Springs Area.

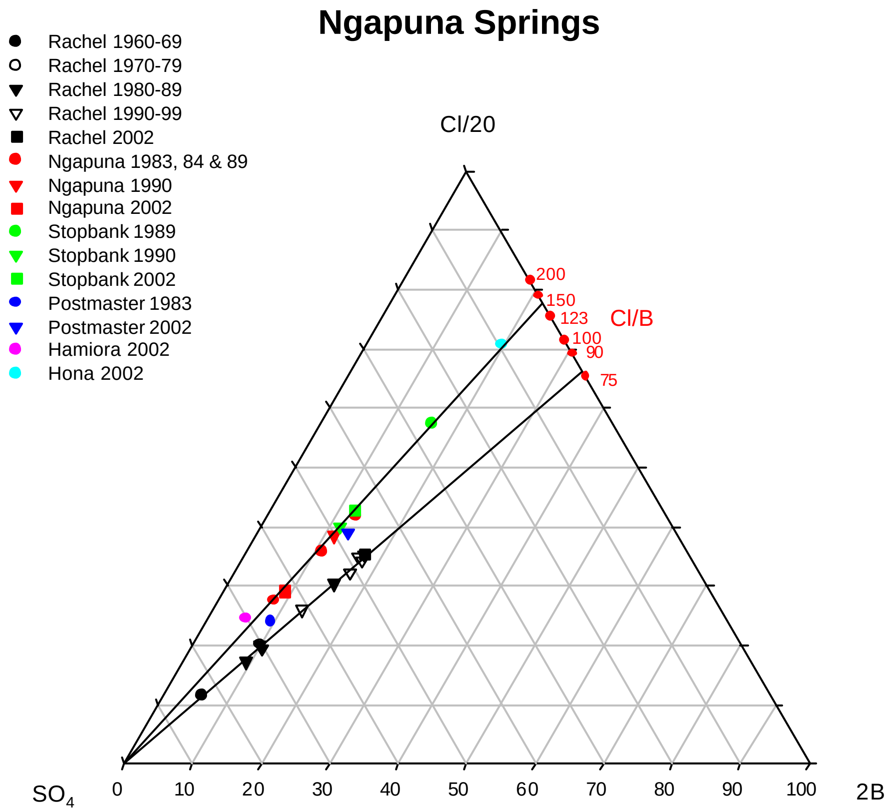


Figure 4. Relative B-Cl-SO_4 – Ngapuna Springs Area.

6.2 Whakarewarewa

Results for samples from Whakarewarewa Springs are given in Cl-HCO_3 and Cl-HCO_3-SO_4 plots (Figures 5 and 6). The springs have HCO_3/Cl ratios less than 0.5 and distinct groupings, with some springs on the north end of Whakarewarewa having higher Cl concentrations than the majority of the springs. These include S952 (Cl 1000 mg/l, HCO_3 120 mg/l) and Ororea (Cl 800 mg/l, HCO_3 200 mg/l), which appear to be transitional between Ngapuna and the main Whakarewarewa springs. The main group of springs has almost constant Cl (~560 mg/l) and variable HCO_3 (0-240 mg/l) concentrations, suggesting that the waters are all diluted to the same extent, but have different degrees of interaction (neutralisation) with rock. The springs with the lowest HCO_3 concentrations tend to be those with the highest sulphate concentrations (see Cl-HCO_3-SO_4 plot Figure 6), suggesting that they are affected by near-surface processes involving oxidation such as incursion of shallow groundwater.

The main Whakarewarewa springs have lower Cl/B ratios (~ 90) than S952 and Ororea (~123) showing that the former have been more strongly altered by rock-water interaction, see Figures 5 and 7.

Figure 7 also highlights the close relationship between S952 and the Ororea springs. These features are also in relatively close proximity (~200m) but less dilute (higher chloride) fluids are discharged from S952 which is not surprising given that this feature formed as a result of problems with a nearby bore. It is probable that the S952 is fed directly from the deeper aquifer. Since 1993, S952 fluids have shown a small increase in Na/K geothermometer temperatures (215°C between 1988 and 1993 compared to 222°C in 2002) and chloride (1024 to 1052 ppm). In contrast Ororea spring fluid chloride compositions have decreased since 1993 from 835 ppm to 746 ppm and sulphate increased from 52 to 256 ppm. That the deeper aquifer exemplified by S952 is not similarly affected suggests it only a question of time before the shallower Whakarewarewa features respond to increasing aquifer pressures. Recent gauging of the Puarenaga Stream suggested loss of water to groundwater aquifers and perhaps to the deeper geothermal aquifers (Gordon et al., 2001), but the composition and behaviour of S952 and Ororea Springs as well as other Eastern Whakarewarewa springs means that the continued dormancy of few springs and geysers in this area unlikely to be as a result of quenching at depth with cold groundwater.

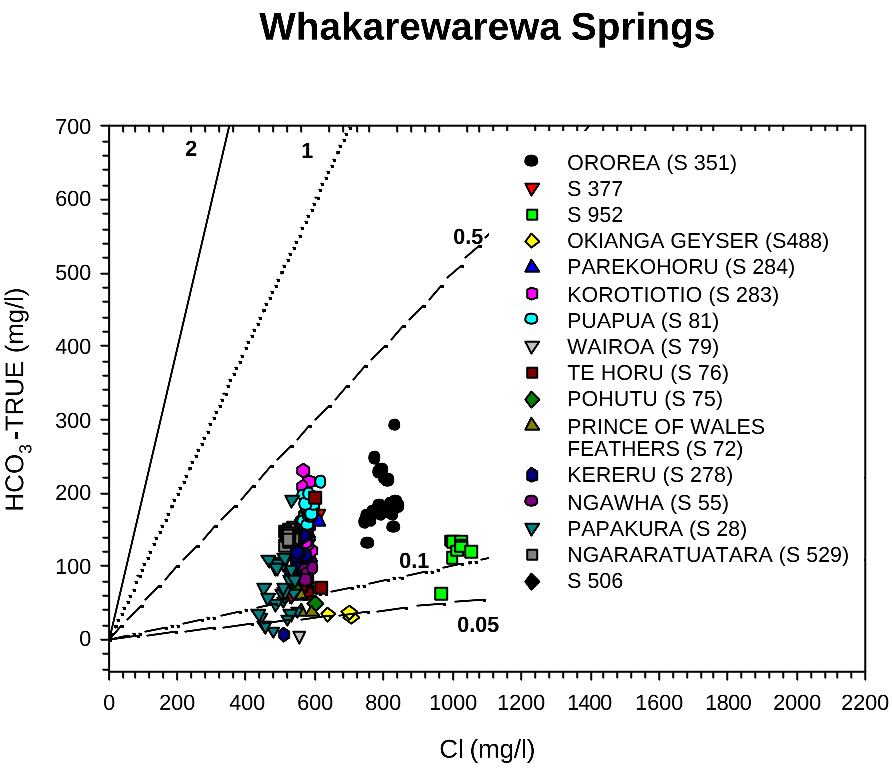


Figure 5. HCO_3 (true) versus Chloride – Whakarewarewa Springs.

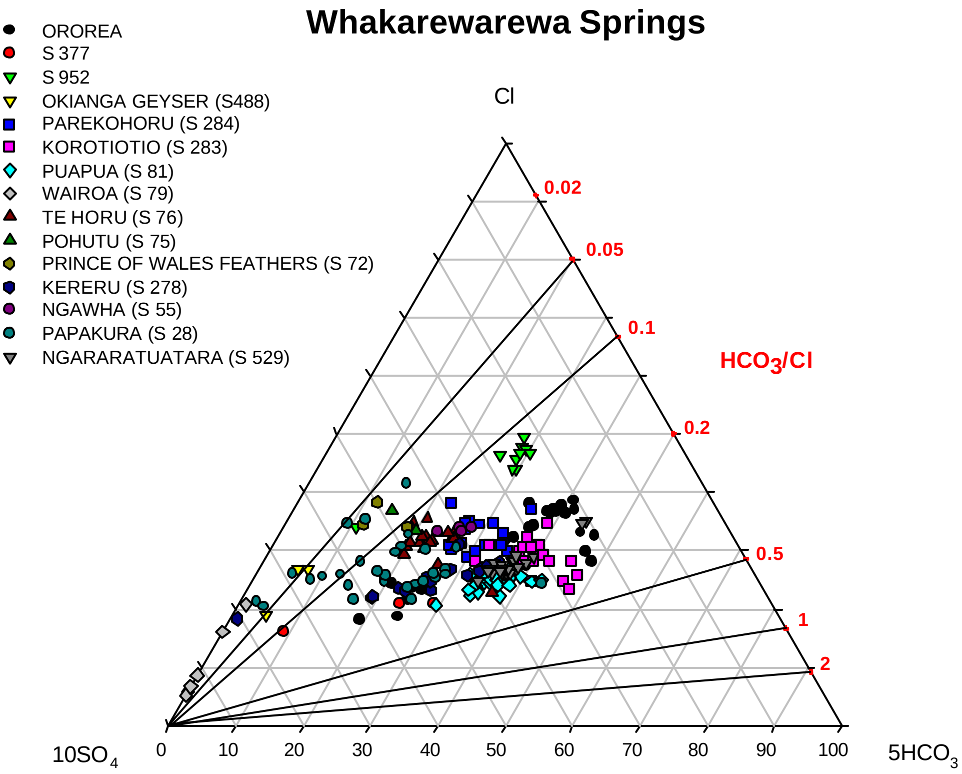


Figure 6. Relative HCO_3-Cl-SO_4 – Whakarewarewa Springs.

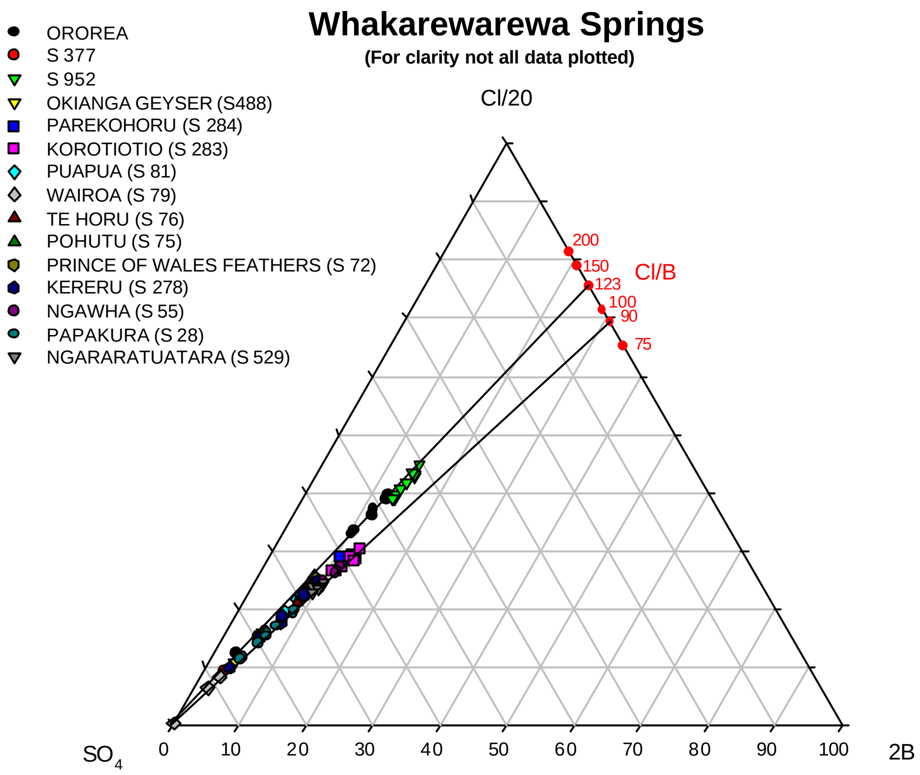


Figure 7. Relative B-Cl-SO_4 – Whakarewarewa Springs.

6.3 Kuirau-Ohinemutu

The Kuirau springs have variable HCO_3 (240-360 mg/l), nearly constant Cl (320 mg/l), and HCO_3/Cl ratios about 1 (Figures 8 and 9). Ohinemutu springs have lower HCO_3 (200 mg/l) with similar Cl, and HCO_3/Cl ratios of about 0.6. Samples from wells RR681 and 913 show similar patterns, in particular they have similar chloride concentrations. If the nearly constant Cl concentrations are not an artefact of limited sampling, they could indicate input of two waters with moderate and low HCO_3 respectively, but similar Cl concentrations; these would result from the same dilution, but different degrees of rock-water interaction. The Cl/B ratios of the Kuirau-Ohinemutu samples are all very similar (about 50) and markedly different from the Ngapuna samples (about 140), compare Figures 4 and 10.

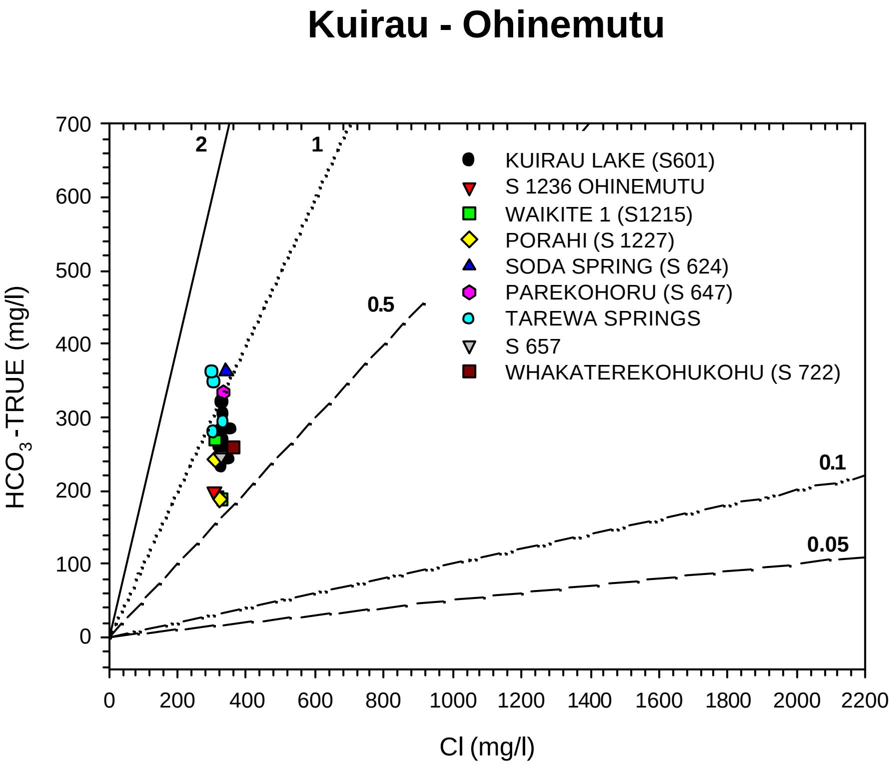


Figure 8. HCO_3 (true) versus Chloride – Kuirau – Ohinemutu Springs.

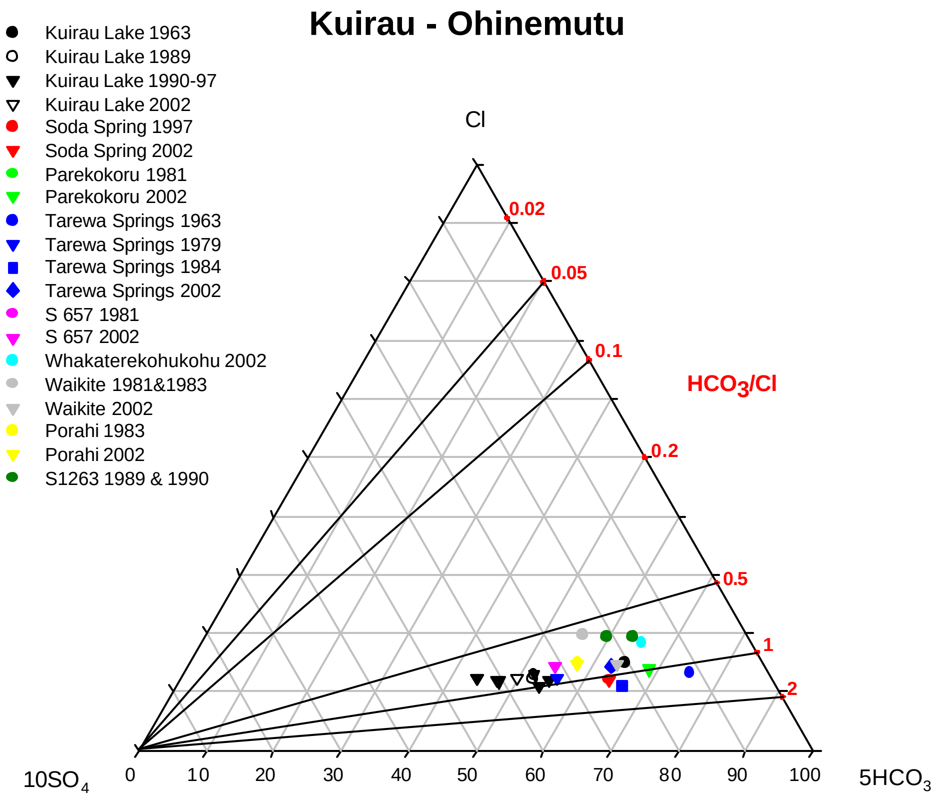


Figure 9. Relative HCO_3-Cl-SO_4 – Kuirau – Ohinemutu Springs.

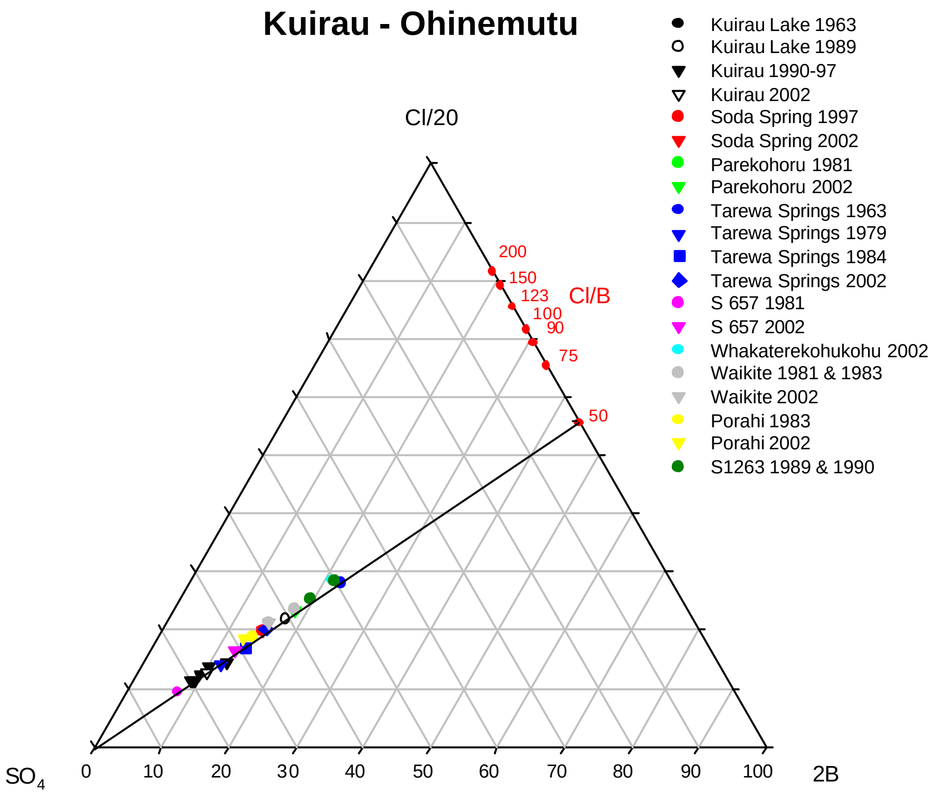


Figure 10. Relative B-Cl-SO_4 – Kuirau – Ohinemutu Springs.

6.4 Wells

Although the wells cover a wider area than the springs, the well waters were accessible only in areas outside of the Pohutu exclusion zone, so the numbers of samples were quite limited. The well results reinforce the results from the springs, with accessible wells in the Ngapuna-Government Gardens and Kuirau-Ohinemutu areas showing the same compositional variations as springs in the respective areas (Figures 11 to 13). At Ngapuna, wells RR889 and M25 have similar HCO_3/Cl ratios to Stopbank Spring (S1100), Hona Baths and spring S940, while at Government Gardens, wells RR885 and RR887 form a trend with Rachel Spring and Postmaster Baths (although the springs have higher HCO_3 and Cl concentrations). At Kuirau, RR681 and 913 have the same compositions as Kuirau Lake (S601), Soda Springs (S624), Parekohoru (S647), Tarewa Springs, S657 and S722. RR741, 627 and 865 are three wells in the mid-region near the saddle between the two buried Rhyolite domes (Wood, 1992), they have compositions like the Kuirau samples but containing higher Cl and HCO_3. The wells further south (near the northern edge of the Pohutu exclusion zone) have Cl and HCO_3 concentrations increasing eastwards across the southern Rhyolite dome. These are RR653, 825, 738, 816, 1016 and 638. RR638 was previously found to be transitional between the Ngapuna-type and Kuirau-type waters.

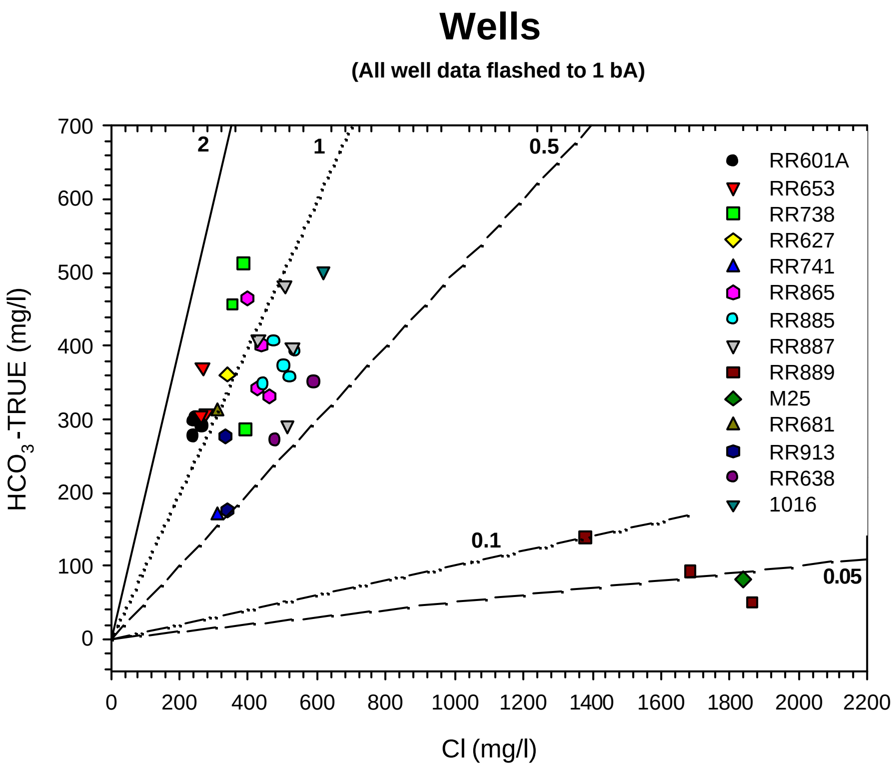


Figure 11. HCO$_3$ (true) versus Chloride - Wells.

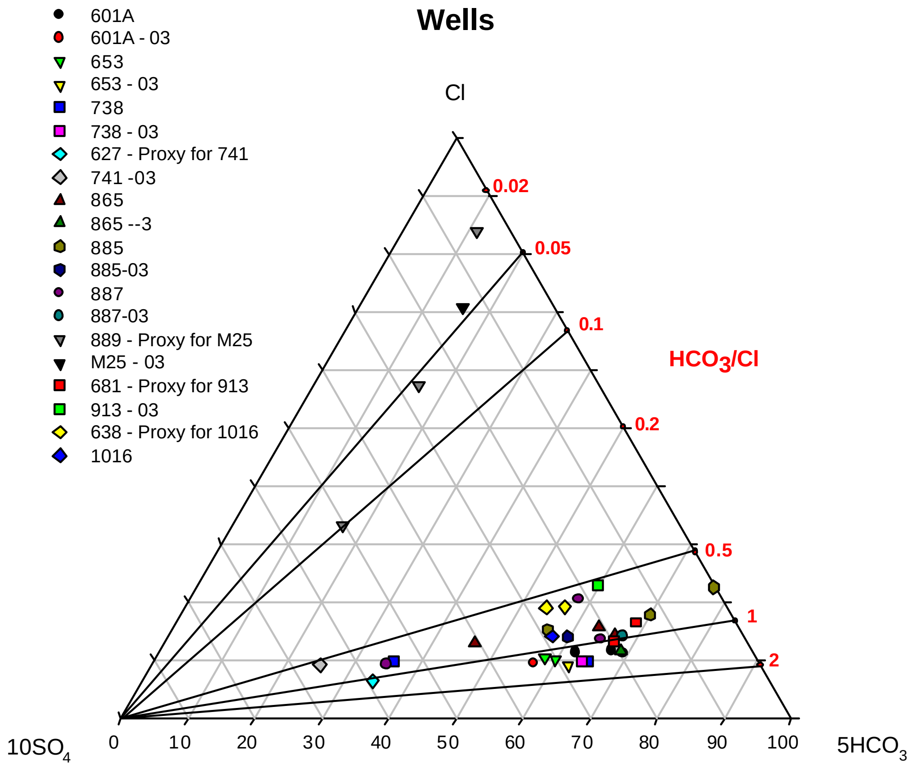


Figure 12. Relative HCO$_3$-Cl-SO$_4$ – Wells.

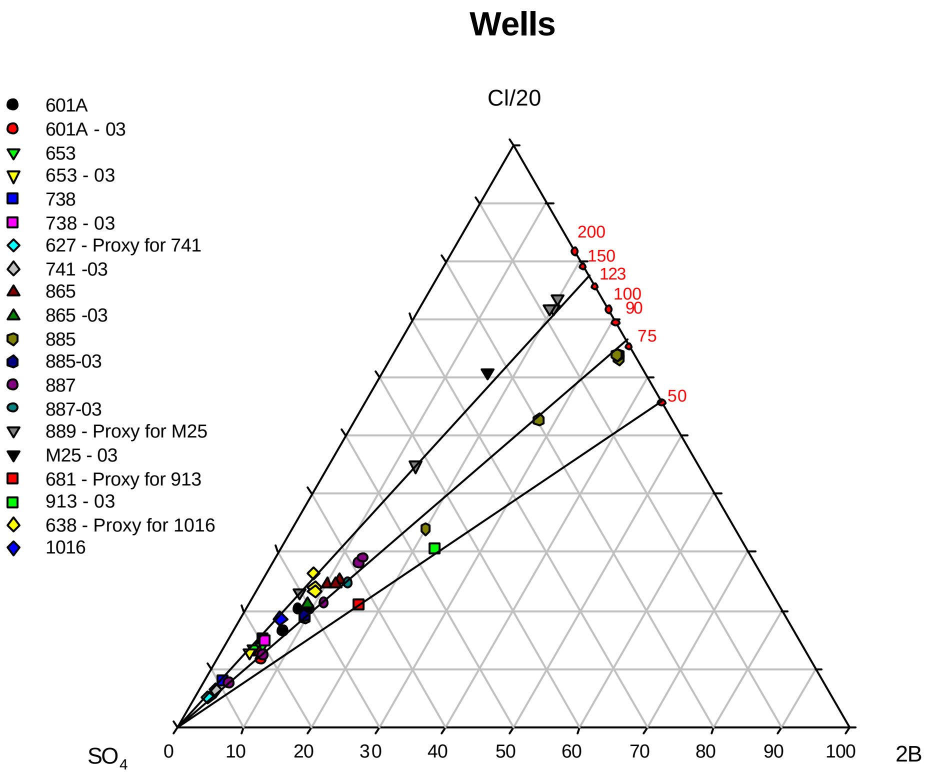


Figure 13. Relative B-Cl-SO_4 – Wells.

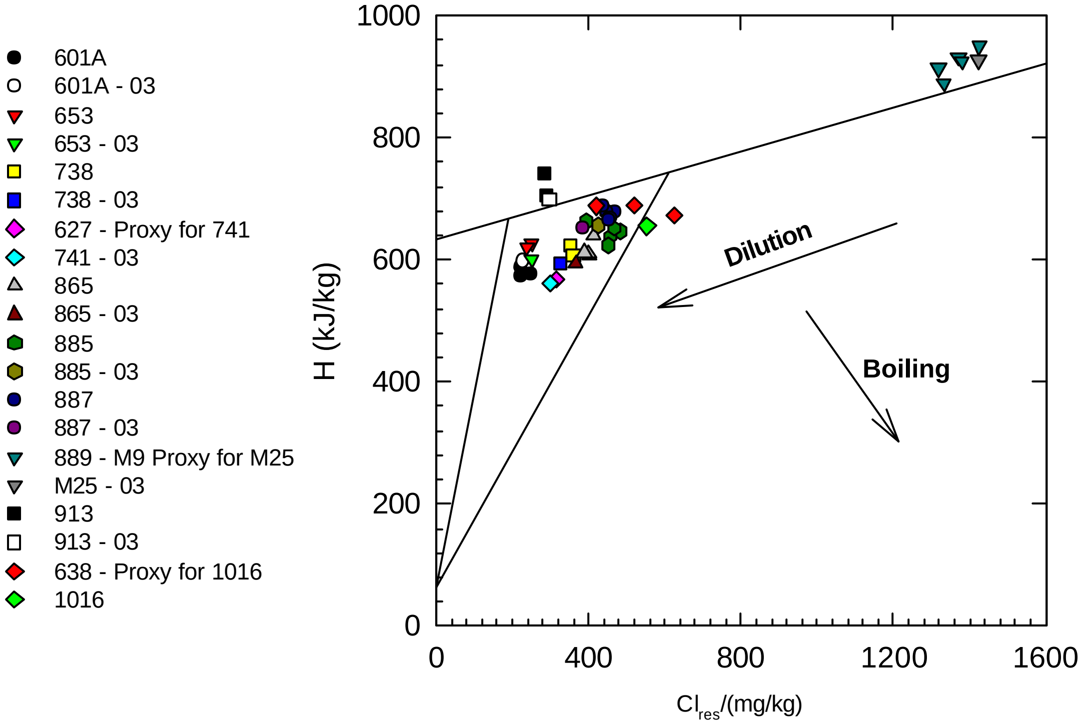


Figure 14. Chloride-Enthalpy diagram for the sampled and proxy wells.

6.5 Enthalpy – Chloride Correlations

The plot of chloride vs enthalpy for the unboiled fluids discharged by the wells is shown in Figure 14. There are two clusters of points, the high chloride – high enthalpy "parent" fluids represented by wells M25 and RR889 and the rest of the cooler diluted fluid sampled in the remaining wells. Although there are changes in the reservoir chloride and enthalpy, they are not large and the historical and recent data tend to plot in the same portions of the Chloride-Enthalpy diagram. This suggests that there is little change and no **substantial** cooling, reheating or dilution of the aquifers in the feed zones surrounding the wells. Nevertheless there are small decreases in both H and Cl_{res}, mainly in the West Rotorua wells. This may now the stable pattern with small "natural" fluctuations, further sampling may determine whether this is the case. Extrapolation to zero chloride of all historical data for wells with downhole temperatures close to the quartz/chalcedony silica geothermometer temperatures enabled Glover and Mroczek (1998) to determine the initial diluting fluid temperature to be 150°C.

6.6 Geothermometers

Figure 15 is the ternary K-Na-Mg ternary diagram used for evaluating Na-K and K-Mg geothermometer temperatures for well fluids. This figure clearly shows the high temperature of the M25/RR889 fluids, which lie on the full equilibrium line, separated from the remaining cooler fluids. Well RR 885, in Government Gardens also appears to be fully equilibrated but at lower temperatures. Close agreement can be expected between the fast and slower acting geothermometers if all fluids were at similar temperatures for long periods of time. However there are other effects that could cause an apparent change in geothermometer temperature include removal of Mg in clays and silica during boiling (Giggenbach and Glover, 1992).

The equations for the cation geothermometers are based on concentration ratios, so that neither boiling nor dilution (with low mineralized fluid) alters the derived temperature, despite affecting the absolute concentrations.

For many of the recently collected samples the derived K-Mg geothermometer temperatures are unchanged since the 1980s while the Na-K temperatures have increased by up to 16°C, indicative of an increase in source fluid temperatures in the deep aquifer.

Kuirau well RR913 has a higher Na/K geothermometer temperature than any of the other Western Bores and similarly higher silica (cristobalite) geothermometer temperatures (See Figure 14. The silica geothermometer reflects fluid aquifer temperatures close to the feedzones of the well while the Na/K geothermometer reflects the deeper source fluids temperatures. The present downhole temperature of RR913 is unknown.

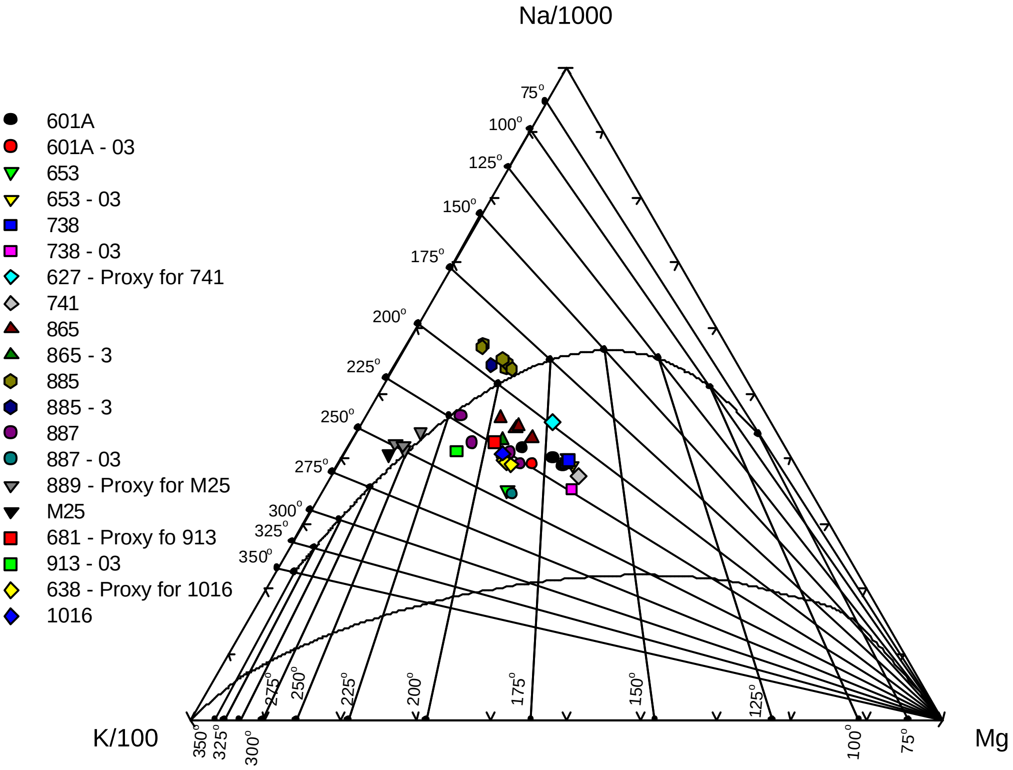


Figure 15. K-Na-Mg ternary diagram for evaluating Na-K (Giggenbach, 1991) and K-MG (Giggenbach, 1991) geothermometer temperatures.

Using spring compositions for evaluating changes in aquifer temperatures is more problematic than for wells due to possible re-equilibration of the geothermometer to lower temperatures or a switch to a controlling reaction which is not the one on which the geothermometer is based. Nevertheless the changes observed in the silica as well in Na/K geothermometers correlate well with other changes in compositions, particularly SO_4 and Cl. For example at Pohutu Geyser (S75) the silica geothermometer temperatures have increased since 1984 by 15-20°C to 183 or 226°C (depending whether cristobalite or quartz is assumed to be control the silica solubility) and by 7°C in the Na/K (Giggenbach, 1991) geothermometer temperature to 255°C. This has been accompanied by increase in chloride from 549 to 600 ppm with no change in sulphate. These trends signify discharge of a greater proportion of the deeper source fluids and less dilution with shallow low chloride fluids. Other springs with similar beneficial changes include Parekohoru (S284), Okianga Geyser (S488), Ngararatuatara (S529) and THC Blowout (S952); see Appendix B for a summary of results for all springs sampled in Part 1 if this study.

6.7 Gas compositions

In 2003 steam sampling was undertaken so that detailed gas analyses could be conducted. However the comparison of gas results is restricted due to the paucity of previous data. Giggenbach and Glover (1992) is the only published study to have interpreted the chemistry of the gas discharges and this was based on one limited data set collected in 1989. Based on the relative proportions of argon (Ar), nitrogen (N_2) and helium (He) Giggenbach and Glover (1992) identified three upflow zones; Kuirau Park, Ngapuna and Whakarewarewa. The gases most highly enriched in He were from Ngapuna. However well RR889 (M9) did not fit this pattern and was found to be in the group most depleted in He and containing a high proportion of atmospheric gases (see their Figure 7, Giggenbach and Glover; 1992). Figure 16 shows that the present M25 (replacement well for M9) value now plots well into the He enriched field, suggesting that the previous RR889 results was either in error or as suggested by Giggenbach and Glover subject to secondary exploitation induced processes.

To the North East very high He enrichment is also apparent, particularly RR885, which is similar to the Ngapuna features reported by Giggenbach and Glover (1992) but also in 1016 and RR887. Two previous samples exist for RR887, one very enriched in He and the other contaminated with air so perhaps this area was always enriched with He. Giggenbach and Glover (1992) sampled well RR877 ("Polynesian Pool"), but this sample is highly depleted in helium and plots near the relative proportions of air, unlike the 2003 sample from RR887 which lies 114 mE of RR877. In November 2004 further steam samples were collected from wells RR887 and RR913 and both show similar results to those observed in 2003.

There was also high relative enrichment in He for the Western bores that could be sampled could be collected. In particular 1016 and RR865 are more enriched in He than Kuirau or Whakarewarewa features but similar to Ngapuna, as reported by Giggenbach and Glover (1992). RR638, the proxy well for 1016, is less enriched but still lies in the same “Kuirau” region of the diagram as does RR738.

These data suggest that the “upflow” zones identified through enrichment of He relative to Ar and N_2 may cover a wider and more diffuse geographic area than identified previously. The mobility of steam means that gases respond much more quickly than fluids to field wide perturbations however the small number of wells available for sampling and a paucity of temporal data means that the conclusion is not certain.

Relative H_2S-CH_4-CO_2 composition was used by Giggenbach and Glover (1992) to show that fluids over the eastern part of the field are degassed with respect to methane (CH_4), this being due to boiling in the inferred upflow zone. Equilibration of the gases at high temperatures, which could also explain the relative loss of the sparingly soluble CH_4, was discounted as there was no shift observed towards the CO_2 apex of the diagram. H_2S is considerably more soluble than CO_2 so that boiling results in a relative decrease in CH_4 and an increase in H_2S. In contrast at Kuirau the fluids ascend without boiling and the gases remain relatively enriched in CH_4.

As shown in Figure 17, the present data fits in with the trends identified by Giggenbach and Glover (1992). The Kuirau samples from Wells RR913 and RR601A are relatively enriched in CH_4 (CO_2/CH_4 ˜ 50-100), while Ngapuna well M25 is depleted in CH_4 (CO_2/CH_4 ˜ 1000). Wells with intermediate ratio (CO_2/CH_4 ˜ 500), include the Western wells, RR885, RR738 and 1016 (and proxy 638) but all are variably enriched in H_2S, RR738 being highly enriched in H_2S. Samples for RR887 are the most depleted in CH_4 (CO_2/CH_4 ˜ 2500).

The relative enrichment of methane in the steam phase is a strong evidence for a deep upflow zone in the West, at Kuirau, separate from that at Whakarewarewa and Ngapuna.

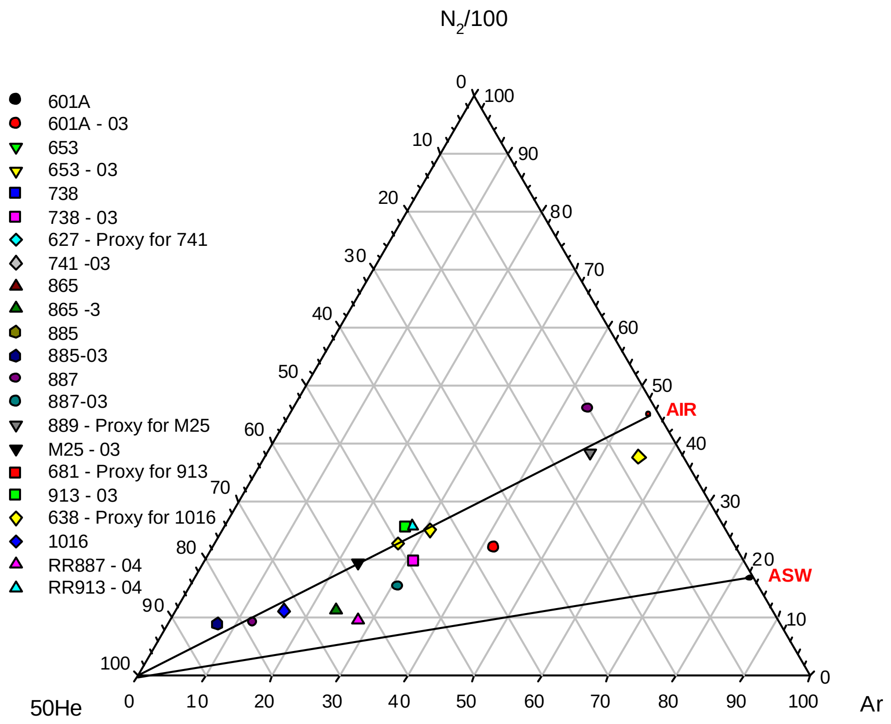


Figure 16. Ar-N_2-He ternary diagram; ASW – relative air saturated water composition, AIR – relative air composition.

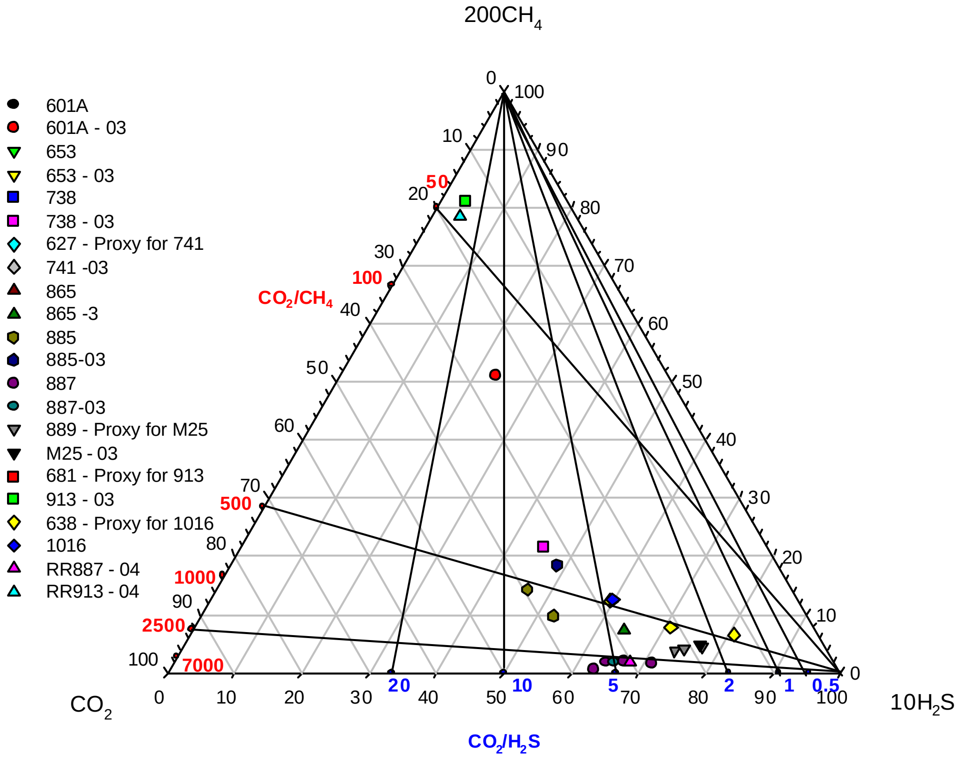


Figure 17. H_2S-CH_4-CO_2 ternary diagram.

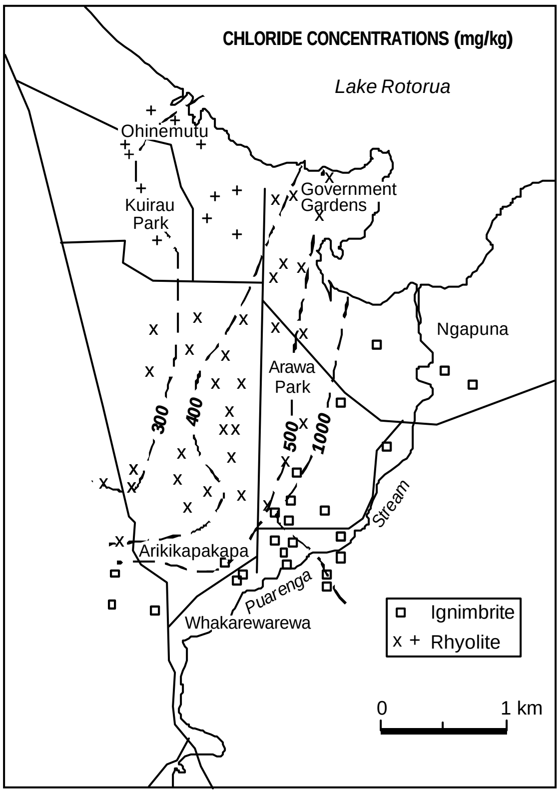
7.0 DISCUSSION

Giggenbach and Glover (1992) have established that two fundamental types of water are involved in the Rotorua Geothermal Field (Ngapuna and Kuirau-type waters). These are typically alkali-chloride waters as seen in many of the "rift" type geothermal fields on the west side of the Taupo Volcanic Zone (Wairakei, Mokai, etc.), and a more altered bicarbonate-chloride, water previously seen in bicarbonate-rich springs (Waikite). They also consider that both are derived from the same source at depth. The disposition of these waters as they approach the surface is controlled by the geological structure, the geohydrological properties of the rocks and the hydrological situation (Wood 1992, Stewart *et al*. 1992). The geological structure and material properties are not known below the drilled depth of 300 m.

Wood (1992) has described the geological structure with Mamaku Ignimbrite to the east stepping down beneath the Rotorua Rhyolite domes underneath Rotorua City, both covered by Rotorua Basin Sediments. The ignimbrite has high vesicularity and fracturing because of partial welding following its emplacement providing high permeability and porosity. In addition, fractures are likely to provide permeability at deeper levels. The rhyolite domes are brecciated and highly fractured in their upper 40 m, and massive and weakly fractured below. Hence permeability is better in the upper 40 m than below. The Kuirau Fault on the west side of the Pukeroa north rhyolite dome channels hot fluids upwards to the Kuirau and Ohinemutu areas, and there may also be permeability on the east side of the domes allowing passage of hot fluids. The Rotorua Basin sediments are a layered sequence of mixed primary and redeposited tephra, alluvium and lake sediments. The range of sediment types is wide, and permeability and porosity are dependent on the proportions of fine and coarse sediments. Sediments on the west side of the south rhyolite dome are comprised of predominantly coarse sands with relatively high permeability and porosity; those on the east side of the domes and overlying the north dome are mainly fine muddy sediments with poor permeability and porosity. Wood (1992) reports a temperature anomaly in the Kuirau area again supporting an upflow in this area.

The most striking comparison is between the Ngapuna and Government Gardens areas where the two types of water are seen in their most extreme forms within a short distance of each other. The highest chloride concentrations in alkali-chloride waters are resident in the ignimbrite below Ngapuna, and the most concentrated altered bicarbonate-chloride waters are within the east side of the north rhyolite dome beneath the Government Gardens area. Wood (1992) has shown that the water temperatures are high on the east and west sides of the north rhyolite dome and lower in the middle (by 50-60°C), clearly showing that the (altered bicarbonate-chloride) water is sourced independently on each side of the dome. The south dome, in contrast, has higher temperatures on the east side decreasing smoothly across the dome, showing that the water is sourced on the east side in this case. Colder water flows into the domes from the west side particularly in the saddle area between the domes, sourced from the coarse sediments on the west side of the domes, and possibly from deeper sources. The change in chloride and bicarbonate across the field is illustrated in Figure 18.

This analysis shows clearly that there are deep sources feeding altered bicarbonate-chloride water to both sides of the northern rhyolite dome and to the east side of the southern rhyolite dome. These waters are generated by dilution and cooling of the alkali-chloride water followed by prolonged interaction with rock at lower temperature. The waters are highly reactive because of their high dissolved CO_2 contents and the lower temperature. The question of how deep this occurs is difficult to answer without more information on the conditions at depth, but possibly 1-2 km depth is a reasonable estimate. The alkali chloride water at Ngapuna on the other hand is water that has had little or no dilution with groundwater and the waters are less reactive because of their lower dissolved CO_2 contents because of boiling as it rises.



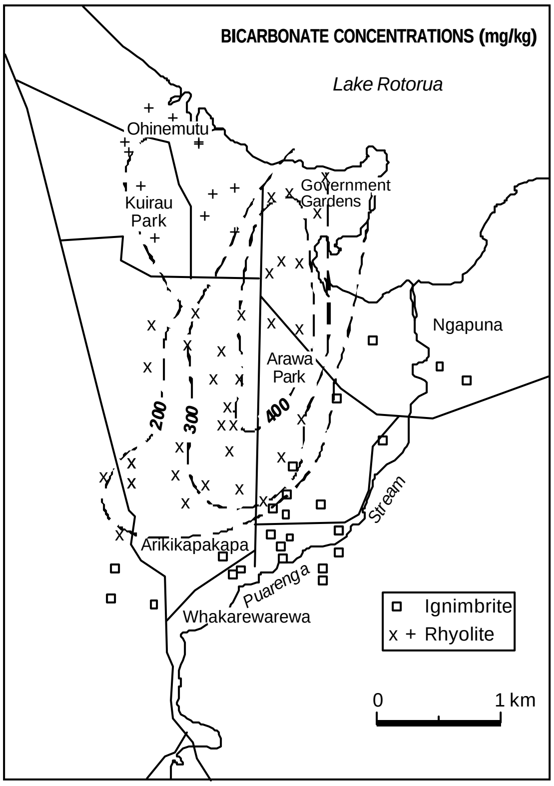


Figure 18. Contours of constant chloride and bicarbonate in water from geothermal wells. (after Stewart et al., 1992).

8.0 CONCLUSIONS

1. The chemical and isotopic evidence incorporating the historical and recent well and spring results supports previous work that indicates that at least two separate plumes make up the overall Rotorua system (Wood, 1992 and Giggenbach and Glover, 1992). The primary upflow is to the east of the Rhyolite Domes, and then subsequently flows Southeast to Whakarewarewa. The smaller separate upflow to the Kuirau area is chemically distinct, although the geological evidence (Wood, 1992) suggests that they are hydrologically connected. Excessive exploitation of one is likely to cause significant changes in the primary upflow that supplies Whakarewarewa (Giggenbach and Glover, 1992).

2. The chemical evidence shows that the fluids discharged in the northern area of the field at Kuirau Park now match those discharging in the early 1960s and it is probable that this part of the field is near full recovery.

3. The Wakarewarewa springs do not appear to be fed directly by a primary upflow and consequently the recovery has been mixed as the hydrology between the upflow and the surface outlets are influencing conditions. However recovery has been particularly notable at Parekohoru and Pohutu, but also evident for Okianga Geyser, Ngararatuatara and THC Blowout, with increases in aquifer (geothermometer) temperatures and a greater proportion of deep geothermal fluid being discharged.

4. The shallow aquifer feeding the wells over the last decade shows relatively minor changes in reservoir chloride and small increases in heat (~16^{o}C). This indicates stability and no deleterious processes are affecting the Rotorua Geothermal Field.

5. The initial bore closure programme and the subsequent Environment Bay of Plenty Regional Council’s operative resource management plan for the field appear to have achieved the key objective of reversing the deleterious changes to the geothermal reservoir and ensuring the continued recovery of the springs and geysers.

9.0 RECOMMENDATIONS

This study provides a baseline with which to compare future changes. Frequent chemical monitoring of the natural features and wells is unnecessary. However as is apparent the chemical and isotopic compositions are one of the most important indicators of the health of the geysers and springs and in general the hydrology of the geothermal system. At the present rate of fluid withdrawal the recommendation is to repeat the sampling and analysis of these features and wells in five and again in 10 years time, thereafter to be reviewed.

10.0 ACKNOWLEDGEMENTS

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APPENDIX A. DISCHARGING WELLS – CHEMICAL AND ISOTOPIC COMPOSITIONS

A.0 2003 WELL RESULTS

A.1 Summary

A chemical and isotopic survey of ten production wells over the Rotorua Geothermal Field was undertaken to collect a modern data set that could be used for comparison with historical data. The choice of suitable wells to sample was severely curtailed due to the implementation of the well closure programme. The locations of the ten sampled wells are listed in Table A1 and plotted in Figure A1. The analytical and derived data are listed in Tables A2 to A10.

The shallow aquifer feeding the wells over the last decade shows relatively minor changes in heat and reservoir chloride. This indicates stability and no deleterious processes are affecting the Rotorua Geothermal Field. Geothermometer temperatures of the deeper source waters appear to have increased typically by 16°C. Nevertheless three wells, two in Western Rotorua and one in Government Gardens show minor decreases in silica enthalpy and reservoir chloride which may due to natural variability. See Mroczek et al., 2002 for further detail.

A.2 Individual Well Commentary

A.2.1 Kuirau - Ohinemutu

RR601A

This well is located immediately south of Kuirau Park near the western side of the Rotorua Field. The well is 173 m deep, cased to 134 m with a maximum temperature of 153°C. There has been a small increase in Cl_{res} and H over the last decade but the fluids are still slightly more dilute than in 1983. Na-K and K-Mg geothermometers temperatures have increased slightly, about 10°C. There is no increase in HCO_3 relative to B and Cl and a small increase in sulphate.

RR913

Well RR913 is located within Kuirau, being drilled to 146.5 m (cased 121 m) with a maximum downhole temperature of 152.5°C. There has been small increase in Cl_{res} compared to samples collected in 1986 and there is essentially no change in H. This well used to alternate as a reinjection/production well for the Aquatic Centre but there appears not to have been any significant cooling effect on the aquifer. There are no previous RR913 samples with K analyses, but in the present sample temperatures are higher by about 16°C than the nearby proxy well RR681 sampled in 1984. The Cl/HCO_3 ratio has halved (2.2 to 1.2) compared to a RR913 sample collected in 1986 (not included in the plots as B missing). The Cl/HCO_3 ratio in the proxy well RR681 is about 1.

Little change in the conservative components suggest that the shallow aquifer is similar to that present in the 1980s, expect there is an indication of higher temperature source fluids.

A.2.2 Government Gardens

RR885

Well RR885 is located in the northern part of the Gardens, near Rachel Spring. It is drilled to 112 m, cased to 68 m. The maximum downhole temperature is 161°C. The 2003 samples are essentially similar in composition to samples collected in 1984-1990. There is some variability, in Cl_{res}, e.g. higher by 30 mg/L than in 1990 but lower by 20 mg/L than in the sample collected in 1989. Only a very small increase in cation geothermometer temperatures (5°C). There is also a small increase in relative amounts of HCO_3 and Cl with respect to B. Compared to the sample collected in 1990, there is an increase in sulphate but the sample is very similar to that collected in 1989.

RR887

This well is located to the southeast, near the lake and Sulphur Bay. It is drilled to 107 m, being cased to 96 m with a maximum temperature of 149°C. There is only a slight decrease in H, but a significant decrease in Cl_{res} compared to samples collected in 1984-89. The difference between the Na-K and K-Mg is instructive in the light of this apparent dilution. The K-Mg geothermometer is essentially unchanged from previous samples, at 185°C for the present analysis, but the Na-K geothermometer has increased by about 14°C to 244°C. Thus although the shallow hydrology may have changed with increased dilution, the deep fluid fraction appears to be hotter. The relative proportions of Cl-B-SO_4 are similar to samples collected in 1984-89 but the present sample contains more bicarbonate.

A new sample was collected in November 2004. Preliminary results indicate an increase in both silica (277 to 292 mg/L) and chloride concentrations (386 to 400 mg/L).

A.2.3 Ngapuna

_M25_

M25 is the replacement well for RR889 (M9) being drilled and cased to 245 m, with a maximum downhole temperature of 211°C. Giggenbach and Glover (1992) suggested that all Rotorua waters could be derived from one high chloride parent water with a composition close to that tapped by RR889. Ignoring one “anomalous” high chloride weirbox sample, there has been a small progressive increase in Cl_{res} since 1983 from 1318 mg/L to 1424 mg/L in 2003 but no change in H. Na-K and K-Mg temperatures are essentially unchanged from previous RR889 values (6°C higher). There now appears to be slightly less bicarbonate in the fluids and slightly more sulphate, but these changes are probably well within the natural variations.

A.2.4 West Rotorua

_RR653_

This well on the southwestern boundary of the Rotorua Field is drilled to 131 m, and cased to 100 m. A maximum downhole temperature of 141°C is recorded. A small decrease in H (equivalent to 4-7°C) is observed but no change in Cl_{res} since the 1989 sample. Na-K and K-Mg temperatures are lower than measured in 1990 but similar to 1989. The present sample has similar relative proportions of B-Cl-HCO_3 and B-Cl-SO_4 as previous data.

_RR738_

RR738 is drilled in the central southern part of the field where the rhyolite domes dominate the subsurface geology. A small decrease in H (equivalent to 3°C) and also in Cl_{res} (33 mg/L) is recorded. As in RR887 where there was also a decrease in Cl_{res}, the Na-K temperature has increased by 13°C while K-Mg is essentially unchanged. The relative amount of HCO_3 has also decreased. The absolute concentration of sulphate (92 mg/L) is lower than for the sample collected in 1990 (211 mg/L) but about the same as in 1989.

RR741

Well RR741 is drilled to 130 m, being cased to 104.4 m. A maximum downhole temperature of 123°C has been recorded. This well is located in the central area of the rhyolite aquifer. Both the H and Cl_{res} (16 mg/L lower) are similar as the nearby proxy well RR627 sampled in 1984. Na-K temperatures are higher by 16°C, while K-Mg are similar. The relative proportion of HCO_3 is much lower than in RR627.

RR865

This well is drilled to 105 m (cased to 89.5) with a maximum recorded downhole temperature of 130°C. It is in the central area of the rhyolite aquifers. There is a small decrease in H (equivalent to 3°C) and also in Cl_{res} (23 mg/L), compared to previous samples. Na-K temperature is higher by 11°C and K-Mg is similar to previous values. The relative amount of HCO_3 is lower compared to previous values.

1016

Well 1016 is drilled to 120 m (cased to 91 m) with a maximum downhole temperature of 135°C. Well 1016 is slightly cooler than the nearby proxy well RR638 (~ 8°C) but is less dilute. The Cl_{res} of 130 mg/L is higher than the RR638 samples collected in 1990, but only 22 mg/L higher than in 1989. Cation geothermometer temperatures are similar to RR638. This fluid contains much higher bicarbonate than the nearby proxy well RR638, but a similar proportion of sulphate. Large swings in concentration such as between the 1989 and 1990 samples observed in RR638 (and others discussed above) may reflect local exploitation induced effects.

A.3 Isotopic analyses

The isotopic concentrations are expressed as d values with respect to a water standard (V-SMOW), i.e. $d^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{SMOW} - 1] \times 1000$. d^2H is defined similarly.

A.3.1 Kuirau Park

Two bores were sampled in the Kuirau Park area. Well RR601A was sampled in July 1983 and Sep 1989, as well as in Jan 2003. The isotopic composition shows very little change over this time (Table A10). No earlier measurements are available for well RR913, but nearby bores (RR619 and 681) showed similar compositions although cooler water in the 1980s. The Kuirau bores continue the observed pattern of relatively dilute chloride-bicarbonate waters for the area, with temperatures perhaps related to proximity to an upflow.

A.3.2 Government Gardens

Bores RR885 and 887 are in the high bicarbonate (Government Gardens) region. RR885 has slightly more positive d values than RR680 (sampled in 1989), but the bores have similar temperatures and chloride/bicarbonate concentrations. RR887 was sampled in the 1980s and 2003. The 2003 and 1984 samples are similar, but the 1989 sample again has more negative d values.

A.3.3 Ngapuna

M25 is in the Ngapuna area, and is compared with the previously sampled nearby well M9. Both tapped high chloride water, representing the least diluted water in the field. This is the only well from the east and south group that was sampled in 2003. M25 has slightly higher $d^{18}O$ and chloride, but it is not possible to say if this represents a significant change in time, or simply reflects stable dilution patterns in the area. The latter is more likely.

A.3.4 West Rotorua

Five bores were sampled in this area in 2003. The bores (RR653, 738, 741, 865 and 1016) have increasing $d^{18}O$ values, and chloride and bicarbonate concentrations, in this order. Compared with their selected comparison bores, they have similar isotopic and chloride concentrations, but higher bicarbonate concentrations. This would suggests a trend of increasing bicarbonate concentrations in the area, meaning less dilution is occurring of the waters generated deeper in the system by reaction of dissolved CO_2 with rock. However comparison against previously sampled wells, not the isotope proxy wells and reducing the data to atmospheric pressure shows, that for most wells the relative concentrations of bicarbonate are either similar or slightly lower (relative to Cl and B). There is no previous data to compare with well for 1016 where indeed the HCO_3 is much higher than the nearby proxy well. High bicarbonate implies entry of less groundwater from shallow levels from the south (Stewart et al. 1992 demonstrated shallow groundwater entry in this area in the 1980s based on elevated tritium and sulphate concentrations in the waters).

Figure A1. Location map of wells sampled and proxy wells; compiled by Gareth Evans (Environment Bay of Plenty).

Table A1. Location of sampled and proxy wells.

Well Number	Easting	Northing	Location	Cased, m	Drilled, m	Max T, ^{o}C	Enthalpy, kJ/kg	T (Enth), ^{o}C	T(Sil), ^{o}C	T(Sil), ^{o}C
									sampled	**proxy**
West Rotorua										
653	2794180	6333600	330 Old Taupo Rd	100	131	140	560	133	143	
825 (proxy for 653)	*2794297*	*6333681*	*64 Devon St*	*117.4*	*120.4*					*152*
738	2794720	6334070	46 Holland St	96.8	134	121			141	
816 (proxy for 738)	*2795063*	*6334088*	*19 Holland St*	*78*	*116.2*	*155*	*593*	*141*		*147*
741	2794880	6334920	Acacia Lodge Motel, 40 Victoria St	104.4	129.93	123			134	
627 (proxy for 741)	*2794954*	*6334861*	*7 Union St*	*94.5*	*124.9*					*135*
865	2795100	6334650	22 Malfroy Rd	98.5	105	130			141	
1016	2795350	6334060	288 Fenton St (adjacent to the Racecourse)	91	120	135			155	
638 (proxy for 1016)	*2795634*	*6334068*	*Rotorua Race Course, Fenton St*	*101.5*	*133*	*166*	*700*	*165*		*163*
Government Gardens										
885	2795560	6335790	Princes Gate Hotel	68	112.23	161	680	160	156	
680 (proxy for 885)	*2795645*	*6336028*	*QE Hospital*	*92*	*135.9*		*670*	*159*		*145*
887	2795720	6335330	Government Gardens	96.21	107.66	149			154	
Kuirau Park										
601A	2794570	6335500	131 Hinemoa St	137.7	173.7	153			142	
913	2794510	6335890	Aquatic Centre	121	146.5	152.5	865	203	166	
681 (proxy for 913)	*2794348*	*6335915*	*Kuirau Park*	*120*	*200*					*147*
619 (proxy for 913)	*2794267*	*6336405*	*96 Lake Rd (1 Tawera Rd)*	*56.5*	*195.1*					*114*
Ngapuna										
M25	2796178	6334563	Treatment Station	245	245	211			216	
889 (proxy for M25)	*2796178*	*6334580*	*Treatment Station*	*234.5*	*248*	*216*	*912*	*213*		*216*

Table A2. Separated water chemical analyses of wells sampled in January and March 2003.

Laboratory Reference No		**2300016**	**2300017**	**2300018**	**2300019**	**2300020**	**2300483**	**2300484**	**2300485**	**2300519**	**2300520**
Collection Date		**8/01/03**	**8/01/03**	**7/01/03**	**8/01/03**	**8/01/03**	**18/03/03**	**18/03/03**	**18/03/03**	**20/03/03**	**20/03/03**
Well No.		**RR653**	**RR887**	**RR865**	**RR913**	**RR738**	**RR885**	**1016**	**RR741**	**M25**	**RR601A**
Bicarbonate (total)	mg/l	371	600	471	210	413	457	543	170	117	308
pH		8.42	7.88	8.35	9.06	7.96	8.63	7.77	7.44	7.58	8.44
Analysis temperature	°C	21	21	22	22	22	22	23	23	20	20
HCO_3/Date Analysed		9/1/03	9/1/03	9/1/03	9/1/03	9/1/03	19/3/03	19/3/03	19/3/03	21/3/03	21/3/03
Boron	mg/l	2.3	5.2	4.1	5.7	3.2	5.4	4.7	3.0	9.9	3.7
Calcium	mg/l	10.4	9.9	3.3	0.83	14.9	0.89	17.0	12.4	16.7	4.9
Chloride	mg/l	267	386	383	304	345	439	581	310	1516	242
Lithium	mg/l	1.5	3.6	2.6	3.0	1.8	2.5	2.5	1.9	2.6	1.6
Magnesium	mg/l	0.07	0.14	0.05	0.011	0.15	0.015	0.09	0.12	0.02	0.04
Potassium	mg/l	25	58	41	31	37	31	54	31	125	27
Silica (as SiO_2)	mg/l	253	277	243	325	245	290	293	218	343	249
Sodium	mg/l	328	504	473	289	413	514	577	389	950	302
Sulphate	mg/l	86	49	64	23	92	83	118	222	29	87
Sulphide (total as H_2S)	mg/l	43	190	141	14.2	111	110	154	41	95	44
H_2S/Date Analysed		9/1/03	9/1/03	9/1/03	9/1/03	9/1/03	19/3/03	19/3/03	19/3/03	21/3/03	21/3/03
Deuterium	$^o/_{oo}$	-36.3	-35.8	-36.2	-37.7	-36.2	-35.3	-34.8	-36.8	-36.2	-38.3
Oxygen 18	$^o/_{oo}$	-5.3	-4.9	-5.0	-5.5	-5.1	-4.6	-4.7	-5.2	-3.1	-5.7
Separation Pressure	bg	0.4	4	0.93	4.25	0.6	2.55	1.85	0.65	11.5	0.55

Table A3. Separated steam chemical analyses of wells sampled in January and March 2003.

Laboratory Reference No **Collection Date** **Well No.**		**2300012‡** **8/01/03** **RR887**	**2300013‡** **7/01/03** **RR 865**	**2300014‡** **8/01/03** **RR 913**	**2300015‡** **8/01/03** **RR738**
Carbon Dioxide	mmol/100 mol	1236	1637	826	6795
Hydrogen sulphide	mmol/100 mol	248	367	20	921
Ammonia	mmol/100 mol	0.44	0.46	0.42	0.59
Argon	mmol/100 mol	0.03	0.11	0.31	1.88
Helium	mmol/100 mol	<0.001	0.006	0.011	0.06
Hydrogen	mmol/100 mol	4.0	17.1	1.5	78
Methane	mmol/100 mol	0.33	2.1	22	22
Nitrogen	mmol/100 mol	1.5	5.2	30	121
Oxygen	mmol/100 mol	<0.001	<0.001	<0.001	<0.001
Separation Pressure	bg	4	0.93	4.25	0.6

Table A3 continued.

Laboratory Reference No **Collection Date** **Well No.**		**2300481** **18/03/03** **RR885**	**2300482** **18/03/03** **1016**	**2300517** **20/03/03** **M25**	**2300518** **20/03/03** **RR601A**
Carbon Dioxide	mmol/100 mol	781	1711	405	1027
Hydrogen sulphide	mmol/100 mol	115	371	167	93
Ammonia	mmol/100 mol	0.43	0.40	0.41	0.34
Argon	mmol/100 mol	0.03	0.11	0.06	0.58
Helium	mmol/100 mol	0.007	0.01	0.003	0.010
Hydrogen	mmol/100 mol	12.7	22	7.4	5.4
Methane	mmol/100 mol	2.2	3.9	0.51	10.2
Nitrogen	mmol/100 mol	3.8	7.8	5.1	31
Oxygen	mmol/100 mol	<0.001	<0.001	<0.001	<0.001
Separation Pressure	bg	2.55	1.85	11.5	0.55

‡ The gas concentrations for these samples as reported by Mroczek et al. (2003) were in error.

Table A4. Well discharge water compositions for sampled and proxy wells.

Well No	Sample No	Date	WHP, g	Enthalpy, kJ/gm	SP, bg	CT °C	mg/L													
							TA	pH	Li	Na	K	Ca	Mg	Rb	Cs	Cl	SO4	B	SiO2	HCO3	H2Sd
RR601A	5503	21/07/83	0.3					9.05	1.4	309	26	4.5	0.03	0.24	0.2	267	62	3.1	235	291	
RR601A	6724/8/A	25/09/89	0.175			98.2	20	9	1.4	313	25	5.1	0.06	0.21	0.2	240	43	2.4	246	277	50
RR601A	6786/27/A	22/05/90	0.25			98.1	17	8.7	1.4	315	25	6	0.05	0.2	0.12	240	42	2.9	234	297	59
RR601A	2300520	20/03/03			0.55		20	8.44	1.6	302	27	4.9	0.04			242	87	3.7	249	308	44
RR653	6724/29/A	04/10/89	0.7			98.7	16	9.2	1.5	353	26	9.4	0.07	0.21	0.25	277	84	2.4	283	308	37
RR653	6786/24/A	22/05/90	0.7			99.1	19	9.2	1.4	349	40	9.4	0.06	0.19	0.18	262	77	2.7	277	306	38
RR653	2300016	08/01/03			0.4		21	8.42	1.5	328	25	10.4	0.07			267	86	2.3	253	371	43
RR738	6724/21/A	02/10/89	0.8			98.7	17	9.2	1.8	467	36	14	0.13	0.31	0.32	385	100	3.2	280	512	72
RR738	6786/9/A	14/05/90	0.75			98.4	20	9	1.8	452	34	13	0.12	0.29	0.27	393	219	3.4	263	287	68
RR738	2300020	08/01/03			0.6		22	7.96	1.8	413	37	14.9	0.15			345	92	3.2	245	413	111
RR627	5740/A	08/05/84				99	19	9.2	1.95	439	28	9.5	0.06	0.25	0.27	338	311	3.5	230	361	87
RR741	2300485	18/03/03			0.65		23	7.44	1.9	389	31	12.4	0.12			310	222	3.0	218	170	41
RR865	5762/A	04/05/84	1.6			99		9.35	2.52	542	41.5	2	0.09	0.33	0.34	460	146	5.1	297	332	102
RR865	5986/A	11/02/85	1.7			100	NA	NA	2.6	504	38.9	2.3	0.04	0.3	0.3	437	55	<5	265	NA	NA
RR865	6724/31/A	05/10/89	1.7			97.6	20	9.5	2.5	519	40	2.6	0.06	0.32	0.34	437	58	4.4	267	401	114
RR865	6786/28/A	22/05/90	1.6			98.8	18	9.2	2.6	518	39	2.8	0.06	0.3	0.26	426	56	4.9	269	342	132
RR865	2300018	07/01/03			0.93		22	8.35	2.6	473	41	3.3	0.05			383	64	4.1	243	471	141
RR885	5822/1/A	13/06/84				96.3	22	9.31	3.09	561	31.5	1.6	0.01	0.28	0.45	536	10	7	303	393	NA
RR885	5822/1/B	13/06/84	2.75	627	2.1			8.86	2.79	504	29	1.4	0.02	0.25	0.38	474	<1	6.4	275	465	111
RR885	5822/2/A	13/06/84				93.8	22	8.94	3.12	560	32	1.4	0.01	0.28	0.46	522	1	6.9	308	357	NA
RR885	5822/2/B	13/06/84	2.25	627	0.75			9.15	2.89	519	29	1.6	0.02	0.26	0.38	480	<1	6.3	271	472	93
RR885	6724/24/A	02/10/89	2.9			99.8	18	9.5	3	584	33	1.4	0.03	0.27	0.45	503	96	6.4	338	372	61
RR885	6786/21/A	21/05/90	3			98.8	17	9.4	2.9	555	31	1.5	0.02	0.25	0.36	444	30	6.5	321	348	81

Table A4. Continued.

Well No	Sample No	Date	WHP, bg	Enthalpy, kJ/gm	SP, bg	CT, °C	mg/L														
							TA	pH	Li	Na	K	Ca	Mg	Rb	Cs	Cl	SO4	B	SiO2	HCO3	H2Sd
RR885	2300483	18/03/03			2.55		22	8.63	2.5	514	31	0.89	0.015			439	83	5.4	290	457	110
RR887	5767/A	07/05/84	4			99		9.58	2.89	622	54.5	1.4	0.03	0.39	0.41	529	316	7.3	337	398	104
RR887	6004/A	22/02/85	2.8			99	24	9.38	2.87	558	52	2	0.12	0.4	0.4	506	81	6.8	337	482	115
RR887	6004/B	22/02/85	2.8		2.8		24	8.65	2.6	518	47	2	0.08	0.4	0.4	457	151	6.2	320	511	144
RR887	6724/11/A	25/09/89	3.65			99.3	23	9.5	3	576	56	1.4	0.05	0.4	0.43	514	54	6	325	292	119
RR887	6724/11/B	25/09/89	3.65		3.65		20	8.6	2.6	528	50	1.4	0.08	0.36	0.39	461	46	5.3	293	461	164
RR887	2300017	08/01/03			4		21	7.88	3.6	504	58	9.9	0.14			386	49	5.2	277	600	190
RR889	5442/2	02/06/83	10.7	913	10.7		19	7.2	2.8	905	112	15.7	0.03	0.87	0.5	1403	8	9.8	331	99	4.7
RR889	5768/A	08/05/84	6			99		9.32	3.26	1138	123	17.6	0.05	0.99	0.57	1684	79	12.3	368	93	21
RR889	6724/13/A	27/09/89	11			100	19	9.6	3.6	1190	145	19	0.03	1.18	0.74	1865	11	12.7	448	50	21
RR889	6724/13/B	27/09/89	11		6.25		19	8.6	3	986	119	17	0.03	0.95	0.61	1542	7	10.5	368	62	81
RR889	6800/1/D	13/06/90	4.05				18	5.8	2.78	844	106	24.4	0.19	0.84	0.34	1379	210	9.8	320	138	85
M25	2300519	20/03/03			11.5		20	7.58	2.6	950	125	16.7	0.02			1516	29	9.9	343	117	95
RR681	5744/A	07/05/84	2			99	22	9.24	3.62	384	34.5	0.8	0.03	0.33	0.38	310	46	6.1	275	310	7
RR913	6171/A	15/10/85	4.9													332					
RR913	6305/A	27/05/86	6			99	19	9.5	4.21	369		<1	0.02	0.33	0.39	332	30		395	276	6
RR913	6305/B	27/05/86	6		2.6		19	9.4	3.83	335		<1	0.022	0.3	0.34	307	28		383	275	8
RR913	6306/B	27/05/86	5.6		3.5		19	9.3	3.79	338		1.6	0.035	0.18	0.15	301	37		334	273	10
RR913	2300019	08/01/03			4.25		22	9.06		289	31	0.83	0.011			304	23	5.7	325	210	14.2
RR638	6724/12/A	26/09/89	3.2			99.7	23	9.5	2	570	55	18	0.1	0.39	0.37	593	75	4	350	350	86
RR638	6786/31/A	23/05/90	3.4			99	18	9.5	1.9	525	51	18	0.09	0.36	0.26	479	68	4.3	348	271	112
RR638	6786/31/B	23/05/90	3.4		3.4		18	7.8	1.7	475	46	16	0.08	0.33	0.23	431	63	4.1	316	399	158
1016	2300484	18/03/03			1.85		23	7.77	2.5	577	54	17.0	0.09			581	118	4.7	293	543	154

Table A5. Well discharge steam compositions for sampled and proxy wells.

Well No	Sample No	Date	WHP, bg	Enthalpy, kJ/kg	SP, bg	mmol/100 mol								
						CO_2	H_2S	H_2	He	N_2	Ar	NH_3	CH_4	O_2
RR601A	2300518	20/03/03			0.55	1027	93	5.4	0.01	31	0.58	0.34	10.2	<0.001
RR738	2300015‡	08/01/03			0.60	6795	921	78	0.06	121	1.88	0.59	22	<0.001
RR865	2300013‡	07/01/03			0.93	1637	367	17.1	0.006	5.2	0.11	0.46	2.1	<0.001
RR885	5822/1/S	13/06/84	2.75	627	2.1	770	91	9.2		2.1		0.52	1.4	
RR885	5822/2/S	13/06/84	2.25	627	0.75	481	67	4.4		1.9		0.45	0.62	
RR885	2300481	18/03/03			2.55	781	115	12.7	0.007	3.8	0.03	0.43	2.2	<0.001
RR887	6004/S	22/02/85	2.8		2.8	1738	300	2.6		0.65		0.81	0.097	
RR887	6724/11/S	25/09/89	3.65		3.7	1095	207	3.05	0.0034	2.01	0.0271		0.269	0.006
RR887	6786/18/S	21/05/90	1.9		1.9	18354	4810	70	0.047	346			5.1	4.7
RR887	6786/18/SA	21/05/90	0.4		0.4	2150	460	9	0.006	77			0.62	
RR887	2300012‡	08/01/03			4.0	1236	248	4	0.001	1.5	0.03	0.44	0.33	<0.001
RR889	5442/2	02/06/83	10.7	913	10.7	1168	377	13.3		11.7			0.93	
RR889	6724/13/S	27/09/89	11		6.25	200	70	3.9		146	1.68		0.191	12.2
M25	2300517	20/03/03			11.5	405	167	7.4	0.003	5.1	0.06	0.41	0.51	<0.001
RR913	6305/S	27/05/86	6		2.6	235	6.4					0.28		
RR913	2300014‡	08/01/03			4.9	826	20	1.5	0.011	30	0.31	0.42	22	<0.001
RR638	6724/12/S	26/09/89	3.2		3.2	560	359	9.4	0.0101	23.2	0.275		1.43	
RR638	6786/312/s	23/05/90	3.5		3.4	2670	570	40	0.028	80	0.98		5.9	
1016	2300482	18/03/03			1.85	1711	371	22	0.01	7.8	0.11	0.4	3.9	<0.001

‡ The gas concentrations for these samples as reported by Mroczek et al. (2003) were in error.

Table A6. Well discharge steam compositions for sampled and proxy wells, concentration per mole dry gas. Xg is the gas fraction in steam.

Well No	Sample No	Date	WHP, bg	Enthalpy, kJ/kg	SP, bg	Xg mmol /mol	mmol/ mol								
							CO2	H2S	H2	He	N2	Ar	NH3	CH4	O2
2300518	RR601A	20/03/03			0.55	11.7	880	80	4.6	0.0086	27	0.50	0.29	8.7	<0.0009
2300015‡	RR738	08/01/03			0.60	79.4	856	116	9.8	0.0076	15.2	0.24		2.8	<0.0001
2300013‡	RR865	07/01/03			0.93	20.3	807	181	8.4	0.0030	2.56	0.05	0.23	1.04	<0.0005
5822/1/S	RR885	13/06/84	2.75	627	2.1	8.7	881	104	10.5		2.4		0.59	1.6	
5822/2/S	RR885	13/06/84	2.25	627	0.75	5.6	866	121	7.9		3.4		0.81	1.1	
2300481	RR885	18/03/03			2.55	9.2	853	126	13.9	0.0076	4.2	0.03	0.47	2.4	<0.0011
	RR887	*†				280	785	58	76.4	0.0033	75	0.71	0.02	4.7	
6004/S	RR887	22/02/85	2.8		2.8	20.4	851	147	1.3		0.32		0.40	0.05	
6724/11/S	RR887	25/09/89	3.65		3.7	13.1	838	158	2.3	0.0026	1.5	0.02		0.21	0.005
6786/18/S	RR887	21/05/90	1.9		1.9	236	778	204	3.0	0.0020	15			0.22	0.199
6786/18/SA	RR887	21/05/90	0.4		0.4	27.0	797	171	3.3	0.0022	29			0.23	
2300012‡	RR887	08/01/03			4.0	14.9	829	166	2.7	<0.0007	1.01	0.02	0.30	0.22	<0.0007
	RR889	*				2.2	630	268	11.9	0.0062	88	1.1	0.85	0.78	
5442/2	RR889	02/06/83	10.7	913	10.7	15.7	744	240	8.5		7.4			0.59	
6724/13/S	RR889	27/09/89	11		6.25	4.3	461	161	9.0		232	2.63		0.44	0.0**
2300517	M25	20/03/03			11.5	5.9	692	285	12.6	0.0051	8.7	0.10	0.70	0.87	<0.0017
6305/S	RR913	27/05/86	6		2.6										
2300014‡	RR913	08/01/03			4.9	9.0	918	22	1.7	0.0122	33	0.34	0.47	24	<0.0011
	RR638	*				0.9	607	201	2.9	0.0065	184	2.7	0.42	1.1	
6724/12/S	RR638	26/09/89	3.2		3.2	9.5	587	377	9.9	0.0106	24	0.29		1.5	
6786/312/s	RR638	23/05/90	3.5		3.4	33.7	793	169	11.9	0.0083	24	0.29		1.8	
2300482	1016	18/03/03			1.85	21.2	809	175	10.4	0.0047	3.7	0.05	0.19	1.8	<0.0005

* From Giggenbach and Glover (1992). Sampled between 1989-90. These samples correspond to the 6727 series of water and gas samples. It is not known whether Giggenbach and Glover (1992) samples were analyses at Wairakei but there are significant differences in what was reported by them and the internal GNS records.

† This sample corresponds to 6724/11/S and appears to be an outlier and is excluded from all plots

* * Air Corrected

‡ The gas concentrations for these samples as reported by Mroczek et al. (2003) were in error.

Table A7. Well discharge water compositions for proxy wells only.

Well No	Sample No	Date	WHP, bg	Enthalpy, kJ/gm	SP, bg	CT °C	mg/L													
							TA	pH	Li	Na	K	Ca	Mg	Rb	Cs	Cl	SO4	B	SiO2	HCO3	H2Sd
RR619	5515	21/07/83				81.5		7.15	0.9	175	12	10.2	0.06	0.13	0.23	160	30	3.1	155	212	
RR619	6724/9/A	25/09/89				76.2	21	7.8	1	189	15	10	0.07	0.13	0.25	156	34	3.1	162	225	<1
RR619	6786/3/A	14/05/90				64	19	7.71	1.1	185	14	10	0.2	0.12	0.2	159	33	3.3	157	228	<1
RR638	5740/1/A	04/05/84	3.25					9.6	2.25	681	55	9.6	0.06	0.42	0.39	704	103	5.9	332	251	66
RR638	6724/12/A	26/09/89	3.2			99.7	23	9.5	2	570	55	18	0.1	0.39	0.37	593	75	4	350	350	86
RR638	6786/31/A	23/05/90	3.4			99	18	9.5	1.9	525	51	18	0.09	0.36	0.26	479	68	4.3	348	271	112
RR638	6786/31/B	23/05/90	3.4		3.4		18	7.8	1.7	475	46	16	0.08	0.33	0.23	431	63	4.1	316	399	158
RR680	6724/17/A	28/09/89	3.6			100.5	22	9.5	3.1	572	40	1.5	0.04	0.3	0.46	540	25	6.9	314	361	48
RR680	6724/17/B	28/09/89	3.6		3.6		22	8.4	2.7	498	34	1.6	0.04	0.26	0.39	469	29	5.9	280	338	106
RR680	6786/15/A	18/05/90	0.6			98.8	17	8.8	2.6	483	31	8.5	0.33	0.23	0.33	499	20	6	266	379	68
RR680	6786/15/B	18/05/90	1.45		1.45		16	8	2.4	473	31	7.5	0.31	0.24	0.3	499	18	5.8	255	344	91
RR681	5744/A	07/05/84	2			99	22	9.24	3.62	384	34.5	0.8	0.03	0.33	0.38	310	46	6.1	275	310	7
RR816	5509/1	21/07/83	1.45					9.35	2.2	513	46	4.8	0.14	0.34	0.31	432	87	4.1	275	405	
RR825	5752/A	07/05/84	0.85			99	22	9.26	1.66	391	27.5	2.2	0.03	0.24	0.28	274	135	2.7	296	281	36

Table A8. Geothermometer temperatures and reservoir Chloride (Cl$_{res}$).

Well No	Sample No	Date	Tsil, ^{o}C *	H, kJ/gm	Cl$_{res}$, mg/L	Na-K (Arnórsson), ^{o}C	Na-K (Giggenbach), ^{o}C	K-Mg, ^{o}C
rr601A	5503	21/07/83	137	575	248	187	219	184
RR601A	6724/8/A	25/09/89	140	587	222	183	215	169
RR601A	6786/27/A	22/05/90	136	574	223	182	215	172
RR601A	2300520	20/03/03	142	597	228	192	224	180
RR653	6724/29/A	04/10/89	149	627	251	176	209	167
RR653	6786/24/A	22/05/90	147	621	238	214	243	187
RR653	2300016	08/01/03	143	600	250	179	212	166
RR738	6724/21/A	02/10/89	148	624	350	180	212	168
RR738	6786/9/A	14/05/90	144	606	360	178	211	167
RR738	2300020	08/01/03	141	593	327	192	224	166
RR627	5740/A	08/05/84	135	569	315	166	199	173
RR741	2300485	18/03/03	134	562	298	183	215	164
RR865	5762/A	04/05/84	152	641	415	179	212	181
RR865	5986/A	11/02/85	144	608	400	180	212	195
RR865	6724/31/A	05/10/89	145	610	400	180	212	187
RR865	6786/28/A	22/05/90	145	612	389	178	211	186
RR865	2300018	07/01/03	141	594	367	189	221	192
RR885	5822/1/A	13/06/84	153	646	482	157	190	217
RR885	5822/1/B	13/06/84	151	638	458	158	192	197
RR885	5822/2/A	13/06/84	154	651	468	158	191	217
RR885	5822/2/B	13/06/84	148	623	450	156	190	197
RR885	6724/24/A	02/10/89	161	679	445	157	191	194
RR885	6786/21/A	21/05/90	157	664	396	156	190	200
RR885	2300483	18/03/03	156	657	425	162	195	207
RR887	5767/A	07/05/84	161	678	468	190	222	217
RR887	6004/A	22/02/85	161	678	448	195	227	184
RR887	6004/B	22/02/85	163	688	438	193	225	188
RR887	6724/11/A	25/09/89	158	667	457	199	230	206
RR887	6724/11/B	25/09/89	158	666	453	197	228	191
RR887	2300017	08/01/03	154	651	384	214	244	185
RR889	5442/2	02/06/83	214	914	1318	221	250	253
RR889	5768/A	08/05/84	208	890	1332	209	239	245
RR889	6724/13/A	27/09/89	221	950	1425	220	249	268
RR889	6724/13/B	27/09/89	218	933	1370	219	248	257
RR889	6800/1/D	13/06/90	216		1379	223	251	
M25	2300519	20/03/03	216	927	1424	227	255	271
RR681	5744/A	07/05/84	147	619	282	192	224	196
RR913	6305/A	27/05/86	172	727	286			
RR913	6305/B	27/05/86	175	743	285			
RR913	6306/B	27/05/86	167	705	289			
RR913	2300019	08/01/03	166	700	296	208	238	214
RR638	6724/12/A	26/09/89	163	690	522	198	229	190
RR638	6786/31/A	23/05/90	163	688	422	199	230	189
RR638	6786/31/B	23/05/90	163	687	417	199	230	187
RR1016	2300484	18/03/03	155	655	554	196	227	192

* Cristobalite for all wells except for wells RR889 and M25 where quartz is the controlling polymorph.

Table A9. Relative HCO_3-Cl-B. All 2003 data reduced to atmospheric pressure.

Well No	Sample No	Date	Cl, mg/L	B, mg/L	HCO_3,mg/L	HCO3%	Cl%	50B%
5503	rr601A	21/07/83	267	3.1	291	40.8	37.4	21.7
6724/8/A	RR601A	25/09/89	240	2.4	277	43.5	37.7	18.8
6786/27/A	RR601A	22/05/90	240	2.9	297	43.5	35.2	21.3
2300520	RR601A	20/03/03	248.3	3.8	300.9	40.7	33.6	25.7
6724/29/A	RR653	04/10/89	277	2.4	308	43.7	39.3	17.0
6786/24/A	RR653	22/05/90	262	2.7	306	43.5	37.3	19.2
2300016	RR653	08/01/03	267	2.3	371	49.3	35.5	15.3
6724/21/A	RR738	02/10/89	385	3.2	512	48.4	36.4	15.1
6786/9/A	RR738	14/05/90	393	3.4	287	33.8	46.2	20.0
2300020‡	RR738	08/01/03	354	3.28	457	46.9	36.3	16.8
5740/A	RR627	08/05/84	338	3.5	361	41.3	38.7	20.0
2300485	RR741	18/03/03	310	3	170	27.0	49.2	23.8
5762/A	RR865	04/05/84	460	5.1	332	31.7	43.9	24.4
6724/31/A	RR865	05/10/89	437	4.4	401	37.9	41.3	20.8
6786/28/A	RR865	22/05/90	426	4.9	342	33.8	42.1	24.2
2300018‡	RR865	07/01/03	397	4.26	465	43.3	36.9	19.8
5822/1/A	RR885	13/06/84	536	7	393	30.7	41.9	27.4
5822/2/A	RR885	13/06/84	522	6.9	357	29.2	42.6	28.2
6724/24/A	RR885	02/10/89	503	6.4	372	31.1	42.1	26.8
6786/21/A	RR885	21/05/90	444	6.5	348	31.2	39.7	29.1
2300483	RR885	18/03/03	475.1	5.84	406.2	34.6	40.5	24.9
5767/A	RR887	07/05/84	529	7.3	398	30.8	40.9	28.3
6004/A	RR887	22/02/85	506	6.8	482	36.3	38.1	25.6
6724/11/A	RR887	25/09/89	514	6	292	26.4	46.5	27.1
2300017‡	RR887	08/01/03	428	5.8	409	36.3	38.0	25.7
5768/A	RR889	08/05/84	1684	12.3	93	3.9	70.4	25.7
6724/13/A	RR889	27/09/89	1865	12.7	50	2.0	73.1	24.9
6800/1/D	RR889	13/06/90	1379	9.8	138	6.9	68.7	24.4
2300519	M25	20/03/03	1837	12	81.45	3.2	72.9	23.8
5744/A	RR681	07/05/84	310	6.1	310	33.5	33.5	33.0
6305/A	RR913	27/05/86	332		276	45.4	54.6	0.0
2300019‡	RR913	08/01/03	339	6.35	176	21.1	40.7	38.1
6724/12/A	RR638	26/09/89	593	4	350	30.6	51.9	17.5
6786/31/A	RR638	23/05/90	479	4.3	271	28.1	49.6	22.3
2300484	RR1016	18/03/03	618	5.01	501.9	36.6	45.1	18.3

‡ The HCO_3 concentrations were corrected as the corresponding steam concentrations for these samples as reported by Mroczek et al. (2003) were in error.

Table A10. Isotopic measurements for geothermal bores sampled in 2003 and historical data.

Well No	Date	T(Sil), °C	‰		mg/L		
			d^{18}O	d^{2}H	Cl	HCO$_3$	SO$_4$
601A	Jul-83	135	-5.92	-39.0	250	291	62
601A	Sep-89	140	-5.88	-39.3	222	297	43
601A	Jan-03	142	-5.98	-39.7	228	315	89
825*	May-84	150	-5.68	-38.4	248	281	135
653	Jan-03	143	-5.6	-37.8	250	378	88
816*	Jul-83	150	-5.25	-37.7	391	405	87
738	Jan-03	141	-5.35	-37.4	327	424	94
627*	May-84	134	-5.56	-37.4	317	--	311
741	Jan-03	134	-5.37	-37.8	299	175	228
865	May-84	151	-5.19	-39.1	416	332	146
865	Feb-85	143	-5.30	-38.9	402	--	55
865	Jan-03	141	-5.19	-37.1	367	488	66
680*	Sep-89	157	-4.97	-38.7	461	494	20
885	Jan-03	156	-4.73	-35.8	423	493	90
887	May-84	159	-4.87	-36.7	471	398	31
887	Sep-89	158	-5.35	-39.2	454	292	54
887	Jan-03	154	-4.92	-35.9	384	664	54
619*	Jul-83	111	-5.89	-38.6	157	212	30
619*	Sep-89	110	-6.25	-39.0	146	225	34
681*	May-84	145	-5.01	-35.4	284	310	46
913	Jan-03	166	-5.6	-38.1	296	233	26
638*	May-84	158	-4.88	-36.7	627	251	103
638*	Sep-89	161	-5.03	-38.7	523	350	75
1016	Jan-03	155	-4.89	-35.6	554	156	125
M9*	Aug-83	213	-3.53	-37.8	1378	--	--
M9*	May-84	205	-3.45	-37.4	1344	93	78
M9*	Sep-89	218	-3.46	-36.2	1372	62	11
M25	Jan-03	216	-3.27	-36.6	1427	141	35

*Proxy well.

APPENDIX B. NATURAL FEATURES - CHEMICAL AND ISOTOPIC COMPOSITIONS

B.0 2002 NATURAL FEATURE RESULTS

B.1 Summary

B.1.1 Whakarewarewa

In the Whakarewarewa area features show a range of chemical and isotopic changes with apparently no consistency to geographical location or spring type. These changes range from continuing decline or no recovery to stable or recovery with aquifer re-heating. These changes are discussed in detail in Mroczek et al., 2003.

In summary, the features can be grouped as:

- **Stable** – Kereru, Korotiotio (but slight increase in SO_4),
- **Declining or dominantly acid chloride fluids** - Papakura, Wairoa, Waikite Geyser, Ororea,
- **Minor recovery** - Ngawharua (increase in Cl but also SO_4), Prince of Wales Feathers, Te Horu, Puapua,
- **Significant recovery** - Parekohoru (less dilute fluids), Pohutu – substantial heating of the shallow aquifer indicated by the increase in dissolved silica and the composition (Cl and Na/K) now appears to be similar to fluids discharged in 1937,
- **Possible increase in temperature of the deeper water component** - Okianga Geyser, Ngararatuatara (small), THC Blowout (especially).

The isotope analysis indicates that Ngawharua, Korotiotio, Ororea and Ngararatuatara fluids have an increase of steam heating, whereas Prince of Wales Feathers and Pohutu geysers have a greater input of “boiled” (i.e. bicarbonate-poor) deep water. Puapua and Parekohoru springs have a greater input of “diluted” (bicarbonate-rich) deep water, and Okianga Geyser is fed by deep water, which is now more dilute. Kereru shows no change and springs S506 and THC Blowout have no previous data.

B.1.2 Ohinemutu - Kuirau Park

In the Kuirau Park area all features sampled are springs which have recommenced overflowing (i.e. recovering or recovered). It is probable that fluids discharged from features like the J C Fountain area, Soda Springs and Tarewa Springs are typical of fluid discharged in the early 1960s and perhaps prior to exploitation. In the Ohinemutu area there has been little change over the last 20 years. The fluids discharged closely match those now being discharged at Kuirau Park, but the deeper aquifer fluids are cooler relative to the Kuirau aquifer.

B.1.3 Ngapuna and Government Gardens

In the Government Gardens, Rachel spring is similar in composition to that measured a decade ago. The springs in the Ngapuna area generally show a decline in the portion of deep fluid with dilution and an increase in sulphate. The isotopic compositions also indicate more dilution with steam heated water which may explain the continued decline in S940 and the Stopbank spring. The Postmaster's spring and Hamiora Baths compositions indicate dilution and cooling at depth. The springs in Ngapuna have substantially reheated (Gordon et al., 2001) with increased outflows so it is puzzling why this is not reflected in the chemistry. Lack of sufficient temporal data may be the reason and the compositions may in fact reflect a reversal in decline.

B.2 Individual Natural Feature Commentary

B.2.1 Whakarewarewa Springs

Papakura geyser (S28)

Historically always active until March 1979 when boiling and geysering stopped. Thereafter, water levels and temperatures declined and this feature shows no recovery. The relative proportion of SO_4 with respect to Cl and B has increased progressively since 1960s, as the temperature and pH have declined. The apparently low geothermometer temperature of 150°C based on the Mg-Na-K plot is likely to be incorrect (too low) due to an anomalous high magnesium value for the sample collected in 1997. Similarly the extraordinarily high relative concentration of Ca for a sample collected in 1980 is due to incorrect Ca analysis that possibly could be a typographical error in the original data tables. Hence these values are excluded in this discussion.

Ngawharua spring (S55)

There is essentially no change in the fluids discharged by this spring since the 1980's when the first detailed sampling was made. The latest samples have slightly more absolute Cl and SiO_2 but also more SO_4. The higher Mg suggests equilibration at a lower temperature which is at odds with the observed increase in SiO_2 of 13 ppm, just over the likely uncertainty in the analysis (±5%). Use of silica concentrations to calculate geothermometer temperature in hot-spring fluids must be interpreted with caution due to the unknown fraction of steam separation during boiling and conductive cooling and possible deposition.

Prince of Wales Feathers geyser (S72)

Data from this sampling show there is little change between the 1991 and 1997 samples. No data are available pre-1991 to examine longer trends. There is slightly more Cl and relatively more K, perhaps indicative of deeper hotter fluid feeding this geyser, but no increase in SiO_2.

Pohutu geyser (S75)

There is only one sample with full analyses collected in 1984 that can be compared to the present sample. The relative proportions are similar but there has been a significant increase in absolute concentration of Cl, 549 to 600 ppm and particularly SiO_2, increasing from 374 to 462 ppm. This represents a change from $207^{o}C$ to $226^{o}C$ in the chalcedony/quartz geothermometer (assuming maximum steam loss), which is a substantial increase. The chemistry of Pohutu is now very similar to Prince of Wales Feathers, suggesting similar fluids feed both geysers. Cody (1998) pointed out that features on Geyser Flat (Pohutu, Te Horu, Waikorohihi and Mahanga) previously all had similar waters based on dye tracing experiments by Lloyd (1975). Analyses compiled by Glover (1967), as well as data for the 1984 and 2002 samples are given in Table B1. Increasing Cl relative to SO_4 and decreasing Na/K compared to 1984 all indicate deeper-sourced fluids are being erupted by Pohutu. Pohutu now discharges a fluid with compositions comparable to that recorded by Grange in 1937 (as reported by Glover, 1967).

Table B1. Analyses of water from Pohutu Geyser, 1937-2002.

Year	Na	K	Cl	SO_4	SiO_2	Na/K	Cl/B	Cl/SO_4
	mg/l							
1937	466	65	600	106	439	7.1		5.6
1955	412	70	579			5.9	108	
1961	485	58.5	560	88	490	8.2	105	6.3
1984	462	56	549	76	374	8.3	102	7.2
2002*	463	61	600	79	462	7.6	115	7.6

* In Mroczek et al. (2002) the results for K and SO_4 were incorrect in this table.

Te Horu (S76)

The composition of these waters is now very similar to Pohutu and compared to the early 1990s data samples, there have been increases in Cl, cations and silica. The temperature is low (53.7^{o}C) and Gordon et al., (2001) suggest this feature is receiving discharge fluids from Pohutu, which is supported by these results.

Wairoa geyser (S79)

This geyser has not erupted naturally since 1940, however human induced eruptions did occur during 1958-59. In 1982 the fluid was an acid-chloride mixture of deep and steam heated waters, SO_4 (450 ppm), pH 3, and Cl (442 ppm). In 1987 there was dramatic reversal coincident with local earthquakes, resulting in an inflow of alkaline-chloride fluids (Glover, 1993; Cody, 1998a). This was not sustained and the fluid is now substantially more acidic than the previous sample collected in 1997; SO_4 up from 325 to 1903 ppm, Cl down from 451 to 108 ppm and pH down from 3.4 to 1.7.

Puapua spring (S81)

The relative proportion of SO_4 has decreased suggesting a greater portion of high chloride deep water is present. In absolute terms the SO_4 concentration is similar to that measured in the early 90's but the Cl and cation concentrations have increased. There is no change in SiO_2. The Cl at 619 ppm is now higher than any sample back to the first collected in 1969 (554 ppm).

Waikite geyser (S130)

Historically this was the highest discharging feature at Whakarewarewa. Eruptions ceased in 1967 and the vent remained dry until the early 1990s when a collapse allowed fluids to return into the vent. The first sample from this feature was collected in 1996 (Cody, 1998) and was shown to be acid sulphate fluid, pH 2.3 and SO_4 1760 ppm. The latest sample shows a reduction in SO_4 to 1180 ppm but still negligible chloride at 1.5 ppm that indicates it is still essentially steam heated water.

Kereru geyser (S278)

Eruptions recommenced at this geyser in 1988, which were the first in over 16 years. The latest sample is very similar to that collected in 1993 which at that time was more concentrated than the average (Glover, 1993).

Korotiotio spring (S283)

This spring ceased reliable overflow into the Oil Baths in 1978. Since 1996 water levels have gradually risen but overflow has not been established. Between 1982 and 1993 this feature had stable chemistry and the latest sample is very similar to that collected in 1993. However there has been a slight increase in SO_4, from 59 ppm to 68 ppm and a drop in silica from 350 ppm to 325 ppm. These are relatively minor changes but do suggest less deep geothermal aquifer fluid is present in this spring. Glover (1967) reports a 1878 analysis of 585 ppm Cl and 72 ppm SO_4. This compares with the 2002 sample of 571 ppm Cl and 68 ppm SO_4.

Parekohoru spring (S284)

Historically this pool has always overflowed but during the winter of 1986 several cessations occurred. By the late 1990s strong overflows and boiling surges were again occurring. Glover (1993) noted that this feature has displayed stable compositions between 1969 and 1993. The 2002 sample shows compositional changes very similar to those observed at Puapua (over 250 m away). There is little change in SO_4 and SiO_2 but there are significant increases in absolute concentrations of Cl (561 pm to 610 ppm), Na, K and HCO_3, that all exceed previous values but the relative proportions do not differ greatly. This is indicative of higher chloride, deeper aquifer fluid reaching the surface now and is consistent with recent increases in spring activity.

Ororea springs (S351, S352)

This group of springs have shown variable activity since the 1930s when they were used to supply the Ward Baths in Rotorua city. This was discontinued after cessation and eruptions between 1938 and 1943. Activity recommenced in 1982 and boiling overflows continued until 1996. Water levels and temperatures are now low, similar to those during a period of low activity (65-85^{o}C) between 1983 and 1986 with reduced chloride and increased sulphate. Between 1987 and 1993 the composition of the Ororea S351 fluids was stable and less dilute than prior to 1987 (Glover, 1993). The latest sample (Ororea S352) is similar to those collected during the 1983-86 low activity period. The change in absolute concentrations since 1993 has been large, Cl decreasing from 835 ppm to 746 ppm and sulphate increasing from 52 ppm to 256 ppm.

Spring 377

This is one of several springs along the western side of Lake Roto-a-Tamaheke, which showed recovery in the 1980s, however in March 2001 boiling and overflowing stopped. In 1983 this spring was a near neutral chloride-sulphate spring (Cl 613 ppm, SO_4 147 ppm) spring at 98^{o}C. The latest sample shows a decline in temperature to 70^{o}C with increasing dilution with steam heated fluids with SO_4 increasing to 250 ppm and chloride declining to 533 ppm. There has also been a drop in silica, 282 ppm to 236 ppm. The chemistry changes are consistent with decreased spring activity.

Okianga geyser (S488)

During the 1980s-90s this small geyser erupted about once an hour to about 4 m height. In 1999 many small vents opened in the area and the geyser activity stopped. Compared to samples collected in 1983 and 1984 the latest sample shows dilution in Cl, SO_4 and B but the relative proportions of these components have not altered significantly and the silica concentration is unchanged. However the Na has decreased compared to K, suggesting an increase in temperature of the deeper water component. For the 1983 and 1984 Okianga spring samples the Na/K geothermometer temperatures were 184^{o}C and 183^{o}C respectively, while the 2002 sample now gives a value of 203^{o}C. The isotopic composition (see section 5.1) suggests this geyser is fed by deep water, which is now more dilute.

Spring 506

This feature was selected for sampling as it represents a small continuously discharging hot chloride feature in the western portion of Whakarewarewa. No previous analyses appear to exist for this feature. It is a hot (90°C) alkaline chloride spring with low sulphate (pH 9.1, Cl 551 ppm, SO_4 73 ppm). The composition is like the way Ngararatuatara (S529) was, and like Korotiotio spring (S283) is now. The cooler aquifer temperatures of S506 and lower bicarbonate indicate different subsurface processes/sources than Ngararatuatara, where it appears the groundwater dilution takes place at a deeper level.

Ngararatuatara (S529)

This continuously discharging feature has been sampled regularly since 1979 and has shown relatively stable Cl compositions. The latest sample (523 ppm) is similar to the previous sample collected in 1993 (522 ppm). Between 1979 and 1993 the average Cl was 528 ± 9 ppm (24 samples) with a high of 544 ppm measured in 1982 and a low of 512 ppm in 1990. Glover (1967) reports values of 580 ppm and 568 ppm in samples collected in 1937 and 1955 respectively.

However as for the Okianga Geyser, the Na has decreased while K has remained essentially constant. In Ngararatuatara the geothermometer temperature increase is much smaller, from an average of 248 ± 3°C between late 1984 an 1993 to 257°C in 2002, a value which had not been exceeded since 1984.

THC Blowout (S952)

This feature formed in 1987 as a result of problems with a nearby bore. Between 1991 and 1993 the "blow-out" discharged fluid with a stable concentration higher than any other Whakarewarewa spring (Glover, 1993). The latest sample shows a slight increase in Cl (1024 ppm to 1052 ppm) and lower sulphate (66 ppm to 48 ppm). Again as for Okianga and Ngararatuatara springs there is a decrease in Na but an increase in K. Between 1988 and 1993 the average Na/K geothermometer temperature was 215 ± 2°C and for the 2002 sample this is now 222°C.

B.2.2 Ohinemutu-Kuirau

Little Waikite (S1215) and Porahi (S122)

For both Porahi (S122) and Little Waikite (S1215) the Na/K ratios have decreased and this is reflected in the higher geothermometer temperatures. An increased silica in Porahi (286 ppm to 299 ppm) also suggests heating of the shallow aquifer. There is no change in Little Waikite silica concentrations (300 ppm to 301 ppm) but since the last sample collected in 1983, the HCO_3 has increased from 189 to 269 ppm with minor reduction in chloride (330 ppm to 310 ppm). Glover (1967) reports a Little Waikite spring analysis of a sample collected in 1903, which contained 335 ppm Cl and 348 ppm silica

Soda Spring (S624)

Unlike the relatively minor compositional changes at Ohinemutu over the past 20 years, the Kuirau Park features have seen a reversal back from dormancy to discharging acid-chloride fluids and finally in 2002 alkaline chloride fluids. A description of Soda Springs (S624) by Cody (1998) typifies the behaviour of the springs in the area. In 1953 the spring was at 85°C and discharged a alkaline-chloride fluid (pH 9.3, Cl 370 ppm). By 1982 the temperature and pH had decreased to 41.8°C and 4.5 respectively. Recovery began in 1989 with progressively increasing temperatures and pH, so that by 1997 the temperature was 82.1°C, pH 7.5 and Cl 341 ppm. In 2002 the temperature is 86.6°C, pH 9.1 and Cl 361 ppm. Glover (1967) also reports partial compositions of “Soda Springs” for samples collected in 1888, 1937 and 1955. The historical results are variable (i.e. chlorides were 247 ppm in 1888, 240 ppm in 1937 and 315 ppm in 1955) but lower in Cl, Na and SiO_2 than the 2002 sample.

Tarewa Spring (S653), S657 and Whakaterekohukohu (S722)

Similarly for the Tarewa spring (S653) where the latest sample collected was hotter (91.8°C vs 75°C) and less dilute (Cl 332 ppm vs 308 ppm) than the sample collected in 1963 (Glover, 1967). However the relative proportion of sulphate is still higher and the absolute changes are not as dramatic as for the Soda spring. Spring 657 is also showing substantial recovery when compared to the 1981 sample. Cl has increased from 282 ppm to 326 ppm and SO_4 has reduced from 125 to 70 ppm. Whakaterekohukohu (S722 - J C Fountain area) discharges near boiling alkaline chloride fluid (pH 9, Cl 364) with high silica and low sulphate, with relative proportions of B-Cl-SO4 similar to the 1963 Tarewa spring sample. Except for the higher collection temperature and lower SO_4, the composition of this spring is very similar to the recovered Soda Spring and it is likely that these compositions now represent the typical chemistry of these springs prior to exploitation in this part of the Rotorua geothermal field.

Kuirau Lake Feature (S601)

Kuirau lake is the largest hot spring in this area (5000 m^2) and has shown variable activity, often being a warm (about 45-50°C), acidic, low chloride and not overflowing feature (Scott and Cody, 2000). Since 1988 the lake has reheated (70-80°C) and since December 1997 the outflow has fluctuated between 25 and 50 l/min (Scott and Cody, 2000). Lake samples were collected and analysed in 1945 and 1963 (Glover, 1967), biannually between 1989 and 1993 and once in 1997. The 1989-97 sample compositions are all similar. Selected parameter concentrations and collection temperatures are presented in Table B2. This shows that the present lake chemistry is similar to the earliest 1945 and 1963 samples except that the relative proportion of SO_4 remains high, which is also shown in the figures. What is very puzzling is the low sample collection temperature, which may be a consequence of the changes in local hydrology due the recent nearby hydrothermal eruptions, however there appears to be no change in chemical composition. The lake was overflowing strongly at the time of sampling and the historically high Cl is not due to evaporation in a stagnant feature.

Table B2. Analyses of water from Kuirau Lake, 1945-2002.

Year	**t**	**pH**	**Na**	**K**	**Cl**	**SO_4**	**SiO_2**
	°C	**mg/l**					
1945		7.3	339	34	348	97	341
1963	99	7.5	330	31.5	326	45	318
1997	80	7.6	372	36	330	105	330
2002	47.1	7.6	350	32	352	107	304

B.2.3 Ngapuna and Government Gardens

Rachel spring

The latest Rachel spring composition is essentially the same as over the period 1990-1993 but slightly more dilute than in 1955 (Glover, 1967). Cl and SO_4 are now 514 ppm and 39 ppm respectively compared to 558 ppm and 84 ppm respectively in 1955.

Postmaster's Bath spring (Matuatonga)

Since the last sample collected in 1983, the Postmaster's Bath (Matuatonga) spring has had a large increase in HCO_3 (477 ppm to 760 ppm) and H_2S (31 to 115 ppm) and a drop in Cl (512 ppm to 472 ppm), SO_4 (71 ppm to 29 ppm) and only a small decrease in SiO_2 (215 ppm to 202 ppm). The spring has also cooled off (94.7°C to 78°C) with an accompanying drop in pH (8.3 to 7.0). With such few samples it is difficult to know how to interpret such changes. The most likely explanation is dilution (mixing) at depth with consequent cooling and suppression of boiling. Dilution by an oxygenated surface groundwater would have resulted in a considerable increase in SO_4. The "bubbling alkaline pool in front of Postmaster Bath" sampled by Grange in 1937 may be the same feature (Glover, 1967). At that time the composition was Cl 568 ppm, SO_4 190 ppm and silica 214 ppm.

Stopbank spring (S1100) and Hona Baths spring

Of the high chloride springs in the Ngapuna area, there is essentially no change in S940 from the sample collected in 1993, except for an increase in SO_4 (76 ppm to 126 ppm). The Stopbank spring (S1100) appears to be more dilute (Cl 1880 ppm to 1708 ppm) with a slight increase in SO_4. No samples have been previously reported from the Hona Baths but this spring also has high chloride (1617 ppm), approaching that of the Stopbank spring but with significantly more SiO_2 (313 ppm vs 247 ppm) and very low SO_4 (10 ppm). On the day that this spring was sampled it was not overflowing but was observed to be doing so three weeks previously. The low sulphate suggests this feature is not stagnant.

Hamiora Baths spring

The other spring sample collected in this area was from the Hamiora Baths, which are located further east towards the periphery of the geothermal field. The spring waters are dilute compared to the others (Cl 544 ppm) and high in HCO_3 (336 ppm), indicative of groundwater dilution at sufficient depth to suppress boiling and allow the dissolved CO_2 (carbonic acid) to be neutralised to HCO_3 by reaction with country rocks (as for Kuirau). The Cl/B ratio clearly relates this spring to the other Ngapuna features. The more negative isotopic values are consistent with such dilution.

B.3 Isotopic analyses

Isotopic concentrations are expressed as d values with respect to a water standard (VSMOW), i.e. $d^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{SMOW} - 1] \times 1000$.

$d^{2}H$ is defined similarly.

B.3.1 Whakarewarewa

Ngawharua (S55) shows a slightly higher (less negative) $d^{18}O$ and increase in SO_4 since the 1980s indicating extra surface evaporation or steam heating, consistent with the chemical observations. Prince of Wales Feathers and Pohutu geysers have higher $d^{18}O$ and chloride supporting chemical indications of higher-temperature, deeper-sourced fluid now feeding these features. Puapua has a significantly lower $d^{18}O$ indicating less surface or near-surface evaporation, also shown by less sulphate. The higher chloride and bicarbonate values also indicate greater input of diluted deep water. Kereru has unchanged $d^{18}O$. There are no previous analyses for Spring 506. Ngararatuatara has higher $d^{18}O$ and slightly higher sulphate suggesting evaporation combined with dilution.

Korotiotio has higher $d^{18}O$ and sulphate indicating more steam heating/surface evaporation like Ngawharua. Parekohoru has $d^{18}O$ within the range of previous values, but higher chloride and bicarbonate show greater input of diluted deep water like at Puapua.

Ororea shows increased steam heating even compared with the 1983 sample. Okianga Geyser has higher $d^{18}O$ but lower chloride and sulphate indicating more groundwater is mixing with boiled deep water to dilute it. THC Blowout accesses deeper water with higher chloride concentrations. The higher $d^{18}O$ is consistent with higher chloride, but no earlier results are available for comparison.

B.3.2 Ohinemutu-Kuirau

At Ohinemutu, Porahi has similar isotopic and chemical composition to nearby Little Waikite (S1215) sampled in 1983. Its bicarbonate concentration is higher than in 1983. The Kuirau features had not been sampled before. Their concentrations are similar, but slightly elevated compared to the Ohinemutu samples. S653 and S649 (sampled in 1983 and 1984 at Kuirau) have very similar isotopic values, showing that they are affected by similar processes.

B.3.3 Ngapuna - Government Gardens

Rachel Spring (Whangapapiro) shows remarkably little change compared with the 1984 sample, except for lower sulphate. Its sulphate concentration has been variable in the past. Ngapuna springs have lower chloride and higher sulphate and bicarbonate, with little change in isotopic composition indicating more dilution with steam heated groundwater.

Table B3. Natural geothermal features sampled in April 2002.

Whakarewarewa

	English Name	Maori Name	Spring No.
1		Papakura	28
2		Ngawharua	55
3	Prince of Wales Feathers		72
4		Pohutu	75
5		Te Horu	76
6		Waiora Geyser	79
7		Puapua	81
8		Waikite Geyser	130
9		Kereru	278
10	Oil Bath Springs	Korotiotio	283
11	Champagne Pool	Parekohoru	284
12		Ororea	352
13			377
14		Okianga Geyser	488
15			506
16		Ngararatuatara	529
17	THC Blowout		952

Ohinemutu

18	Little Waikite Geyser	Waikite	1215
19		Porahi	1227

Kuirau-Tarewa

20	Kuirau Lake outlet		601
21	Soda Spring		624
22		Parekohoru	647
23		Tarewa	653
24			657
25	J C Fountain Area	Whakaterekohukohu	722

Ngapuna Springs-Government Gardens

26	Rachel	Whangapipiro	
27	Postmasters Bath	Matuatonga	
28	Stopbank Spring	Ngapuna	1100
29	Ngapuna Springs	Ngapuna	940
30	Hona Baths	Ngapuna	
31	Hamiora Baths	Ngapuna	

Table B4. Chemical analyses of selected natural features sampled in April 2002.

Laboratory Reference No		**2200627**	**2200628**	**2200629**	**2200630**	**2200631**	**2200632**	**2200633**
Collection Date		**23/04/02**	**23/04/02**	**23/04/02**	**23/04/02**	**23/04/02**	**23/04/02**	**23/04/02**
Spring No.		**1100**	**940**				**1215**	**1227**
Name		**Stopbank Spr**	**Ngapuna Spr**	**Hamiora Bath**	**Hona Bath**	**Postmaster's**	**Little Waikite**	**Porahi**
Bicarbonate (total)	mg/l	94	78	336	**72**	**760**	**269**	**244**
pH		6.88	8.25	6.56	7.51	6.98	9.20	8.81
Analysis temperature	°C	20	19	20	20	20	20	21
HCO_3/Date Analysed		24/4/02	24/4/02	24/4/02	24/4/02	24/4/02	24/4/02	24/4/02
Boron	mg/l	12.1	8.9	3.0	11.3	4.0	5.5	5.5
Calcium	mg/l	10.7	7.3	16.6	19.3	5.1	0.79	2.4
Chloride	mg/l	1708	1178	544	1617	472	310	312
Collection Temperature	°C	89.9	52.2	54.8	51.7	78.0	98.1	76.3
Lithium	mg/l	2.7	1.8	1.2	2.3	2.0	2.6	2.1
Magnesium	mg/l	0.31	0.32	1.7	0.1	0.07	<0.01	0.06
Potassium	mg/l	105	81	47	100	34	17.4	19.5
Silica (as SiO_2)	mg/l	247	232	324	313	202	301	299
Sodium	mg/l	1070	743	397	956	553	342	327
Sulphate	mg/l	90	126	78	10.9	29	46	58
Sulphide (total as H_2S)	mg/l	27	4.6	36	16.8	115	4.2	2.2
H_2S/Date Analysed		24/4/02	24/4/02	24/4/02	24/4/02	24/4/02	24/4/02	24/4/02
Deuterium		-28.0	-29.8	-35.7				-32.1
Oxygen 18		-1.29	-1.53	-4.44				-3.85

Table B4 continued.

Laboratory Reference No		**2200634**	**2200635**	**2200636**	**2200637**	**2200638**	**2200639**	**2200647**
Collection Date		**23/04/02**	**23/04/02**	**23/04/02**	**23/04/02**	**23/04/02**	**23/04/02**	**24/04/02**
Spring No.		**284**	**283**	**488**	**352**	**377**	**952**	**28**
Name		**Parekohoru**	**Korotiotio**	**Okianga Geyser**	**Ororea**	**NO 377**	**THC Blowout**	**Papakura**
Bicarbonate (total)	mg/l	162	157	34	161	69	120	38
pH		9.28	9.16	9.16	8.38	7.22	8.48	6.30
Analysis temperature	°C	21	20	20	21	21	22	21
HCO_3/Date Analysed		24/4/02	24/4/02	24/4/02	29/04/2002	29/4/2002	29/4/2002	29/4/2002
Boron	mg/l	5.5	5.7	5.5	5.4	4.6	8.6	4.7
Calcium	mg/l	1.6	1.5	5.1	5.4	4.6	3.4	2.2
Chloride	mg/l	610	571	638	746	533	1052	456
Collection Temperature	°C	96.2	99.5	97.7	75.0	70.2	88.5	37
Lithium	mg/l	4.2	3.9	3.2	4.2	3.1	3.8	2.8
Magnesium	mg/l	0.02	0.01	0.02	0.11	0.14	0.01	0.15
Potassium	mg/l	52	43	33	72	44	60	40
Silica (as SiO_2)	mg/l	379	324	202	282	236	310	253
Sodium	mg/l	483	438	486	589	433	681	343
Sulphate	mg/l	63	68	156	256	250	48	170
Sulphide (total as H_2S)	mg/l	15.9	11.0	20	11.6	6.0	1.3	<0.2
H_2S/Date Analysed		24/4/02	24/4/02	24/4/02	24/4/02	24/4/02	24/4/02	29/4/02
Deuterium		-32.6	-32.3	-31.7	-27.8		-30.3	
Oxygen 18		-3.52	-3.55	-3.43	-2.01		-1.96	

Table B4 continued.

Laboratory Reference No		**2200648**	**2200649**	**2200650**	**2200651**	**2200652**	**2200653**	**2200654**
Collection Date		**24/04/02**	**24/04/02**	**24/04/02**	**24/04/02**	**24/04/02**	**24/04/02**	**24/04/02**
Spring No.		**55**	**72**	**75**	**76**	**79**	**81**	**130**
Name		**Ngawharua**	**Prince of Wales**	**Pohutu**	**Te Horu**	**Waiora Geyser**	**Puapua**	**Waikite Geyser**
Bicarbonate (total)	mg/l	81	37	48	71	*	217	*
pH		9.35	9.73	9.73	9.67	1.69	8.22	2.02
Analysis temperature	°C	21	20	22	22	22	21	22
HCO_3/Date Analysed		29/4/2002	29/4/2002	29/4/2002	29/4/2002	29/4/2002	29/4/2002	29/4/2002
Boron	mg/l	5.9	5.1	5.2	5.3	1.2	5.2	0.40
Calcium	mg/l	1.3	1.9	1.9	1.9	11.5	2.0	0.72
Chloride	mg/l	575	591	600	619	108	619	<3
Collection Temperature	°C	95	100	100	53.7	95	100	100
Lithium	mg/l	3.9	3.5	3.4	3.5	0.65	3.4	<0.05
Magnesium	mg/l	0.07	0.03	<0.01	<0.01	1.4	0.01	0.04
Potassium	mg/l	35	61	61	63	22	67	1.7
Silica (as SiO_2)	mg/l	214	461	462	469	378	403	196
Sodium	mg/l	434	439	463	467	93	485	2.5
Sulphate	mg/l	75	77	79	86	1903	80	1155
Sulphide (total as H_2S)	mg/l	9.8	12.1	10.9	2.2	0.34	7.2	<0.20
H_2S/Date Analysed		29/4/02	29/4/02	29/4/02	29/4/02	29/4/02	29/4/02	29/4/02
Deuterium		-32.2	-31.1	-29.9			-29.9	
Oxygen 18		-3.82	-3.42	-3.32			-3.63	

Table B4 continued.

Laboratory Reference No		**2200655**	**2200656**	**2200657**	**2200658**	**2200659**	**2200660**	**2200661**
Collection Date		**24/04/02**	**24/04/02**	**24/04/02**	**24/04/02**	**24/04/02**	**24/04/02**	**24/04/02**
Spring No.		**278**	**506**	**529**	**601**	**624**	**647**	**653**
Name		**Kereru**	**S506**	**Ngararatuatara**	**Kuirau Lake Outlet**	**Soda Spring**	**Parekohoru**	**S653**
Bicarbonate (total)	mg/l	142	85	138	301	258	339	295
pH		8.99	9.09	8.15	7.57	9.11	8.14	8.49
Analysis temperature	°C	21	22	20	20	20	20	20
HCO_3/Date Analysed		29/4/2002	29/04/2002	30/4/2002	30/4/2002	30/4/2002	30/4/2002	30/4/2002
Boron	mg/l	5.3	5.8	5.5	7.3	6.8	6.6	6.4
Calcium	mg/l	1.7	2.1	1.8	2.4	0.99	0.94	0.86
Chloride	mg/l	566	551	523	352	361	334	332
Collection Temperature	°C	100	90	95	47.1	86.6	88.2	91.8
Lithium	mg/l	3.4	3.2	2.0	3.0	2.8	3.0	2.5
Magnesium	mg/l	0.01	<0.01	<0.01	0.08	<0.01	0.01	0.02
Potassium	mg/l	53	33	52	32	32	35	35
Silica (as SiO_2)	mg/l	397	202	344	304	367	345	309
Sodium	mg/l	439	409	385	350	367	345	326
Sulphate	mg/l	87	73	78	107	59	42	53
Sulphide (total as H_2S)	mg/l	2.9	3.3	1.3	<0.20	1.8	<0.20	<0.20
H_2S/Date Analysed		29/4/02	29/4/02	30/4/02	30/4/02	30/4/02	30/4/02	30/4/02
Deuterium		-26.6	-30.7	-29.0		-33.1		-31.5
Oxygen 18		-3.58	-3.65	-2.86		-3.64		-3.47

Table B4 continued.

Laboratory Reference No **Collection Date** **Spring No.** **Name**		**2200662** **24/04/02** **657** **Spring # 657**	**2200663** **24/04/02** **722** **JC Fountain Area**	**2200664** **24/04/02** **Rachel**
Bicarbonate (total)	mg/l	250	259	499
pH		8.24	9.00	8.88
Analysis temperature	°C	20	21	21
HCO_3/Date Analysed		30/4/2002	30/4/2002	30/4/2002
Boron	mg/l	6.3	6.8	6.0
Calcium	mg/l	1.2	2.4	0.87
Chloride	mg/l	326	364	514
Collection Temperature	°C	70	99.1	95.4
Lithium	mg/l	2.0	2.5	2.5
Magnesium	mg/l	0.03	<0.01	0.01
Potassium	mg/l	33	31	33
Silica (as SiO_2)	mg/l	262	368	268
Sodium	mg/l	320	345	535
Sulphate	mg/l	70	32	39
Sulphide (total as H_2S)	mg/l	<0.20	3.5	56
H_2S/Date Analysed		30/4/02	30/4/02	30/4/02
Deuterium		-29.7		-30.7
Oxygen 18		-2.84		-3.24

Table B5. Isotopic analyses of selected natural features.

No.	Feature Name	Spring	Collection	d^{18}O	d^{2}H	Cl	SO$_4$	HCO$_3$
		No.	Date	‰	‰	mg/l	mg/l	mg/l
	Whakarewarewa							
2	Ngawharua	55	Jul-83	-4.09	-32.0	571	64	95
			May-84	-4.07	-32.3	580	68	90
			Apr-02	-3.82	-32.2	575	75	81
3	Prince of Wales	72	Aug-79	-3.67	-29.3	--	--	--
			Apr-02	-3.42	-31.1	591	77	37
4	Pohutu	75	Jul-83	-3.85	-27.3	--	--	--
			Jun-84	-3.66	-32.6	549	76	66
			Apr-02	-3.32	-29.9	600	79	48
7	Puapua	81	May-83	-3.14	-29.0	574	94	178
			May-84	-3.15	-30.8	577	102	202
			Apr-02	-3.63	-29.9	619	80	217
9	Kereru	278	Jun-84	-3.61	-30.7	554	122	86
			Apr-02	-3.58	-26.6	566	87	142
10	Korotiotio	283	Aug-79	-3.83	-33.5	--	--	--
			May-83	-3.83	-33.4	567	59	154
			May-84	-3.79	-32.1	577	53	186
			Apr-02	-3.55	-32.3	571	68	157
11	Parekohoru	284	Aug-79	-3.68	-33.9	--	--	--
			May-83	-3.25	-32.4	573	66	124
			May-84	-3.51	-33.5	583	60	143
			Apr-02	-3.52	-33.4	610	63	162
12	Ororea	351	May-83	-2.45	-28.9	755	155	172
			Apr-02	-2.01	-27.8	746	256	161
14	Okianga Geyser	488	Jul-83	-3.76	-33.7	704	178	31
			May-84	-3.77	-32.9	701	280	37
			Apr-02	-3.43	-31.7	638	156	34
15		506	Apr-02	-3.65	-30.7	551	73	85
16	Ngararatuatara	529	May-83	-3.38	-32.5	536	66	142
			Jul-83	-3.51	-33.6	539	65	142
			May-84	-3.64	-31.8	537	65	140
			Apr-02	-2.86	-29.1	523	78	138
17	THC Blowout	952	Apr-02	-1.96	-30.3	1052	48	120
	Ohinemutu-Kuirau							
19	Porahi	1227	Jul-83	--	--	324	58	188
			Apr-02	-3.85	-32.1	312	58	244
21	Soda Spring	624	Apr-02	-3.64	-33.1	361	59	258
23	Tarewa	653	Apr-02	-3.47	-31.5	332	53	295
24		657	Apr-02	-2.84	-29.7	326	70	250
	Government Gardens-Ngapuna							
26	Rachel Spring		May-84	-3.31	-29.5	482	162	565
			Apr-02	-3.24	-30.7	514	39	499
28	Stopbank Spring	1100	Apr-02	-1.29	-28.0	1708	90	94
29	Ngapuna Springs	940	May-83	-1.72	-30.2	1415	105	38
			Jun-84	-1.46	-30.2	1554	84	36
			Apr-02	-1.53	-29.8	1178	126	78
31	Hamiora Bath		Apr-02	-4.44	-35.7	544	78	336