Chemistry of the Rotorua Geothermal Field Part 1: Natural geothermal features – update of chemical and isotopic compositions and comparison with historical data

Confidential

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EXECUTIVE SUMMARY

A geochemical survey of 31 selected Rotorua natural features 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.

A review and interpretation of the chemical and isotopic compositions of the fluids indicates that the chemistry of the source fluids feeding the deeper aquifers of the geothermal system is essentially unchanged. However, changes in the relative proportions of chemically inert non-reactive species and chemically reactive species, shows that in parts of the field reheating of the shallow and deeper aquifers has taken place, with a substantially greater proportion of the deep aquifer fluids now discharging at the surface.

The compositions of the 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. At Ohinemutu there have not been any significant changes over the last 20 years and the fluids discharged are similar in composition to those now discharging at Kuirau.

At Government Gardens – Ngapuna area the springs appear to be declining, at odds with the reported increases in heat and outflows. The sparse number of temporal samples means that this conclusion is not certain.

In the Whakarewarewa area features show a range of chemical and isotopic changes ranging from continuing decline to recovery with aquifer re-heating. The most outstanding recovery is at Parekohoru which is now discharging less-dilute fluids and at Pohutu where re-heating of the shallow aquifer is indicated by a significant increase in dissolved silica. Pohutu fluid composition is now comparable to that discharged in 1937. Possible increases in the temperature of the deeper water component are indicted by THC Blowout fluid compositions and by the Okianga Geyser.

The data indicate that the key objective in Environment B·O·P’s operative resource management plan for the field is being achieved. The recovery is particularly apparent in the northern area of the field at Kuirau Park.

1.0 INTRODUCTION

Since the beginning of the bore closure programme in 1986, the recovery of the Rotorua natural surface features has been the greatest over the period 1992-2000 with resumption of fluid flow to many previously dormant springs (Gordon et al., 2001). Over that time, several parameters which define the field, have been intensively monitored, however chemical analysis of the discharging fluids was essentially discontinued in 1993. 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 the changing chemical and isotopic composition of the fluids and the relationships between them are the most important indicators of the hydrology of a geothermal system. In conjunction with physical monitoring this enables a comprehensive understanding of the current state of the field as well as the system's response to exploitation and recovery. In particular the chemistry provides constraints for the complex mathematical models of the field.

The previous geo-scientific work, current understanding and the past and present monitoring programmes on the Rotorua geothermal system have been comprehensively summarised by several workers e.g. Grant-Taylor and O'Shaughnessay (1992), Hodges (1998), Gordon et al., (2001) and are not repeated here. This study, being Part 1 of a two-part study of the geochemistry of the Rotorua geothermal field, is a component of a continuing management programme undertaken by Environment B·O·P. The purpose was to conduct a geochemical survey of selected Rotorua natural features, compare the results to historical data and provide an overall assessment to highlight any changes. The background and project brief are given in Appendix 1. In Part 2 the intention is to continue with a geochemical survey of the wells and to re-interpret that data with the spring data to provide further insight into the shallow aquifer relationships of the Rotorua geothermal system.

2.0 SAMPLING PROGRAMME AND ANALYSIS

The features sampled are listed in Table 1. They were chosen by Dougall Gordon (Environment B·O·P), Bradley Scott (GNS) and Ashley Cody (Geothermal Investigations) to give a wide geographical coverage over the three main geothermal areas, including a selection of previously sampled features, newly recovered features and discharging surface geothermal activity, viz. Ngapuna-Government Gardens, Whakarewarewa and Kuirau Park-Ohinemutu (see Figure 1).

The samples were collected using accepted standards for geothermal fluids (Klyen, 1996) and were analysed to the New Zealand Code of Laboratory Management Practise (NZS/ISO/IEC 17205). The oxygen-18 (^{18}O) isotope was analysed by stable isotope mass spectrometry following the methodology of Brenninkmeijer et al., (1987) which was also extended to deuterium measurements (^{2}H). Stable isotopes are valuable tools for characterising boiling and mixing processes when complemented by and combined with chemical techniques.

The analytical data is presented in Tables 2 and 3. All samples gave acceptable ion balances (< ±5%) except for two acidic fluids (samples 2200652 and 2200654), where all species contributing to the ion balance were not analysed (e.g. Al). Not all samples were analysed for stable isotopes and those selected were chosen on the basis of their importance and the existence of previous data. Digital photographs were taken at each sampling site are included as Appendix 2 (in rear folder).

3.0 COMPARISON WITH HISTORICAL DATA – TREATMENT OF CHEMICAL DATA

3.1 Introduction

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 and could be influenced by local effects such as high rainfall episodes and other 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 easily discerned. All relative concentrations have been calculated by weight% from the analysed fluid composition.

3.2 Triangular diagrams

Following the techniques developed by Giggenbach (1991), we have used four different triangular plots 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 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. High Bicarbonate (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. In the south and east waters cooled by boiling are greatly depleted in CO_2 and consequently contain less 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). 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). These geothermometers are used for evaluating water-rock equilibration temperatures. 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. 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].

iv) Relative Sodium (Na) – Potassium (K) – Calcium (Ca)

The behaviour of calcium in geothermal fluids is governed by a wide range of processes, deposition of calcite, base exchange reactions with final incorporation in a fully equilibrated system into secondary minerals such as zeolites.

3.3 Summary

Using triangular diagrams with relative concentrations between chemically inert non-reactive species and chemically reactive species is a powerful empirical technique for showing chemical relationships and temporal changes across the geothermal field as well as within smaller groups of related springs.

i) B-Cl-SO_4.

These diagrams show source waters and highlight recovery in spring chemistry as progressively lesser admixtures of steam heated shallow waters give a trend line moving away from the SO_4 apex with increasing Cl/SO_4 ratios.

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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.

ii) b) HCO_3- Cl-SO_4

These diagrams show intermediate and shallow depth aquifer processes. Similarly the addition of sulphate in steam heated waters is shown as described in the B-Cl-SO_4 diagram above but also changes in HCO_3/Cl ratio due to water rock interaction and boiling /dilution

iii) Na-K-Mg

These diagrams reflect both shallow and deep aquifer processes through geothermometer temperatures based on various mineral reactions with water. Increasing deep aquifer temperatures are inferred from increasing K/Na ratios while recovery and increasing shallow depth aquifer temperatures are indicated through increasing K/Mg ratios.

iv) Na-K-Ca

As for the Na/K ratio above but also the relative concentration of Ca may increase with dilution by cooler aquifer fluids (solubility of calcite increases) and decrease with increased boiling (precipitation of calcite due to loss of CO_2 on boiling).

4.0 COMPARISON OF RECENT CHEMICAL ANALYSES WITH HISTORICAL DATA

4.1 Data used

The analytical data was abstracted from compilations given by Zeng (1981), Bradford et al., (1987), Glover (1993) and unpublished data held in GNS files. Glover (1967) published the only comprehensive compilation of historical analytical data. This included samples collected between 1878 and 1955. Glover (1967) also undertook an analytical survey between 1961 and 1963, which included many wells but only a few of the natural features. These are considered the most reliable analyses although the earlier historical data is presented for interest and completeness. The reliability of the historical values, particularly for partial analyses, is difficult to judge.

It should be borne in mind that because of the sparse sampling over the last decade, a spring composition may indicate the fluid to be still at the bottom of the recovery cycle even though reversal towards less acidic and higher chloride fluid compositions may have already begun.

Descriptions of spring activity are of necessity very brief but detailed accounts may be found in Mahon (1985), Glover (1993), Cody (1998a), Cody (1998b), Scott and Cody (2000) and Gordon et al., (2001).

In the following sections we discuss the historic data, the status of the hot spring and how the new data relates to these.

4.2 Whakarewarewa Springs

Papakura geyser (S28) – Fig 2

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^oC 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) – Fig 3

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) – Fig 4

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) – Fig 5

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°C to 226°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 (1998a) 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 4. 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 4. 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	79	600	77	462	7.6	115	7.6

Te Horu (S76) – Fig 6

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°C) and Gordon et al., (2001) suggest this feature is receiving discharge fluids from Pohutu, which is supported by these results.

Wairoa geyser (S79) – Fig 7

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) – Fig 8

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, 1998a) 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) – Fig 9

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) – Fig 10

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) – Fig 11

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) – Fig 12

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 – Fig 13

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) – Fig 14

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°C and 183°C respectively, while the 2002 sample now gives a value of 203°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) – Fig 15

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) – Fig 16

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.

4.3 Ohinemutu-Kuirau

Introduction

The dramatic physical recovery of the springs in Kuirau-Ohinemutu area have been well documented (Cody, 1998a, Cody 1998b, Gordon et. al., 2001, Scott and Cody 2000). However compared to Whakarewarewa the number of historic samples analysed is very low, possibly due to the early demise of the natural features as a result of extensive bore use in this area. The chemistry of the area is summarised in Figures 17-19. The Ohinemutu data set is expanded by including spring S1263 which was sampled in 1989 and 1990. The relative proportions of B-Cl-SO_4 clearly shows the close relationship between the Kuirau and Ohinemutu areas, which all have a similar Cl/B ratio of about 55, quite distinct and significantly lower than the Whakarewarewa springs (Cl/B ~ 100).

The cation ratios however show that the deeper aquifer feeding the Ohinemutu area is significantly cooler at Na/K geothermometer temperatures of about 175°C compared to 225°C for the Kuirau Park features. Nevertheless the absolute concentrations of chloride are higher at Ohinemutu (although the Kuirau springs are rapidly catching up) and the relative proportion of SO_4 is lower.

The relationships indicate that Ohinemutu is a cooler outflow zone of the same deeper source fluids that that feed Kuirau Park. The Ohinemutu springs appear to have been less affected by secondary processes caused by fluid withdrawal and lowering pressures and are not substantially degraded in this area. It is unlikely in the future that changes in compositions will occur as the compositions indicate stability. Although there are no early samples with which to compare, mathematical modelling may predict if any further changes in Ohinemutu chemistry could occur if Kuirau recovers more.

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 (1998a) 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 5. 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 5. 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

4.4 Ngapuna and Government Gardens

Introduction

Apart from Rachel (Whangapipiru) spring in Government Gardens there are few analyses of the features in the Government Gardens-Sulphur Bay-Ngapuna area. Gordon et al. (2001)

report that springs in the Ngapuna area have heated and substantially increased in outflow since 1987-88 and the waters have become clear and alkaline. Figures 20 – 21 show the compositional relationships between the various springs. The Ngapuna springs and Postmaster Spring all lie along a mixing line with an end member Cl/B about 140, while Rachel spring Cl/B ratio is about 80. This compares with Cl/B ratios of 100 for Whakarewarewa and 55 for Kuirau-Ohinemutu. The relative proportions of HCO_3-Cl-SO_4 clearly differentiates the chemistry between Rachel and Postmaster springs which have high relative proportions of HCO_3, similar to Kuirau features, and the Ngapuna springs. Ngapuna springs have absolute concentrations of chloride up to 1700 ppm and low HCO_3 (<100 ppm). Similarly the Na-K-Mg diagram shows that the deeper aquifer fluids feeding Ngapuna are hotter (225°C- 250°C) than the fluids feeding the Rachel and Postmaster Bath springs (175°C - 200°C).

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.

5.0 COMPARISON OF RECENT ISOTOPIC ANALYSES WITH HISTORICAL DATA

Results for the features sampled for isotopes are given in Table 3 with earlier measurements from Stewart and Taylor 1985. Isotopic concentrations are expressed as δ values with respect to a water standard (VSMOW), i.e.

$$\delta^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{SMOW} - 1] \times 1000.$$

δ^2H is defined similarly. Chloride, sulphate and bicarbonate concentrations are given where available.

5.1 Whakarewarewa

Ngawharua (S55) shows a slightly higher (less negative) $\delta^{18}O$ 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 $\delta^{18}O$ and chloride supporting chemical indications of higher-temperature, deeper-sourced fluid now feeding these features. Puapua has a significantly lower $\delta^{18}O$ 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 $\delta^{18}O$. There are no previous analyses for Spring 506. Ngararatuatara has higher $\delta^{18}O$ and slightly higher sulphate suggesting evaporation combined with dilution.

Korotiotio has higher $\delta^{18}O$ and sulphate indicating more steam heating/surface evaporation like Ngawharua. Parekohoru has $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ is consistent with higher chloride, but no earlier results are available for comparison.

5.2 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.

5.3 Government Gardens-Ngapuna

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.

6.0 DISCUSSION

6.1 Kuirau Park – Ohinemutu

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.

6.2 Government Gardens and Ngapuna

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.

6.3 Whakarewarewa

In the Whakarewarewa area features show a range of chemical and isotopic changes with apparently no consistency to geographical location. These changes range from continuing decline or no recovery to stable or recovery with aquifer re-heating. 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.

A detailed interpretation of the results from Whakarewarewa is beyond the scope of this report but does support the observations of Gordon et al., (2001) that complex changes are occurring in this area, with inconsistencies in both physical changes and geographical distribution of the changes.

6.4 Summary

A review and interpretation of the chemical compositions of the fluids shows that the chemistry of the deep source fluids feeding the shallow aquifers of the geothermal system is essentially unchanged. However, changes in isotopic compositions and relative proportions of chemically inert non-reactive species and chemically reactive species shows that in parts of the field reheating of the shallow and deeper aquifers has taken place, with a greater proportion of the deep aquifer fluids now discharging at the surface.

7.0 CONCLUSIONS

1. This geochemical survey of 31 selected Rotorua natural features was undertaken to collect a modern data set that could be used for comparison with historical data. All the data were reviewed to provide an overall assessment of the behaviour of the springs following the enforced 1986 bore closure together with the management programme that has been implemented since that time. This study is part of a two-part programme, which will see deeper fluids from production bores sampled and analysed.

2. The data indicate that the key objective in Environment B·O·P's operative resource management plan (regional) for the field, of protection and restoration of natural outflows, is being achieved. The recovery is particularly apparent in the northern area of the field where the 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. At Ohinemutu there have not been any significant changes over the last 20 years in the spring compositions and the fluids discharged are similar to those now discharging at Kuirau.

3. At Government Gardens – Ngapuna area the springs appear to be declining, at odds with the reported increases in heat and outflow. The sparse number of temporal samples means that this conclusion is not certain.

4. Features in Whakarewarewa continue to show a range of chemical and isotopic compositions. The most outstanding recovery is at Parekohoru which is now discharging less dilute fluids and at Pohutu where re-heating of the shallow aquifer is indicated by a significant increase in dissolved silica. Pohutu fluid composition is now comparable to that discharged in 1937. Possible increases in the temperature of the deeper water component are indicted by THC Blowout fluids (especially) and by the Okianga Geyser. The evidence is that the Whakarewarewa springs are only now beginning to respond with decreasing influence of the surficial steam heated waters and increasing aquifer geothermometer temperatures.

5. The data collected, combined with the mathematical models of field, will enable the resource to be effectively and sustainably managed and provide technical data to set withdrawal limits.

8.0 RECOMMENDATIONS

1. Sample well discharges (water and steam) to complete the survey of the Rotorua geothermal field.
2. Repeat the sampling and analysis of these natural features in 5 and again in 10 years time, thereafter to be reviewed.
3. The Government Gardens and Ngapuna springs should be re-sampled within one to two years.

The interpretation of the deeper aquifer chemistry from hot spring compositions is subject to uncertainties and these preliminary conclusions need to be combined with the planned analysis of deeper well fluids and gases to construct an overall interpretation of the recovery and changes. Representative water and especially gas samples of the deeper aquifers can only be collected from discharging wells.

The new survey will also provide data for further insight into the shallow aquifer relationships between east (Ngapuna-Whakarewarewa) and northwestern (Kuirau Park) parts of the field (Appendix 1). The aquifer relationships remain problematic, especially the contrasting chemistry of the northern area of the field. Therefore a detailed analysis and interpretation of the both the springs and well data is needed to investigate the hypothesis proposed by Giggenbach and Glover (1992) that there is a distinct upflow zone centred on Kuirau Park.

Frequent chemical monitoring of the natural features (and bores) 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 in 5 and again in 10 years time, thereafter to be reviewed.

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Table 1. 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 2. 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 2 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 2 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 2 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 2 continued.

Laboratory Reference No		**2200662**	**2200663**	**2200664**
Collection Date		**24/04/02**	**24/04/02**	**24/04/02**
Spring No.		**657**	**722**	
Name		**Spring # 657**	**JC Fountain Area**	**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 3. Isotopic analyses of selected natural featuress.

No.	Feature Name	Spring	Collection	$\delta^{18}O$	$\delta^{2}H$	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

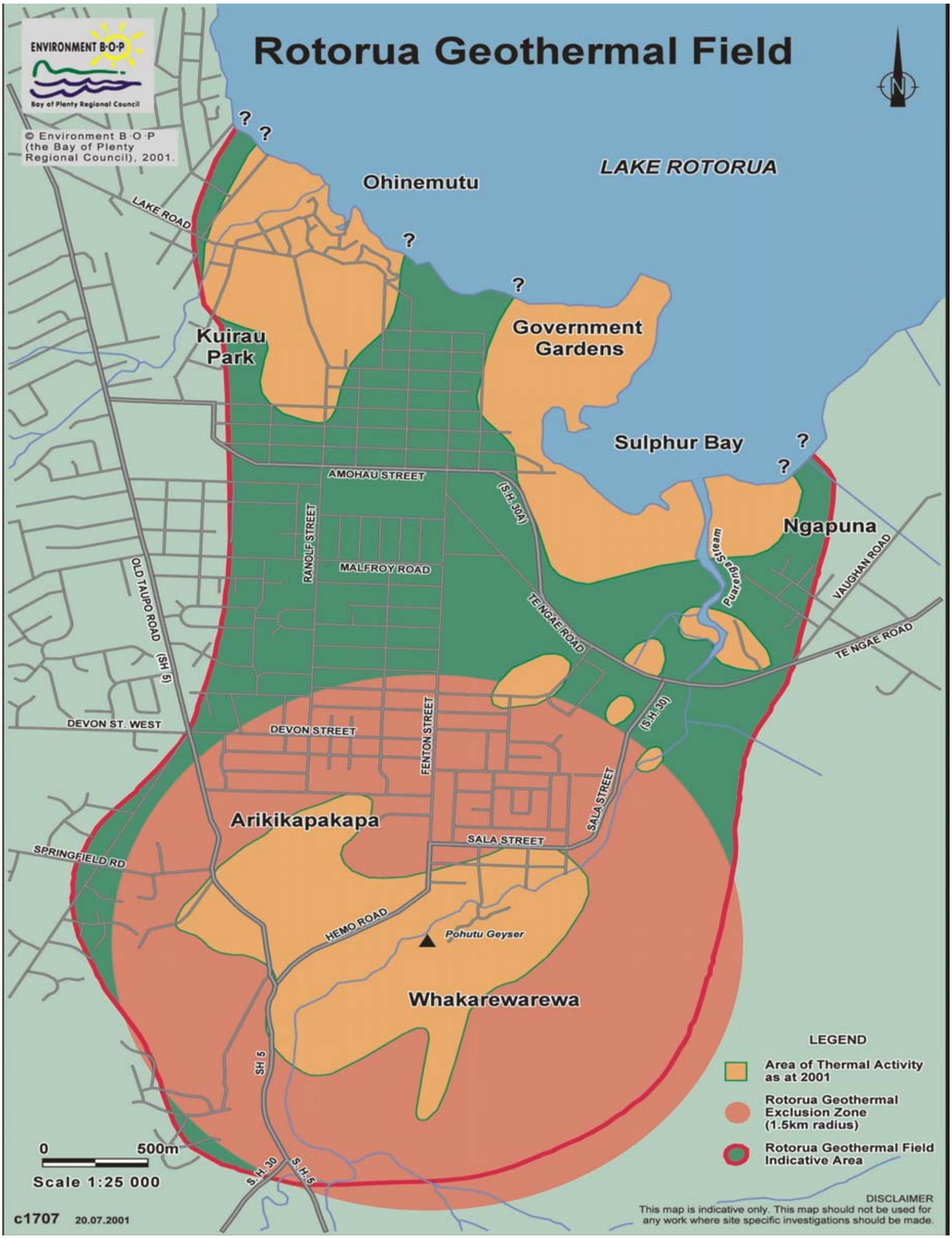


Figure 1. Map of the Rotorua Geothermal Field.

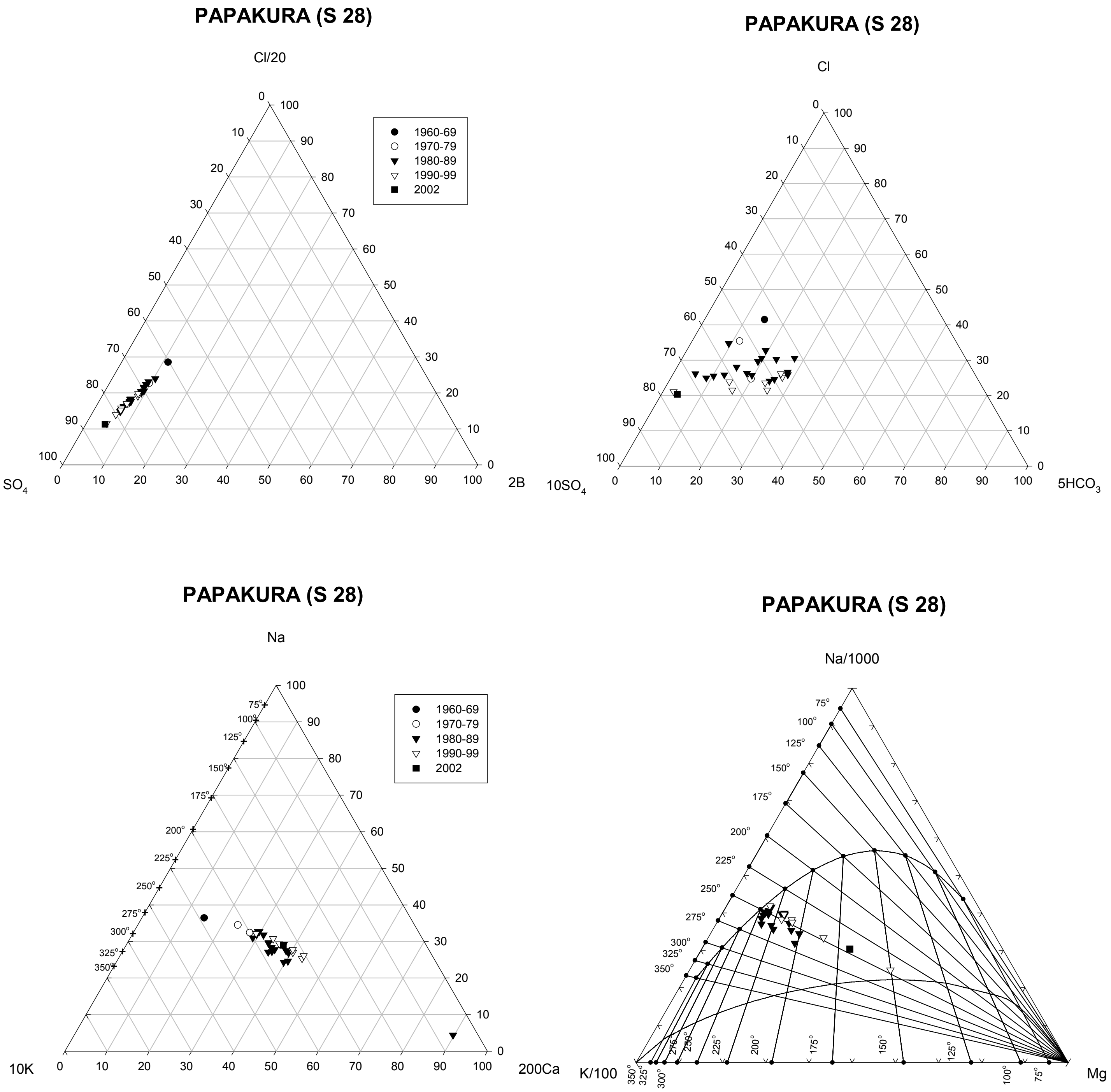

PAPAKURA (S 28)
Cl/20
SO$_4$
2B
PAPAKURA (S 28)
Cl
10SO$_4$
5HCO$_3$
PAPAKURA (S 28)
Na
10K
200Ca
PAPAKURA (S 28)
Na/1000
K/100
Mg
● 1960-69
○ 1970-79
▼ 1980-89
▽ 1990-99
■ 2002
0
10
20
30
40
50
60
70
80
90
100
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°

Figure 2.

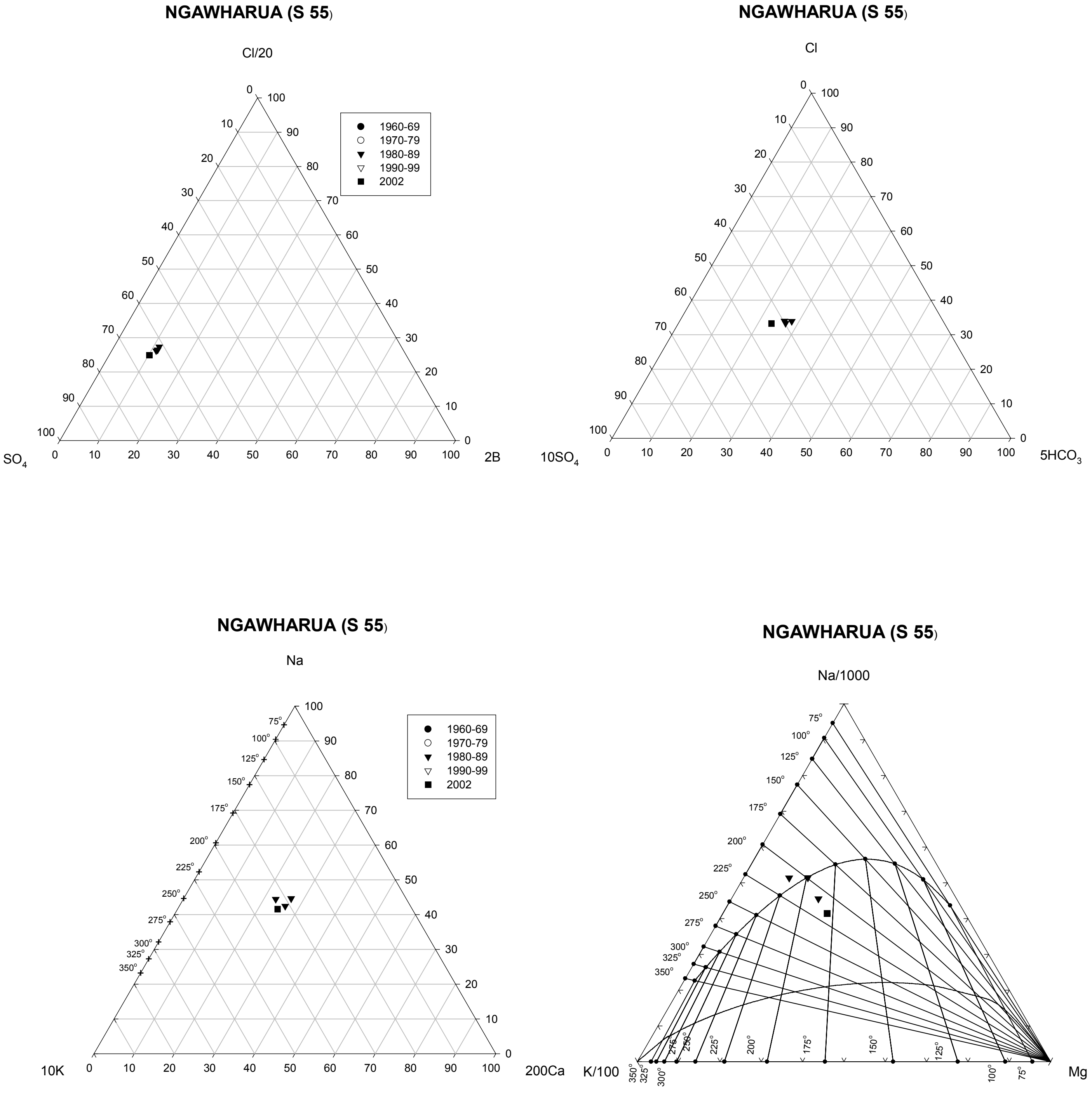

NGAWHARUA (S 55)
Cl/20
SO4
2B
1960-69
1970-79
1980-89
1990-99
2002
NGAWHARUA (S 55)
Cl
10SO4
5HCO3
NGAWHARUA (S 55)
Na
10K
200Ca
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°
NGAWHARUA (S 55)
Na/1000
K/100
Mg

Figure 3.

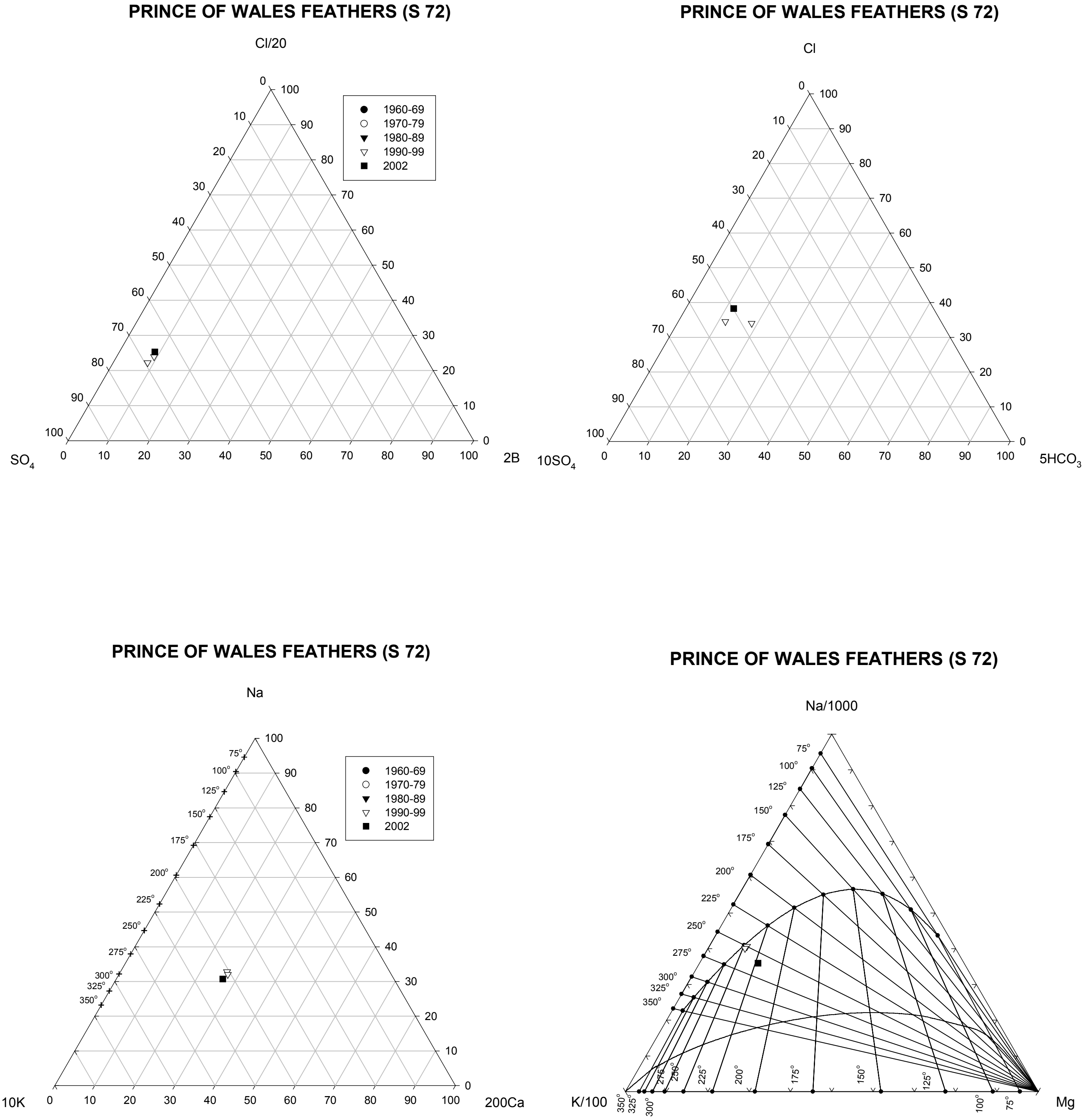

PRINCE OF WALES FEATHERS (S 72)
Cl/20
SO$_4$
2B
1960-69
1970-79
1980-89
1990-99
2002
PRINCE OF WALES FEATHERS (S 72)
Cl
10SO$_4$
5HCO$_3$
PRINCE OF WALES FEATHERS (S 72)
Na
10K
200Ca
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°
PRINCE OF WALES FEATHERS (S 72)
Na/1000
K/100
Mg

Figure 4.

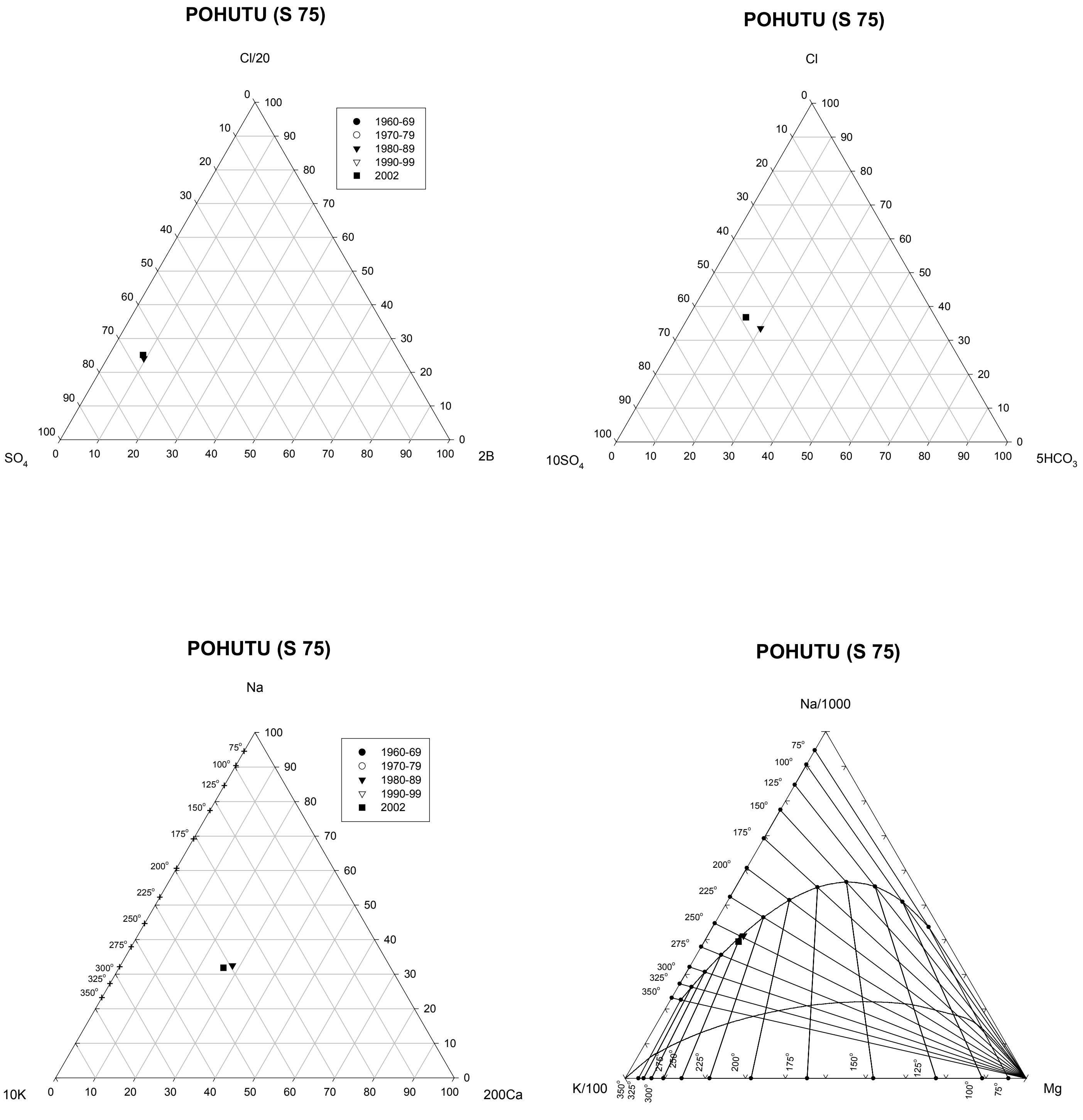

POHUTU (S 75)
Cl/20
SO4
2B
● 1960-69
○ 1970-79
▼ 1980-89
▽ 1990-99
■ 2002
POHUTU (S 75)
Cl
10SO4
5HCO3
POHUTU (S 75)
Na
10K
200Ca
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°
● 1960-69
○ 1970-79
▼ 1980-89
▽ 1990-99
■ 2002
POHUTU (S 75)
Na/1000
K/100
Mg
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°

Figure 5.

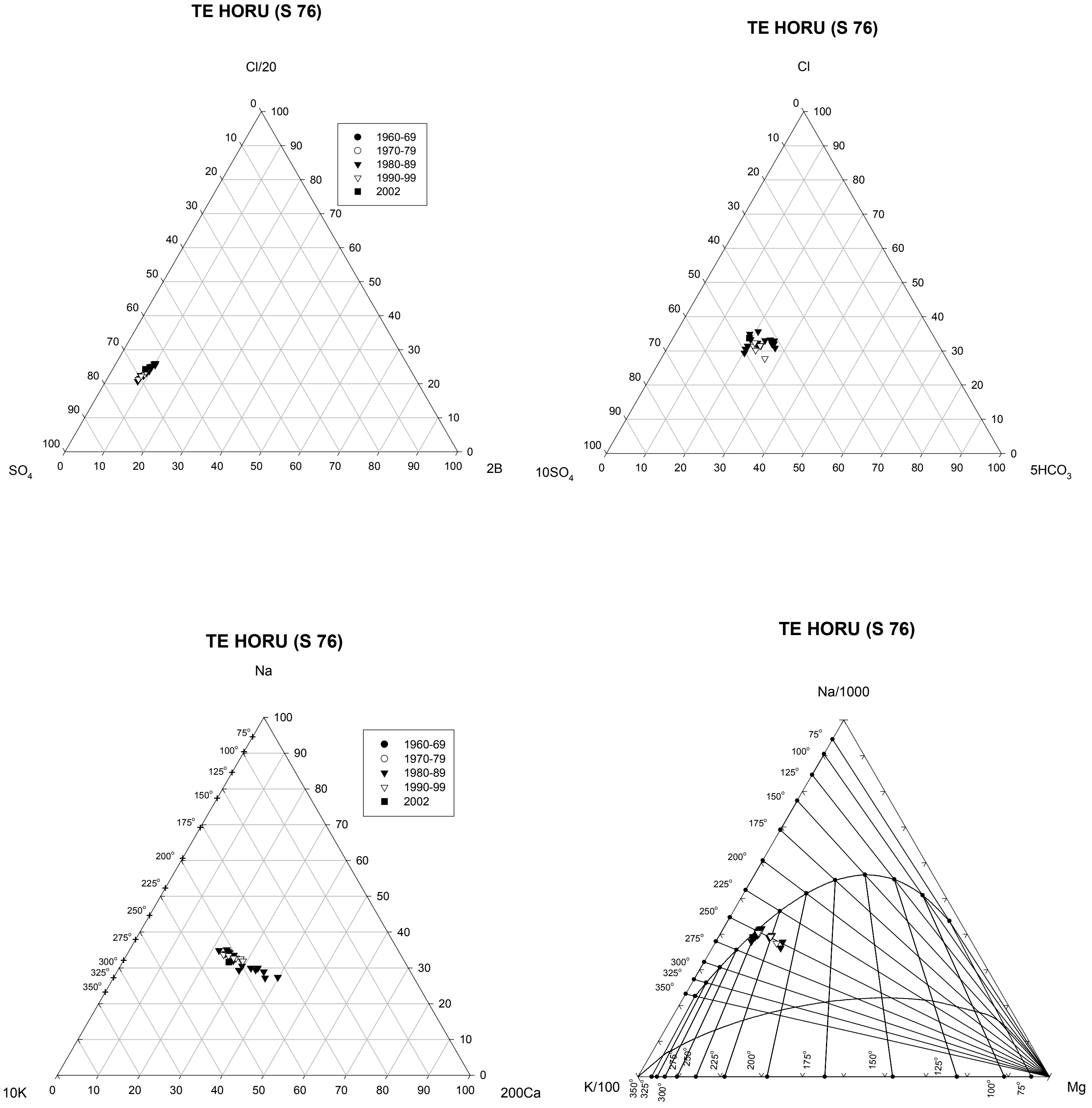

TE HORU (S 76)
Cl/20
SO$_4$
2B
1960-69
1970-79
1980-89
1990-99
2002
TE HORU (S 76)
Cl
10SO$_4$
5HCO$_3$
TE HORU (S 76)
Na
10K
200Ca
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°
1960-69
1970-79
1980-89
1990-99
2002
TE HORU (S 76)
Na/1000
K/100
Mg
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°

Figure 6.

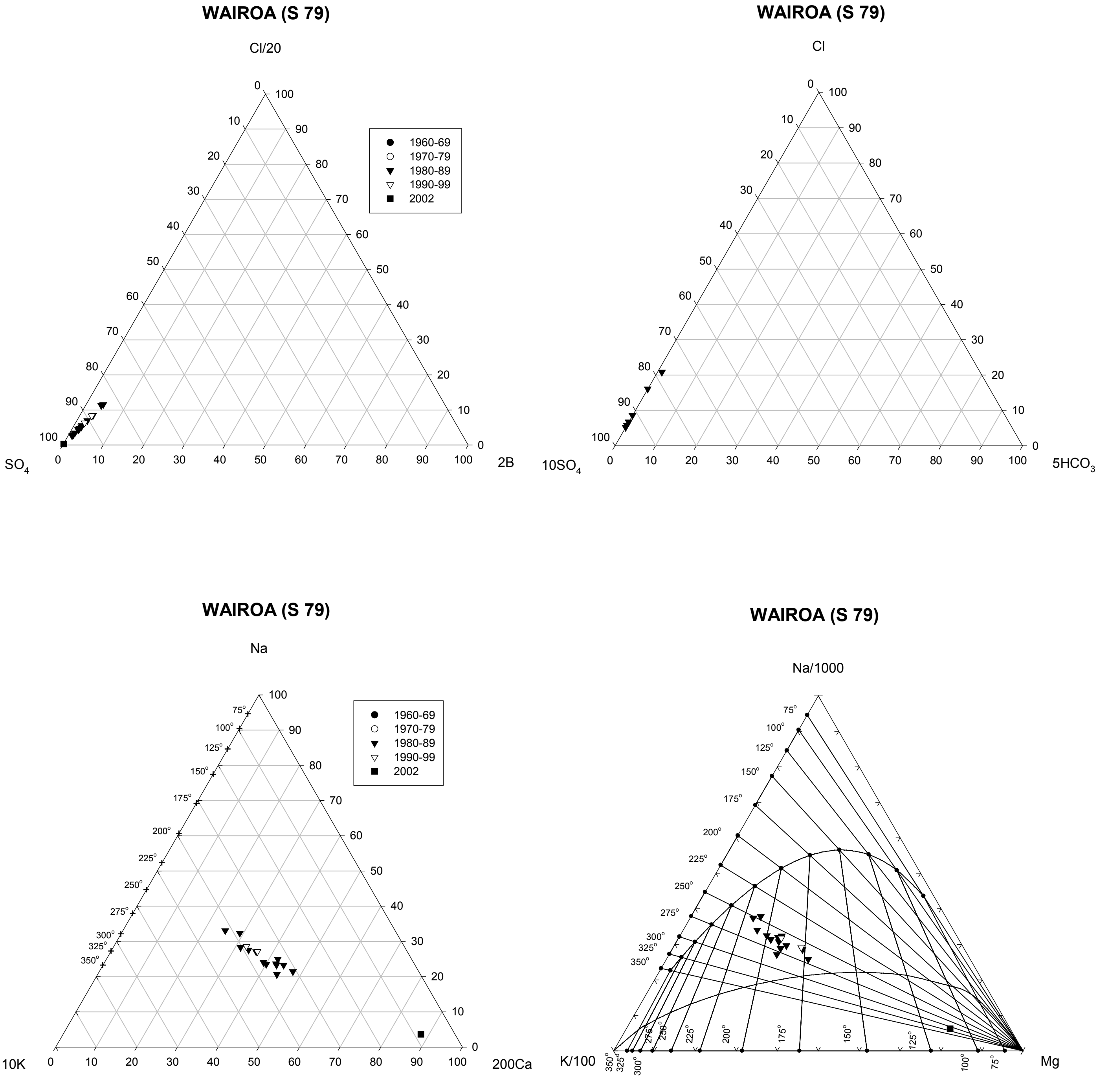

WAIROA (S 79)
Cl/20
SO4
2B
1960-69
1970-79
1980-89
1990-99
2002
WAIROA (S 79)
Cl
10SO4
5HCO3
WAIROA (S 79)
Na
10K
200Ca
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°
WAIROA (S 79)
Na/1000
K/100
Mg

Figure 7.

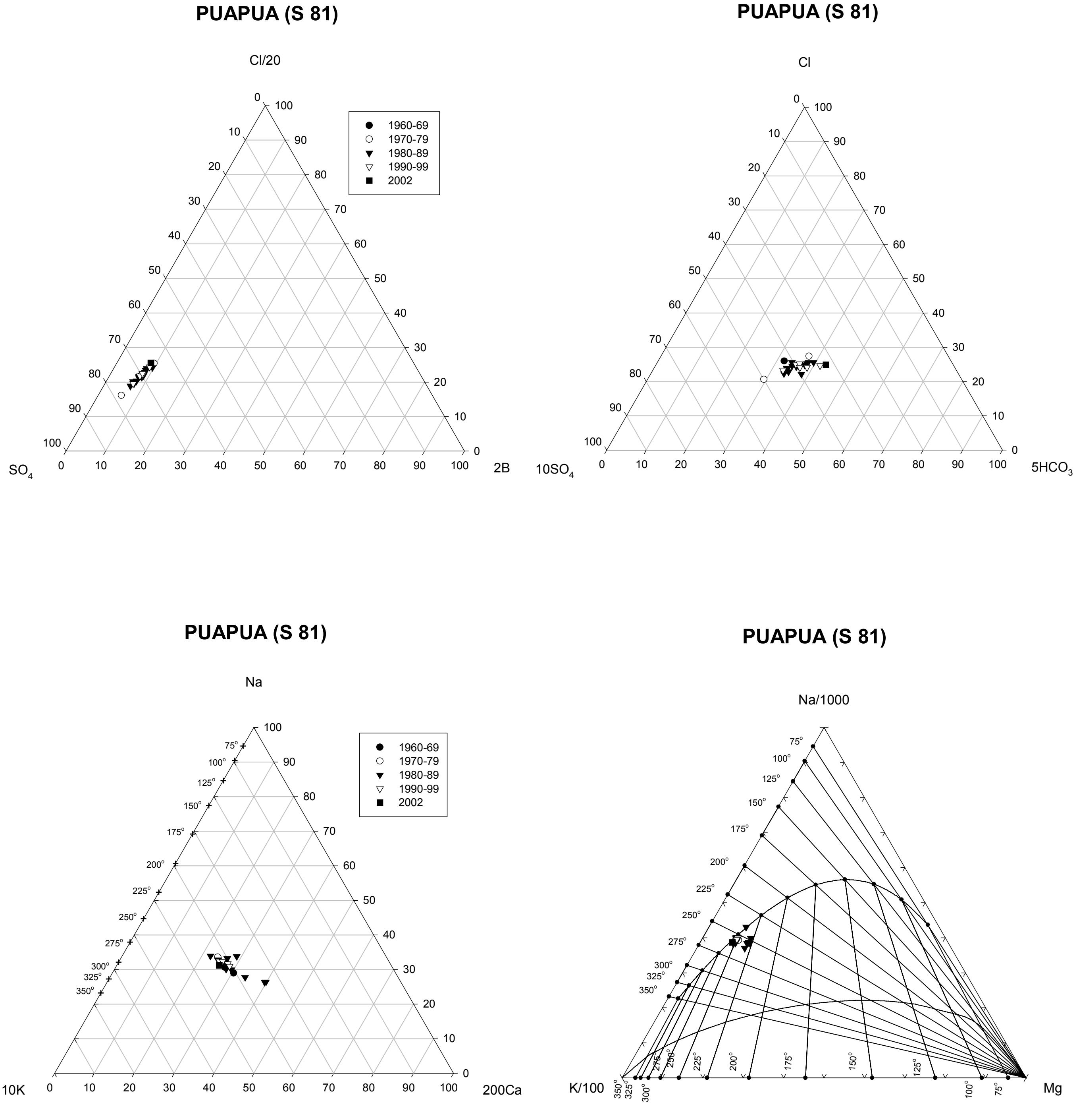

PUAPUA (S 81)
Cl/20
SO4
2B
1960-69
1970-79
1980-89
1990-99
2002
PUAPUA (S 81)
Cl
10SO4
5HCO3
PUAPUA (S 81)
Na
10K
200Ca
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°
1960-69
1970-79
1980-89
1990-99
2002
PUAPUA (S 81)
Na/1000
K/100
Mg
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°

Figure 8.

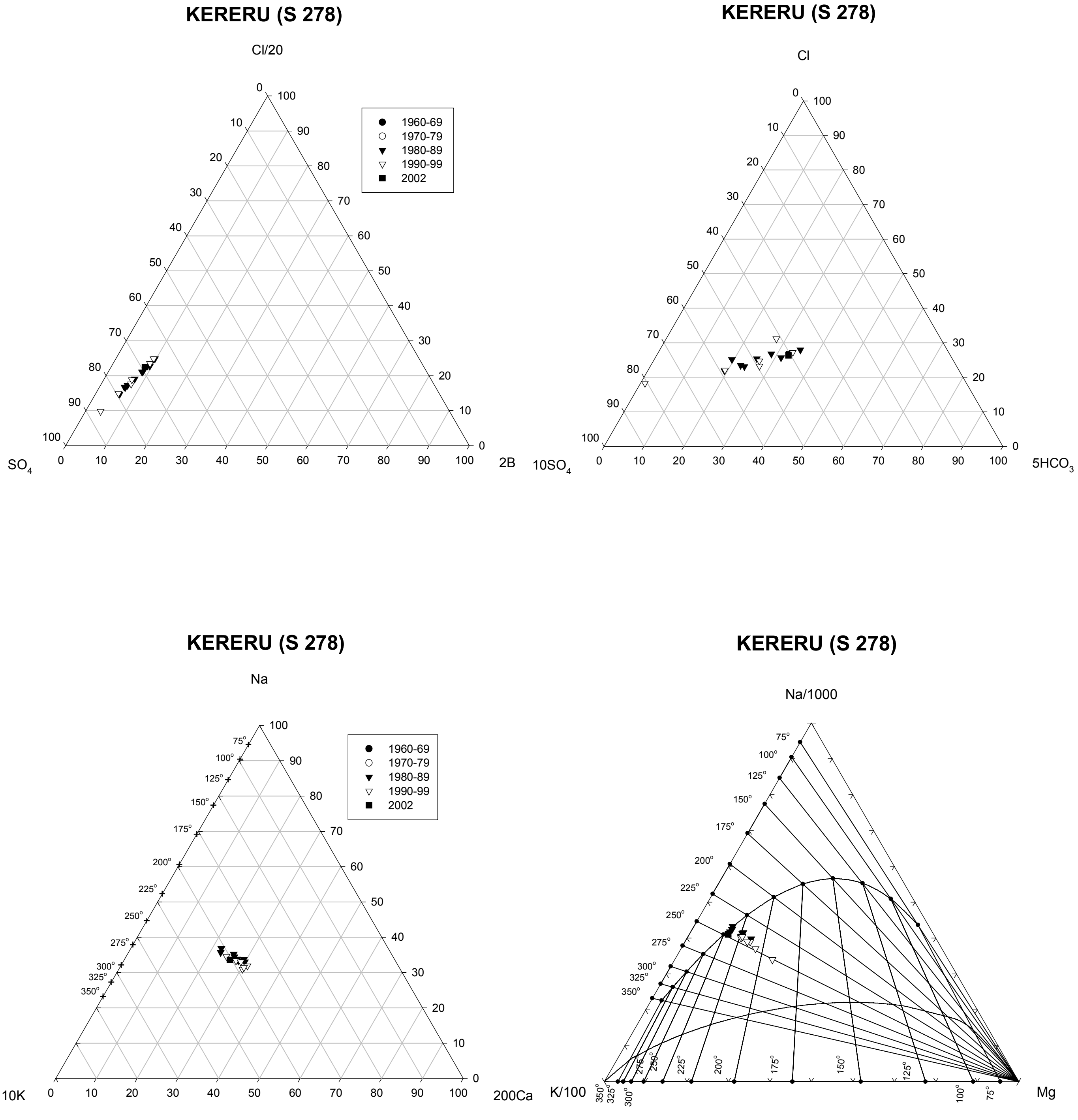

KERERU (S 278)
Cl/20
SO$_4$
2B
1960-69
1970-79
1980-89
1990-99
2002
KERERU (S 278)
Cl
10SO$_4$
5HCO$_3$
KERERU (S 278)
Na
10K
200Ca
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°
KERERU (S 278)
Na/1000
K/100
Mg

Figure 9.

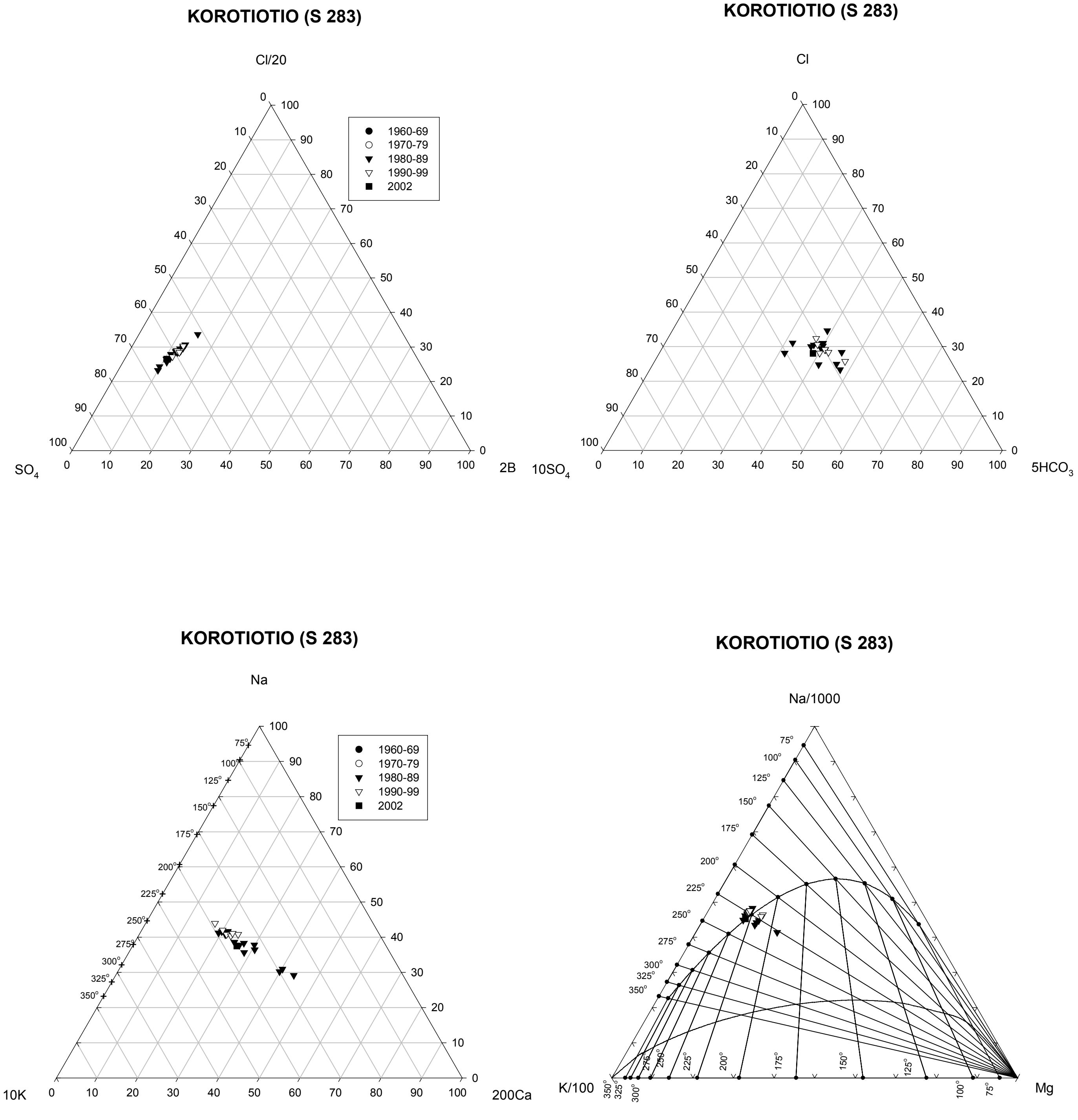

KOROTIOTIO (S 283)
Cl/20
SO$_4$
2B
1960-69
1970-79
1980-89
1990-99
2002
KOROTIOTIO (S 283)
Cl
10SO$_4$
5HCO$_3$
KOROTIOTIO (S 283)
Na
10K
200Ca
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°
1960-69
1970-79
1980-89
1990-99
2002
KOROTIOTIO (S 283)
Na/1000
K/100
Mg
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°

Figure 10.

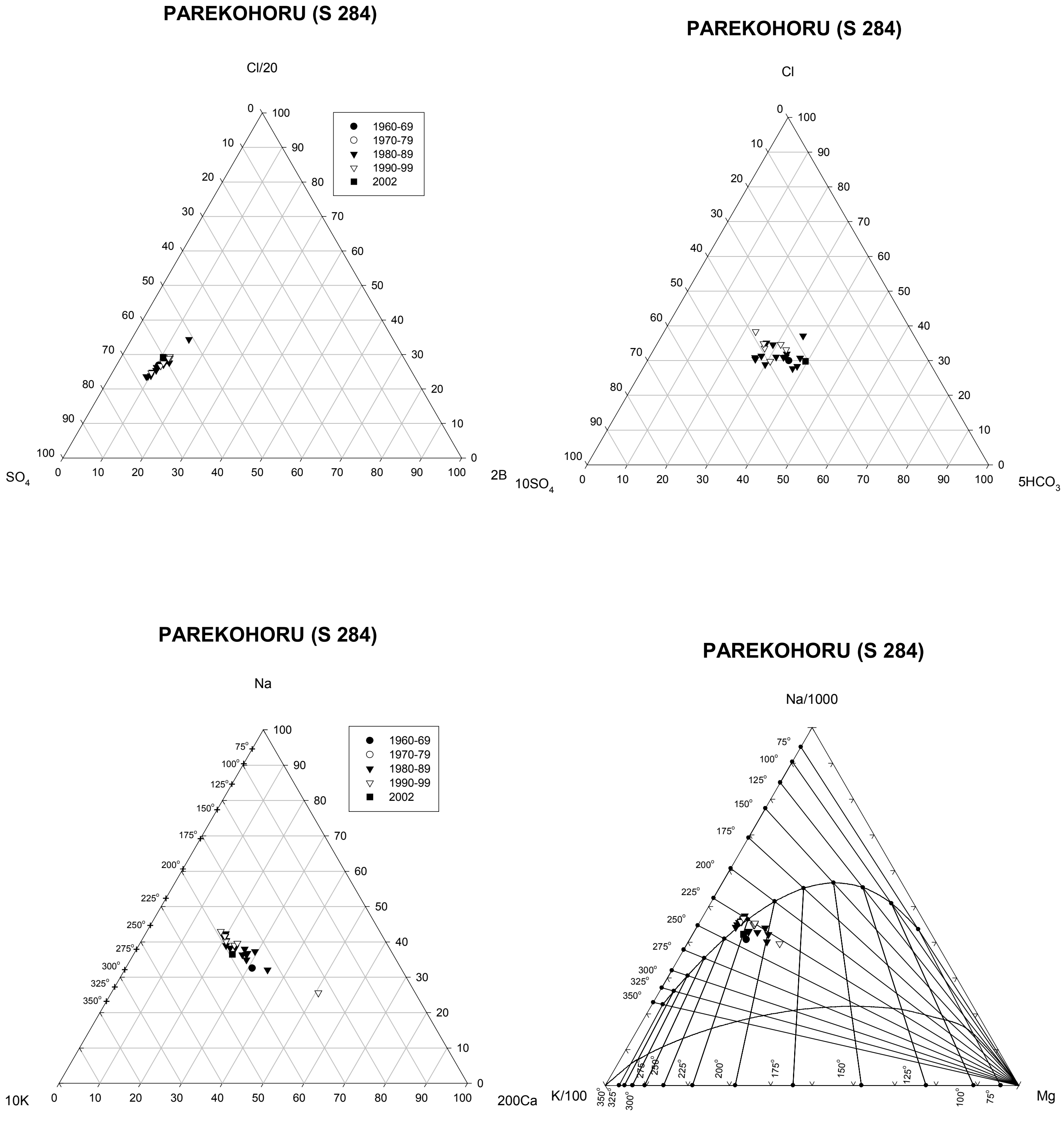
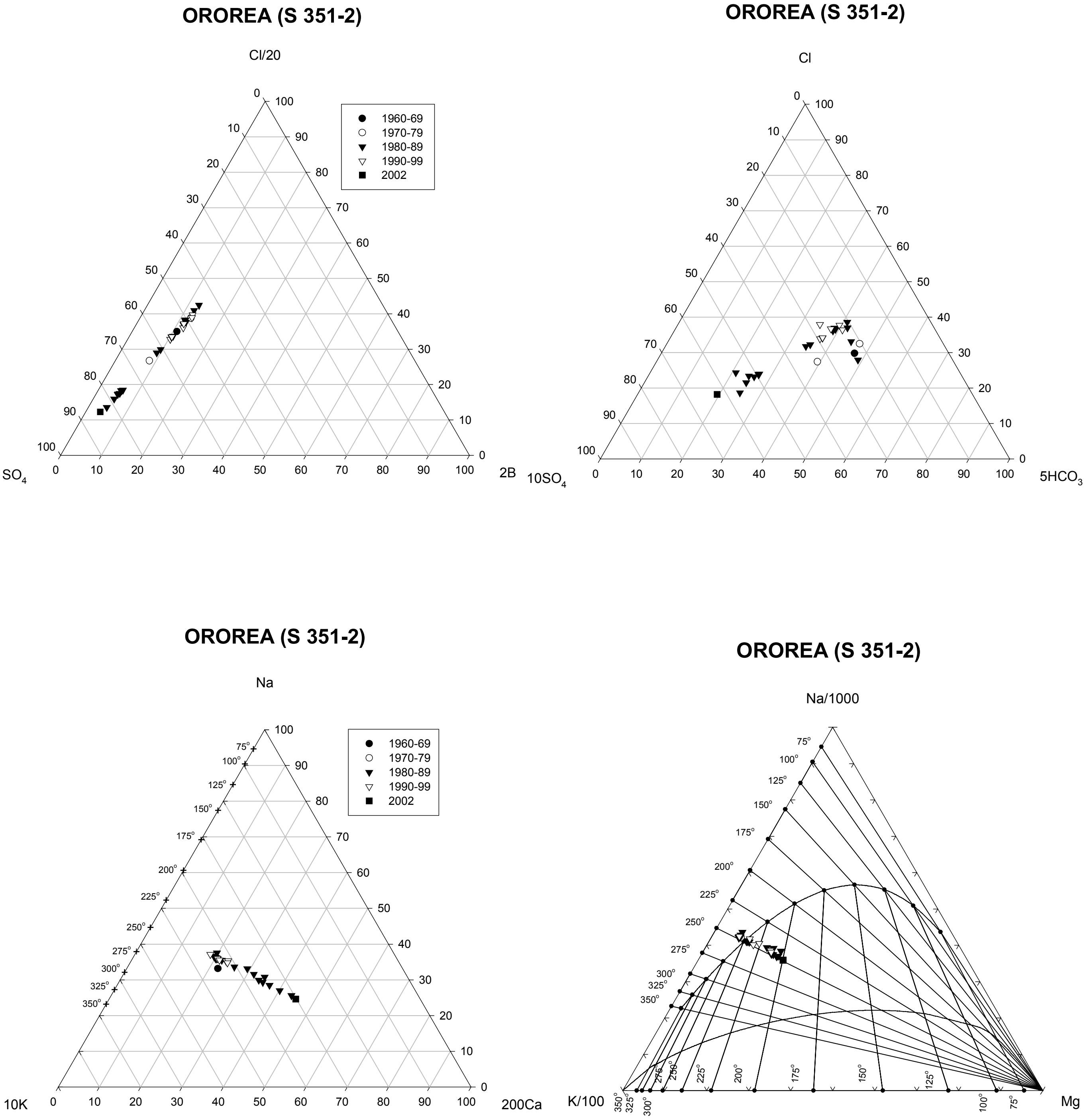

PAREKOHORU (S 284)
Cl/20
SO$_4$
2B
1960-69
1970-79
1980-89
1990-99
2002
PAREKOHORU (S 284)
Cl
10SO$_4$
5HCO$_3$
PAREKOHORU (S 284)
Na
10K
200Ca
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°
1960-69
1970-79
1980-89
1990-99
2002
PAREKOHORU (S 284)
Na/1000
K/100
Mg
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°

Figure 11.

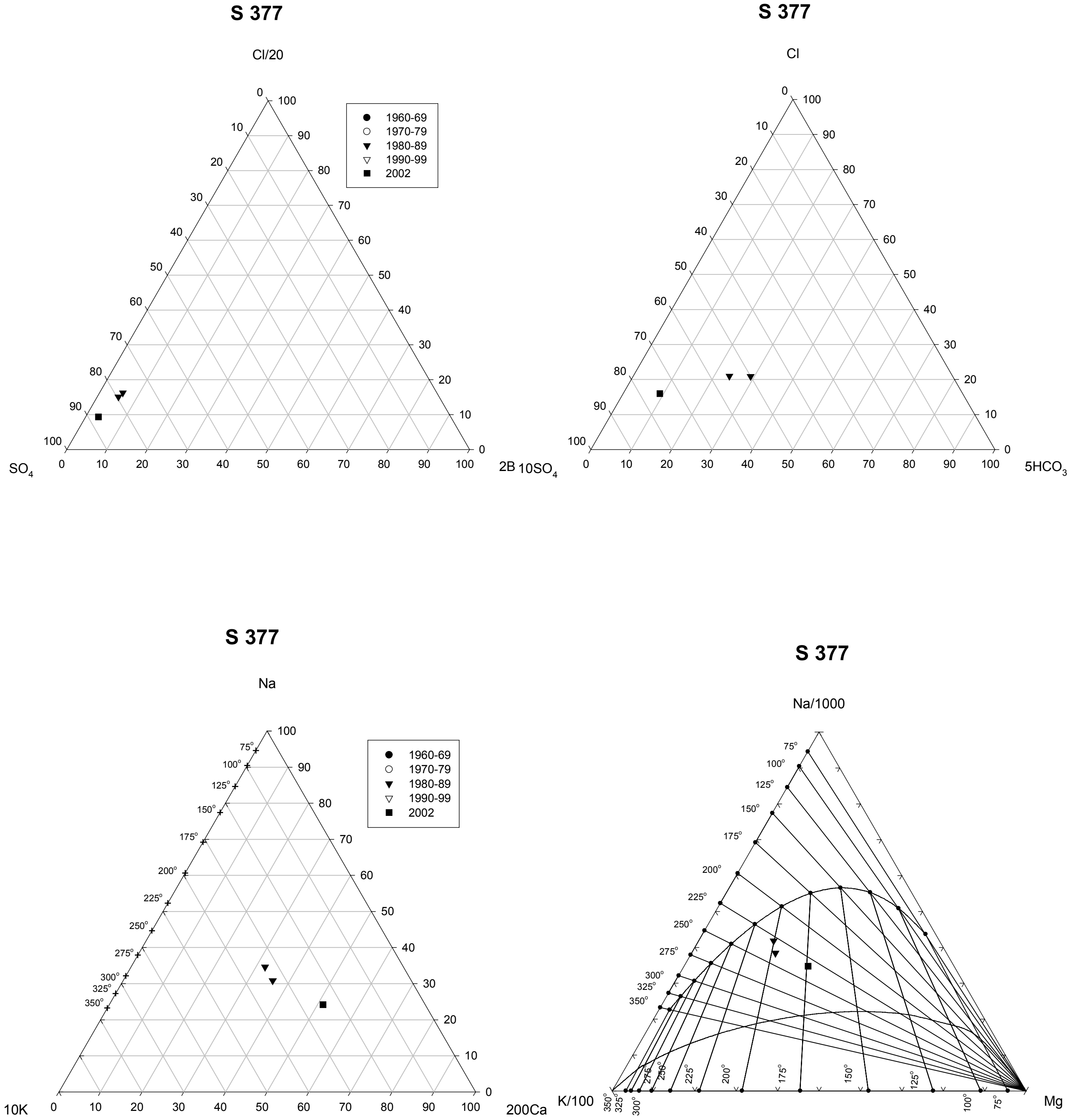

OROREA (S 351-2)

OROREA (S 351-2)

OROREA (S 351-2)

OROREA (S 351-2)

Figure 12.

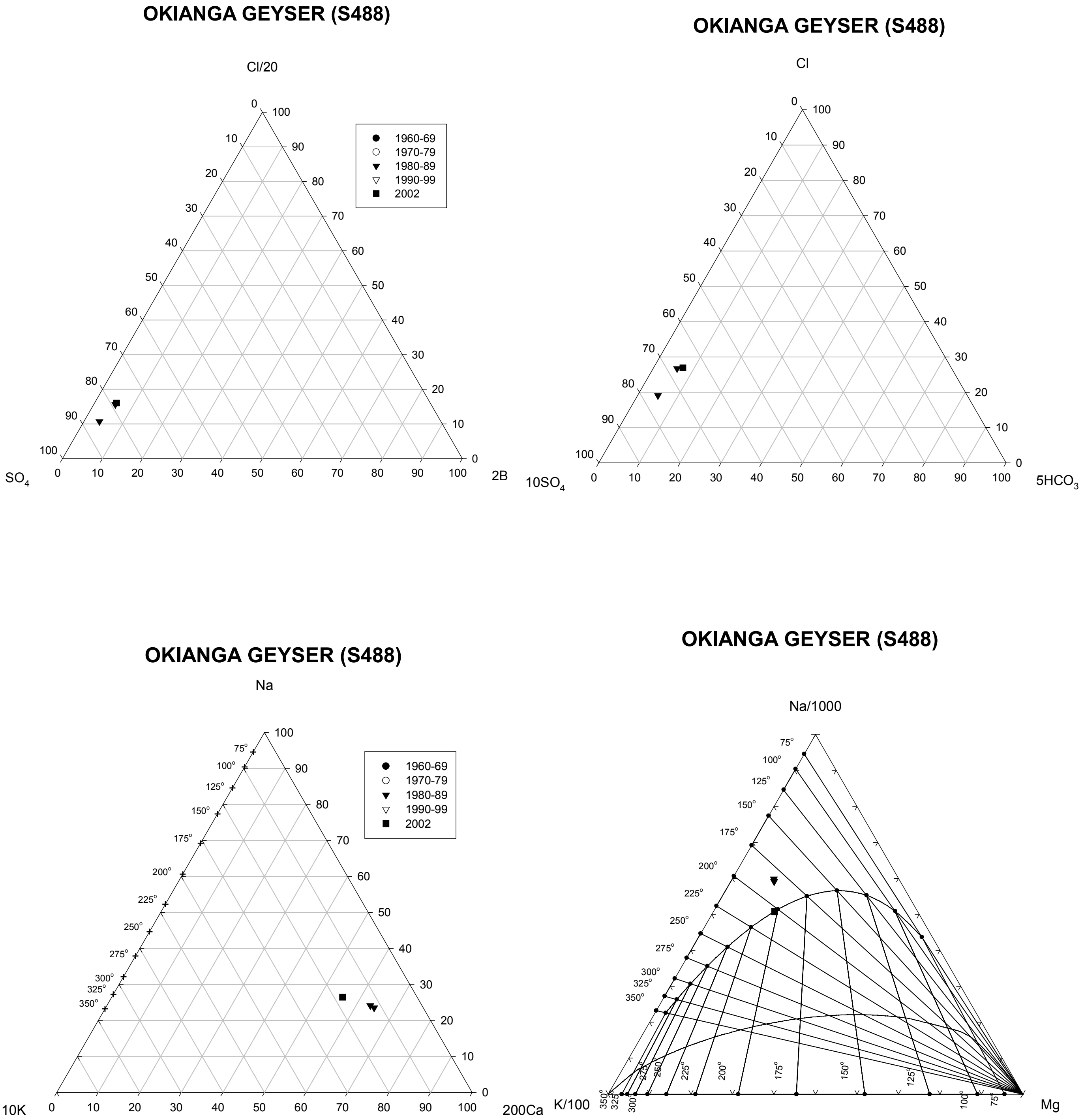

S 377

S 377

S 377

S 377

Figure 13.


OKIANGA GEYSER (S488)

OKIANGA GEYSER (S488)

OKIANGA GEYSER (S488)

OKIANGA GEYSER (S488)

Figure 14.

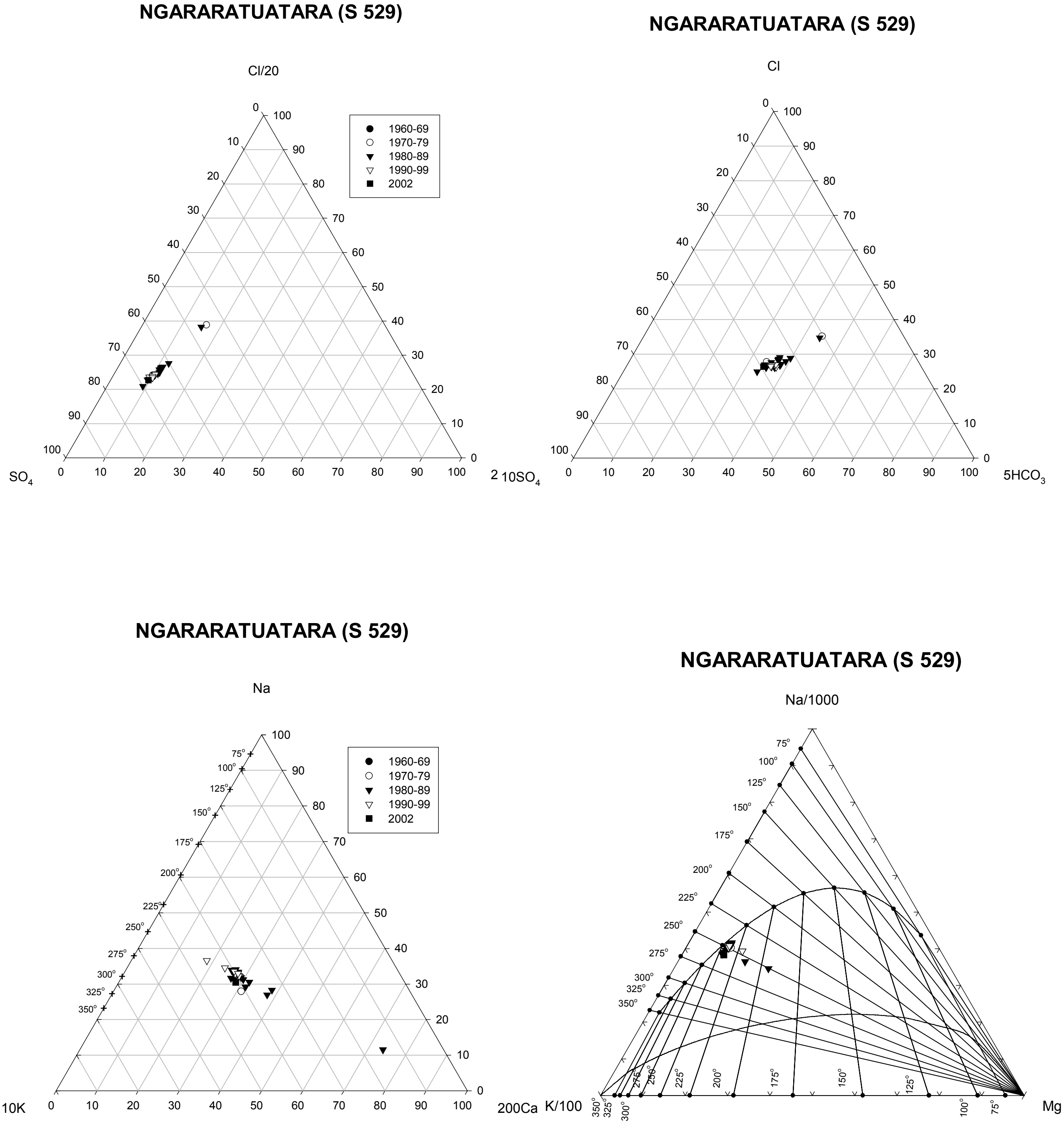

NGARARATUATARA (S 529)
Cl/20
SO4
2 10SO4
1960-69
1970-79
1980-89
1990-99
2002
NGARARATUATARA (S 529)
Cl
10SO4
5HCO3
NGARARATUATARA (S 529)
Na
10K
200Ca
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°
1960-69
1970-79
1980-89
1990-99
2002
NGARARATUATARA (S 529)
Na/1000
K/100
Mg
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°

Figure 15.

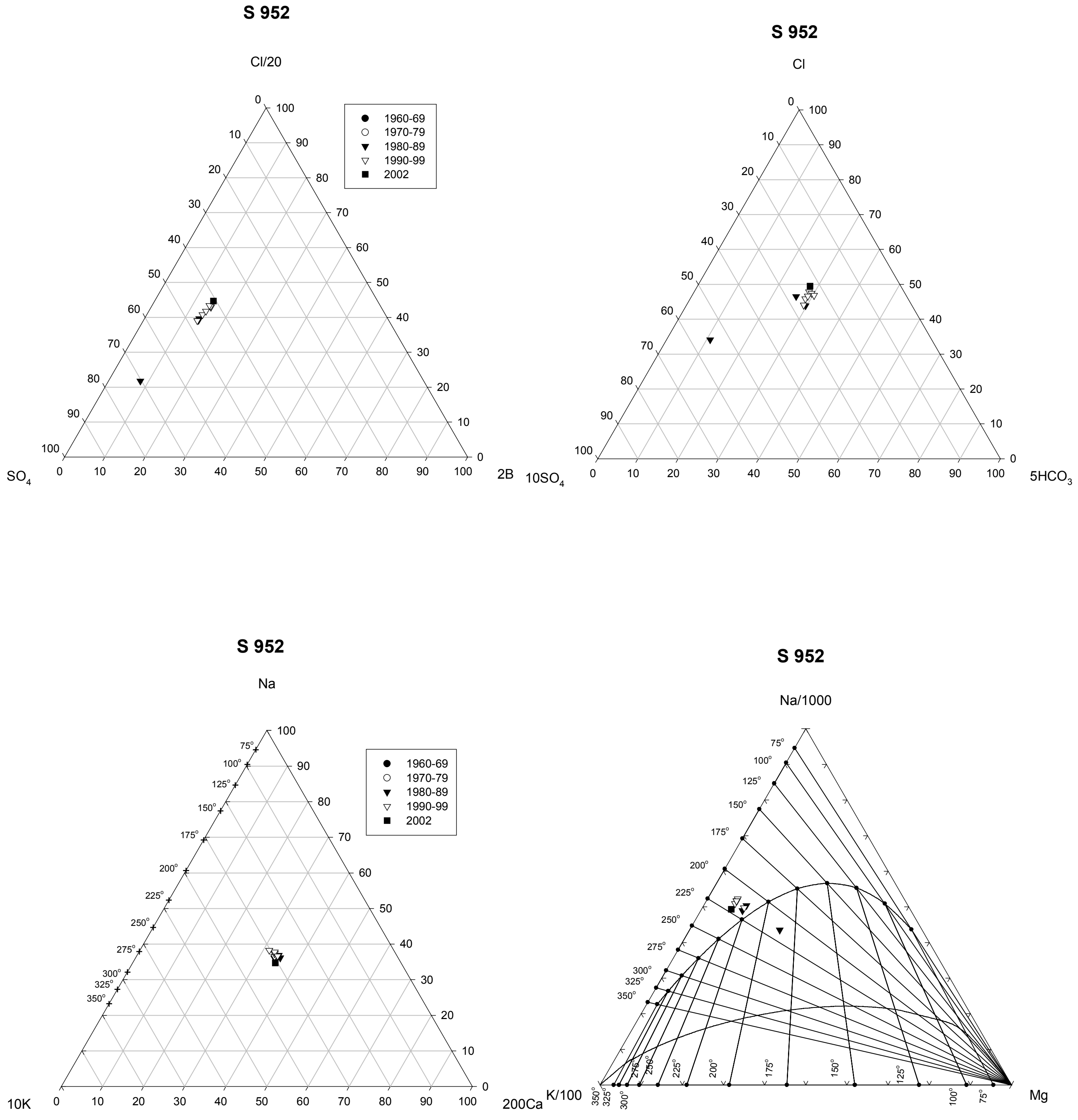
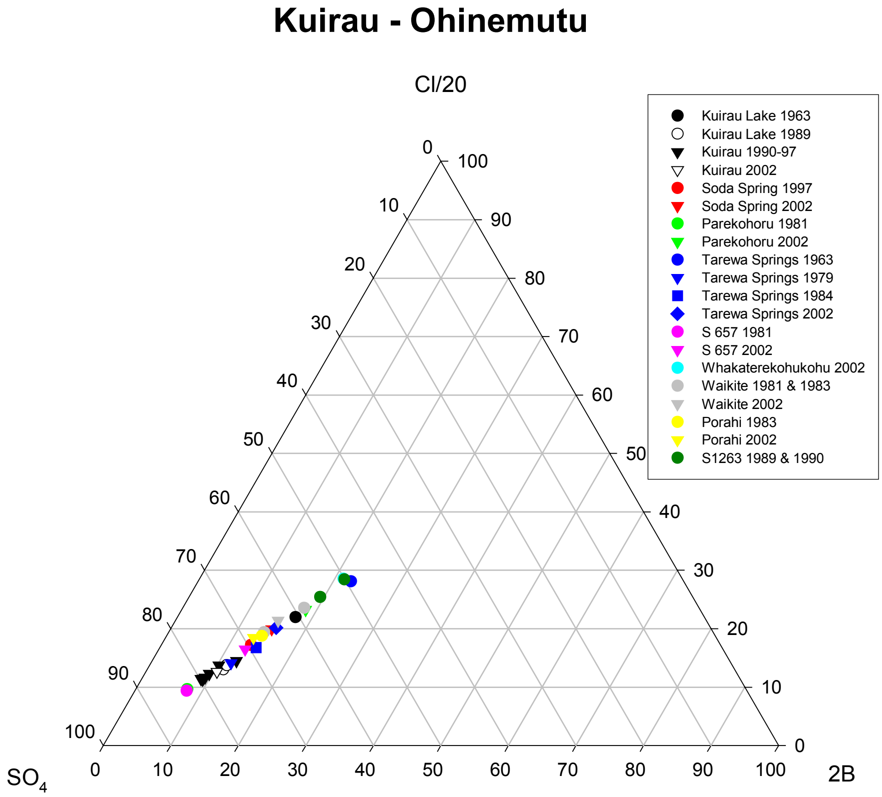

S 952
Cl/20
SO$_4$
2B
1960-69
1970-79
1980-89
1990-99
2002
0 10 20 30 40 50 60 70 80 90 100
S 952
Cl
10SO$_4$
5HCO$_3$
0 10 20 30 40 50 60 70 80 90 100
S 952
Na
10K
200Ca
75° 100° 125° 150° 175° 200° 225° 250° 275° 300° 325° 350°
1960-69
1970-79
1980-89
1990-99
2002
0 10 20 30 40 50 60 70 80 90 100
S 952
Na/1000
K/100
Mg
75° 100° 125° 150° 175° 200° 225° 250° 275° 300° 325° 350°

Figure 16.


Kuirau - Ohinemutu
Cl/20
SO4
2B
0
10
20
30
40
50
60
70
80
90
100
● Kuirau Lake 1963
○ Kuirau Lake 1989
▼ Kuirau 1990-97
▽ Kuirau 2002
● Soda Spring 1997
▼ Soda Spring 2002
● Parekohoru 1981
▼ Parekohoru 2002
● Tarewa Springs 1963
▼ Tarewa Springs 1979
■ Tarewa Springs 1984
◆ Tarewa Springs 2002
● S 657 1981
▼ S 657 2002
● Whakaterekohukohu 2002
● Waikite 1981 & 1983
▼ Waikite 2002
● Porahi 1983
▼ Porahi 2002
● S1263 1989 & 1990

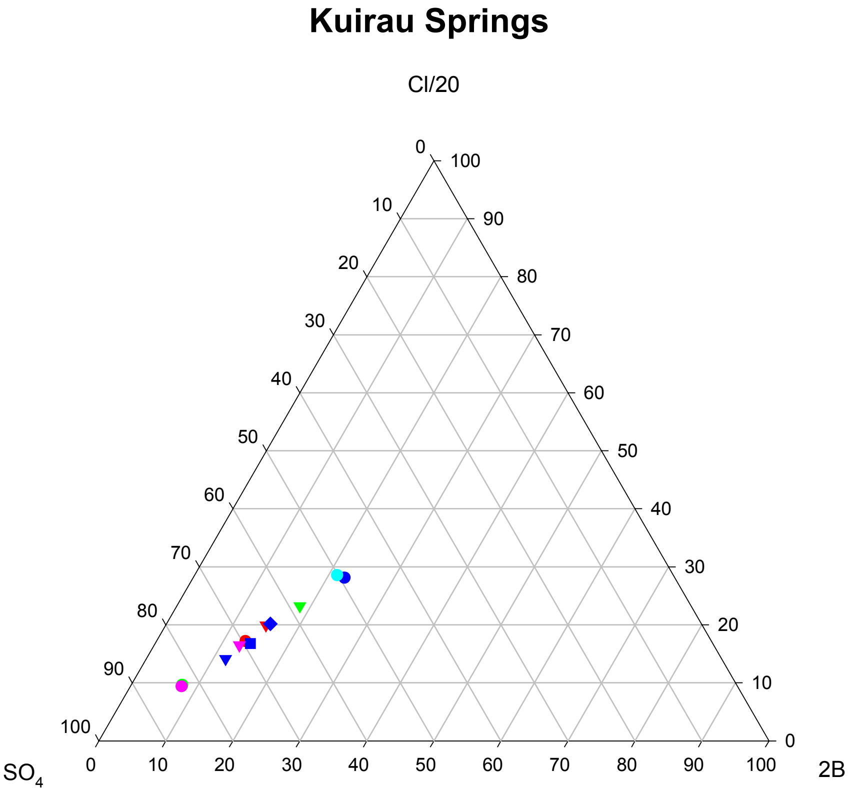

Kuirau Springs
Cl/20
SO4
2B
0
10
20
30
40
50
60
70
80
90
100

Figure 17.

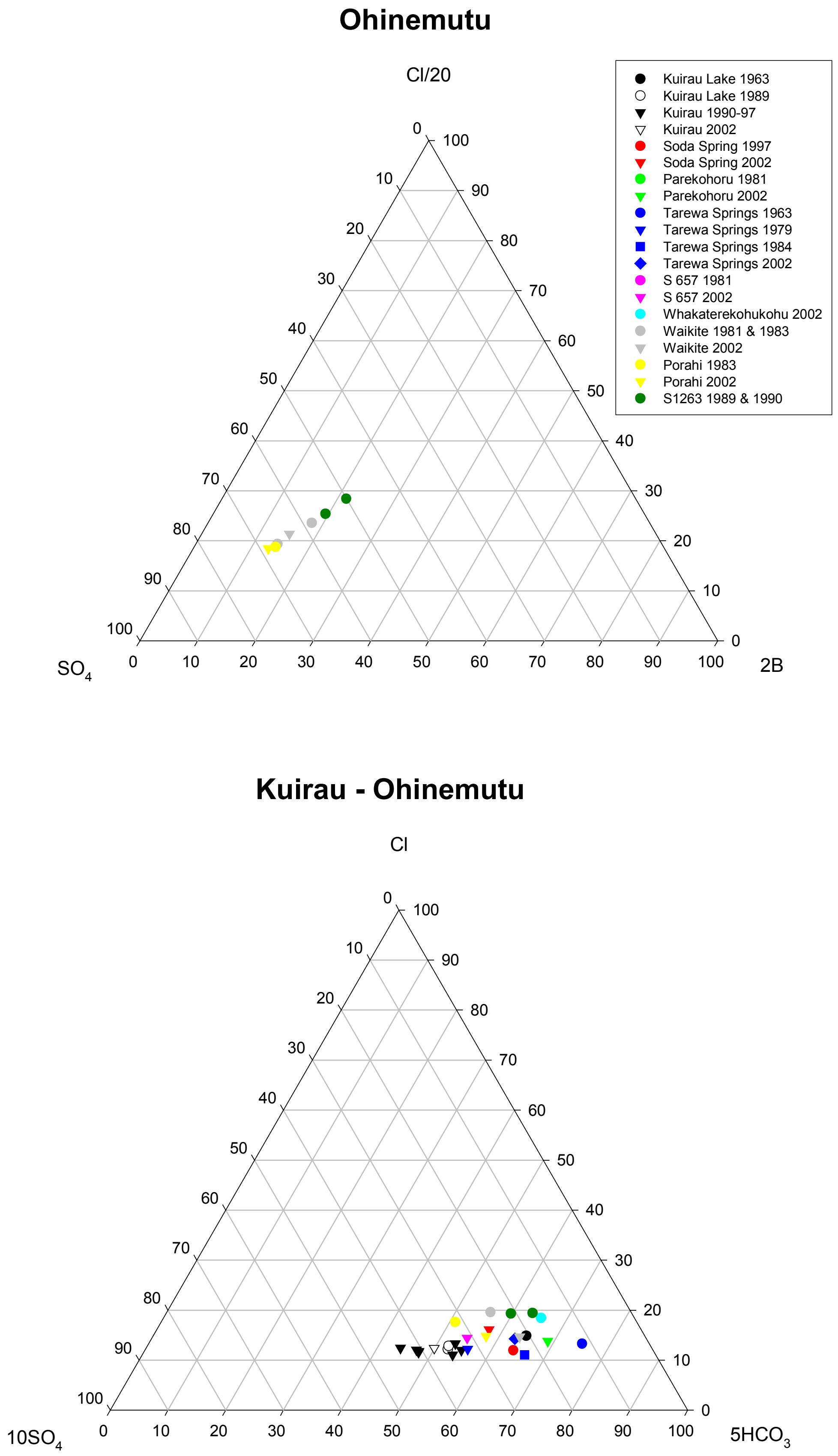

Ohinemutu
Cl/20
SO$_4$
2B
0
10
20
30
40
50
60
70
80
90
100
● Kuirau Lake 1963
○ Kuirau Lake 1989
▼ Kuirau 1990-97
▽ Kuirau 2002
● Soda Spring 1997
▼ Soda Spring 2002
● Parekohoru 1981
▼ Parekohoru 2002
● Tarewa Springs 1963
▼ Tarewa Springs 1979
■ Tarewa Springs 1984
◆ Tarewa Springs 2002
● S 657 1981
▼ S 657 2002
● Whakaterekohukohu 2002
● Waikite 1981 & 1983
▼ Waikite 2002
● Porahi 1983
▼ Porahi 2002
● S1263 1989 & 1990
Kuirau - Ohinemutu
Cl
10SO$_4$
5HCO$_3$

Figure 18.

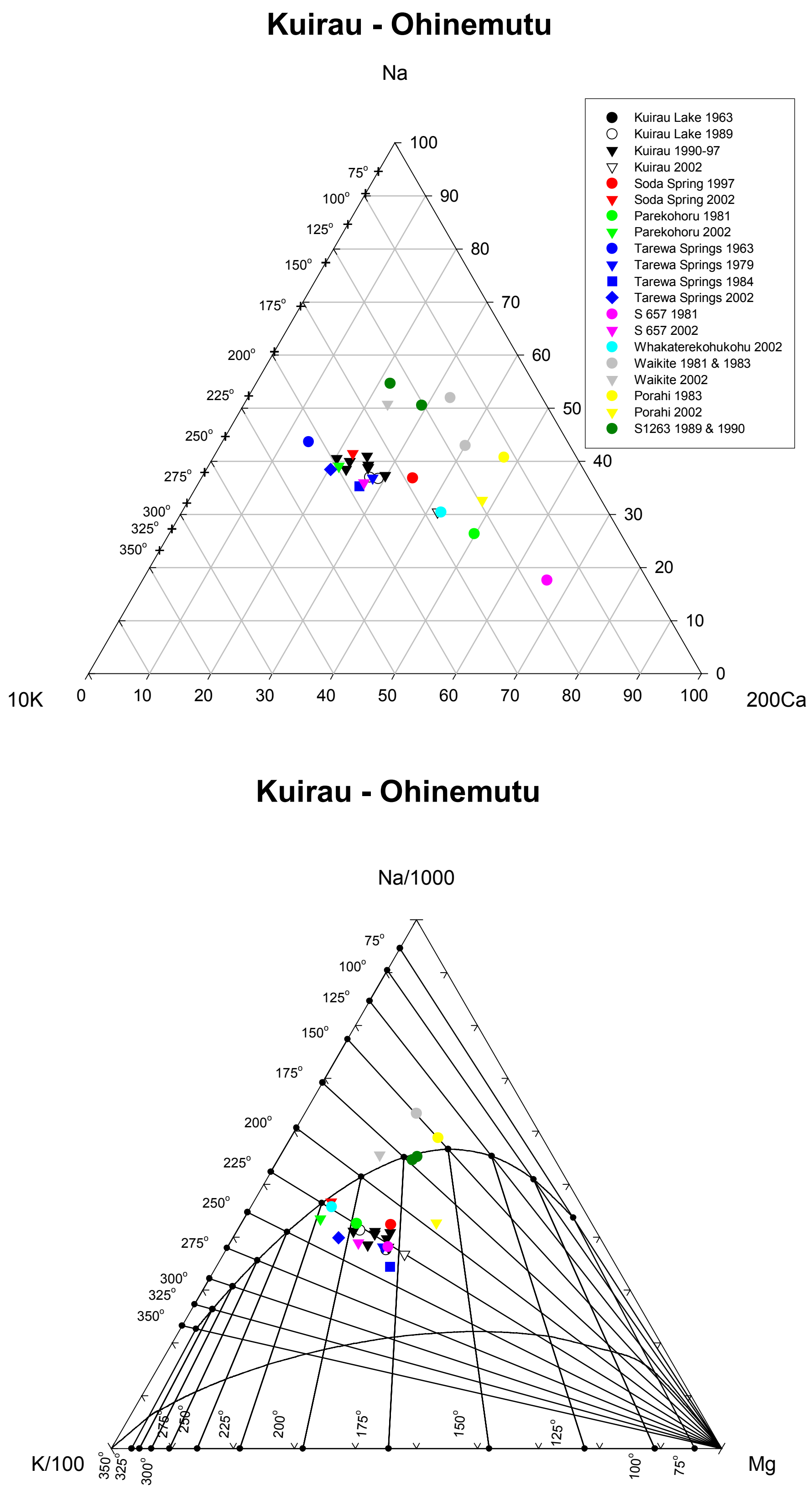

Kuirau - Ohinemutu
Na
10K
200Ca
0
10
20
30
40
50
60
70
80
90
100
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°
● Kuirau Lake 1963
○ Kuirau Lake 1989
▼ Kuirau 1990-97
▽ Kuirau 2002
● Soda Spring 1997
▼ Soda Spring 2002
● Parekohoru 1981
▼ Parekohoru 2002
● Tarewa Springs 1963
▼ Tarewa Springs 1979
■ Tarewa Springs 1984
◆ Tarewa Springs 2002
● S 657 1981
▼ S 657 2002
● Whakaterekohukohu 2002
● Waikite 1981 & 1983
▼ Waikite 2002
● Porahi 1983
▼ Porahi 2002
● S1263 1989 & 1990
Kuirau - Ohinemutu
Na/1000
K/100
Mg
75°
100°
125°
150°
175°
200°
225°
250°
275°
300°
325°
350°

Figure 19.

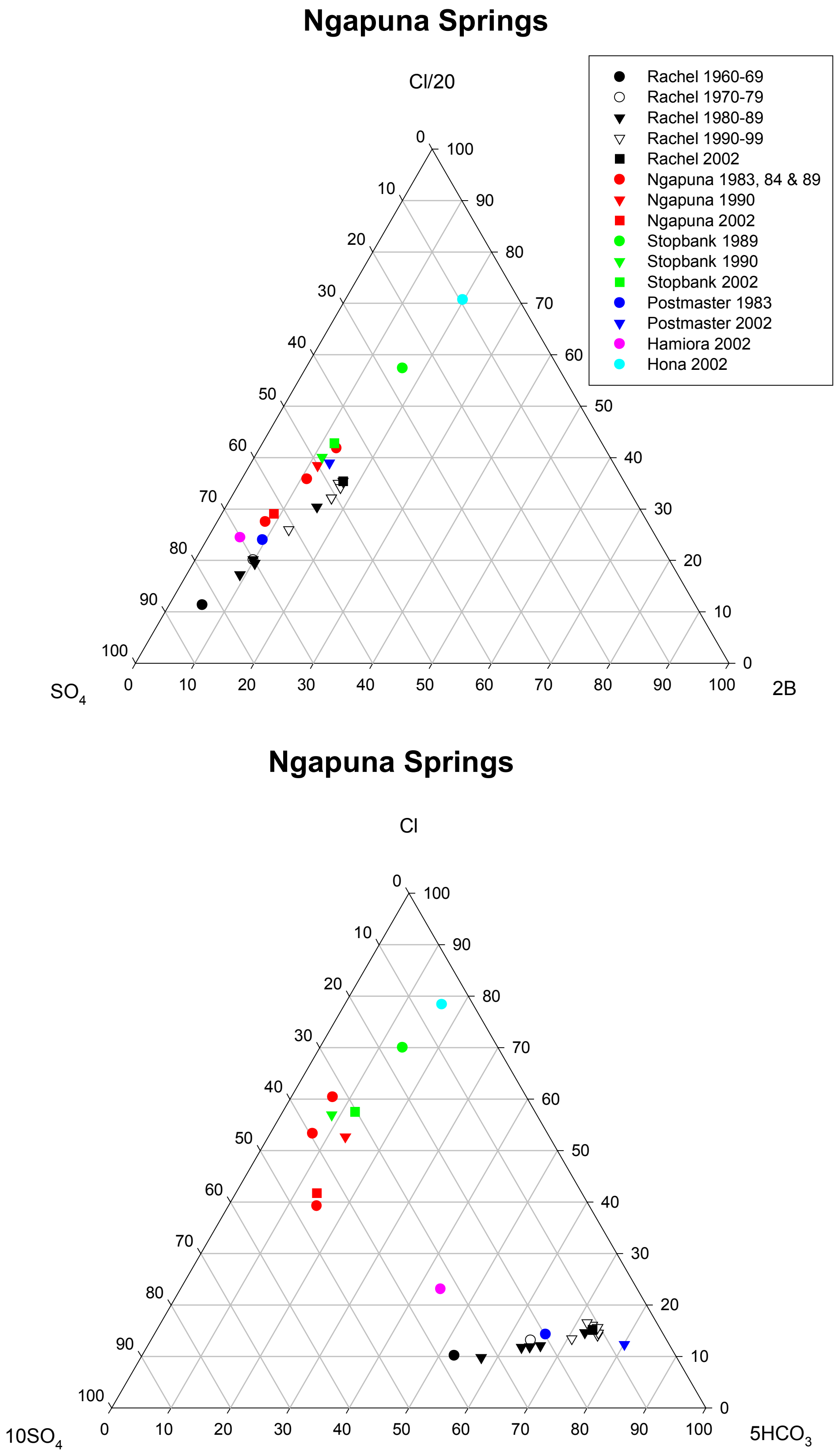

Ngapuna Springs
Cl/20
SO4
2B
0
10
20
30
40
50
60
70
80
90
100
● Rachel 1960-69
○ Rachel 1970-79
▼ Rachel 1980-89
▽ Rachel 1990-99
■ Rachel 2002
● Ngapuna 1983, 84 & 89
▼ Ngapuna 1990
■ Ngapuna 2002
● Stopbank 1989
▼ Stopbank 1990
■ Stopbank 2002
● Postmaster 1983
▼ Postmaster 2002
● Hamiora 2002
● Hona 2002
Ngapuna Springs
Cl
10SO4
5HCO3

Figure 20.

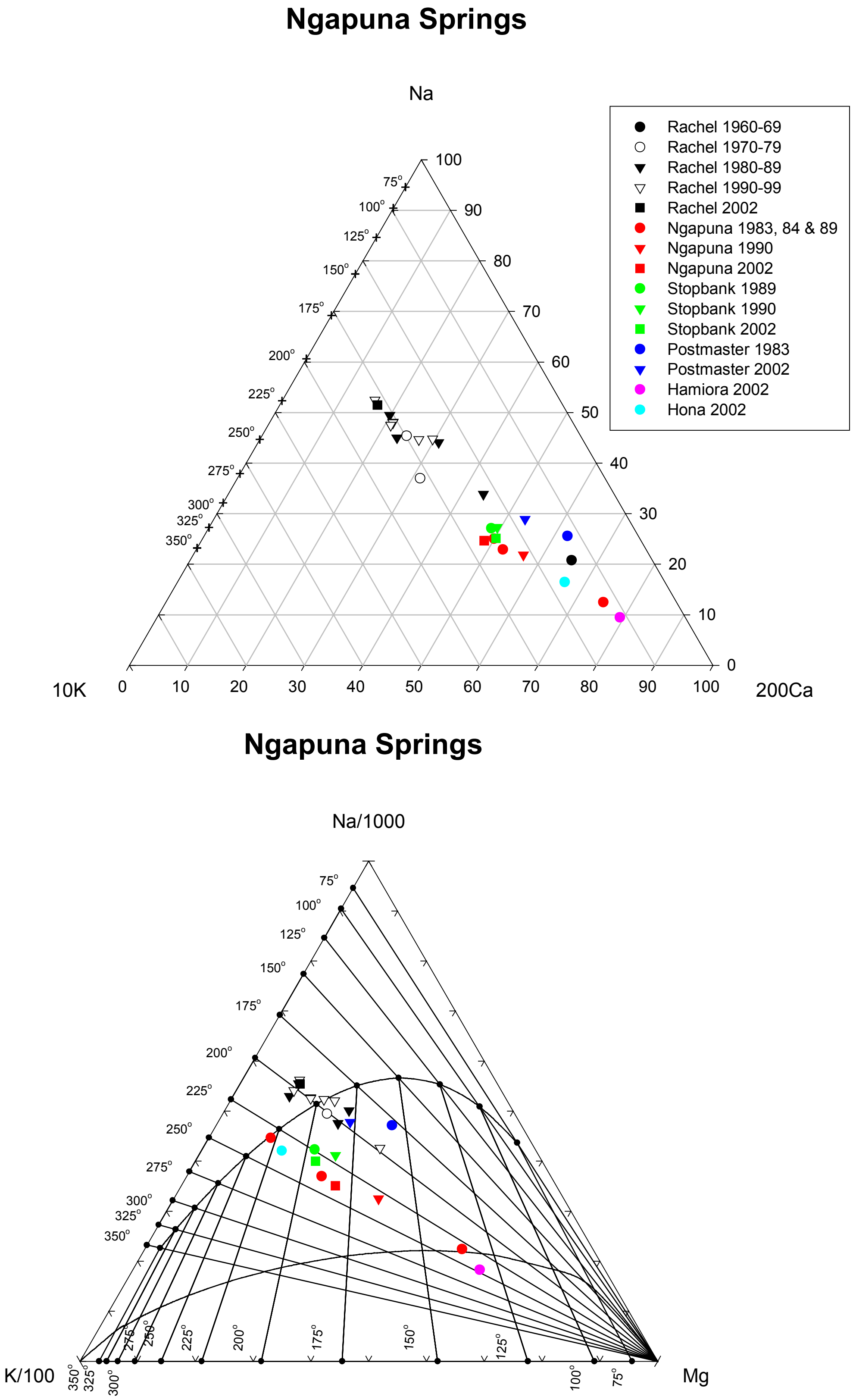

Ngapuna Springs
Na
Rachel 1960-69
Rachel 1970-79
Rachel 1980-89
Rachel 1990-99
Rachel 2002
Ngapuna 1983, 84 & 89
Ngapuna 1990
Ngapuna 2002
Stopbank 1989
Stopbank 1990
Stopbank 2002
Postmaster 1983
Postmaster 2002
Hamiora 2002
Hona 2002
10K
200Ca
0 10 20 30 40 50 60 70 80 90 100
75° 100° 125° 150° 175° 200° 225° 250° 275° 300° 325° 350°
Ngapuna Springs
Na/1000
K/100
Mg
75° 100° 125° 150° 175° 200° 225° 250° 275° 300° 325° 350°

Figure 21.

Appendix 1. Project Brief – Chemistry of the Rotorua Geothermal Field.

D A Gordon

Environment B·O·P.

1. Introduction

In July 1999 the Environment B·O·P's Rotorua Geothermal Regional Plan became operative with the primary purpose to promote the integrated and sustainable management of the Rotorua geothermal resource. The objectives of the Operative Rotorua Geothermal Regional Plan are to ensure that the Rotorua geothermal resource retained its value and potentials, while; protecting geothermal surface features, protecting tikanga Maori, identifying and, as practical, enhancing available geothermal resources, providing for the allocation of that resource for present and future efficient use, and controlling all adverse effects on the field. Some of the key polices of the plan are:

- A 1.5 km radius mass abstraction exclusion zone around Pohutu Geyser to protect the outstanding geothermal features at Whakarewarewa,
- No net increase in abstraction from the field. This has been set at mass extraction for 1992 as the maximum permitted for the field (4400 tonnes/per day for the field),
- Reinjection of all fluid - additional tonnes of fluid has been able to be allocated through reinjection, while still allowing a recovery in water level,
- Setting of strategic level in the geothermal aquifer to sustain geothermal surface features and protect the resources into the future,
- Protection of surface features from physical destruction and restoration of outflows and the avoidance or mitigation of natural geothermal hazards.

2. Background

To effectively manage the geothermal field requires information about the geothermal resource. To achieve this, monitoring and information gathering requirements were included in the Operative Rotorua Geothermal Regional Plan. These policies and methods are:

- Ensuring that the Rotorua geothermal field monitoring programme is oriented to provide information that supports the objectives and polices in the regional plan for the field,
- Continue with field monitoring and research as resources permit, to enable a update quality field management model, tested by peer review.

A variety of different tools to monitor and predict changes in the field are available to Environment B·O·P, and these include: a field model, the assessment of water level monitoring trends, information from bore construction and testing, and the monitoring of chemical and thermal changes across the field.

Implementation of the plan policies has been ongoing since the plan became operative but the recent recovery of surface features has highlighted the issue of field management with stakeholders and the greater community. The Operative Rotorua Geothermal Regional Plan is scheduled for review in 2004.

One the key conclusions from a recent monitoring report (Environmental Report 2001/22 (Grant-Taylor et al. 2001)) for the field confirmed a slow rise rising trend in water levels across the field since bore closure that cannot be fully accounted for by rainfall variation and where usage patterns have essentially stabilised. A possible explanation for this trend is an increase in total output from the field. It has been shown by Kissling (2000) that it is possible for heat and mass output to vary by several percent on timescales of decades. This rise may have started early in the monitoring programme during the 1980's and would have been obscured by the downward trend in water levels in the field until 1986 bore closure.

Computational models of the field suggested that as a result of closure programme the flow from the reservoir to Whakarewarewa would increase from 190 kg/sec to 250 kg/sec but the actual data shows an increase from 200 kg/sec to 300 kg/sec. The models also suggested that the outflow at Kuirau Park/Ohinemutu would increase from 0 kg/sec to 15 kg/sec of 180^{o}C fluid. The measure value in 1993 was about 40 kg/sec, including a large groundwater dilution component (Burnell and Young, 1994).

2.1 Hydrological and Geochemical Models of the Field

The flow of fluids in the field is constrained by geological structure and the physical properties of the fluid.

Glover (1974) compiled previous chemical surveys in the field, and provides a general summary of hot chloride water rising near Whakarewarewa. This flow mixes with a secondary flow arising near Pukeroa Dome and both are diluted with a low chloride ground water in the west and northwest, as they flow northwards. By 1985, Simpson (1985) and Wood (1985) recognise the importance of structural controls on the hydrology, and with the improved techniques of dilution maps (Glover and Heinz, 1985), and isotope measurement (Stewart and Taylor, 1985), bores could be grouped by water type. The general model is of springs at Whakarewarewa fed directly by deep water of approximately 230ºC. This deep hot fluid also rises to the surface in the Ngapuna area and also flows north and west under Rotorua City (Grant- Taylor 2001 et al.). From 1992, the detail of this model had improved due to refinements in measurement techniques and increased computing capability. Different techniques again showed somewhat different conclusions and the data is not sufficiently precise to enable choice between the shallow mixing and direct fluid upflow models. This discrepancy is most noted in the west of the field (Grant-Taylor et al., 2001).

Giggenbach and Glover (1992) suggest that, on the basis of the chemistry of both water and gas the field fluid is derived from the basaltic, or associated rhyolitic sources of "spreading" tectonics, with a main hot fluid plume arising to the east of the field. This plume reaches the surface with little dilution by meteoric waters, and also feeds the Whakarewarewa area. A second, very much more altered plume of high bicarbonate fluid feeds the west. This fluid is cooled by long contact times, and diluted by meteoric water. Glover (1992) used a chloride budget to show that nearly 60% of the total output from the field is discharged through the lake bottom. The geothermal fluid appears to be of similar composition to the south-eastern fluid which would suggest that there is excellent hydraulic connection between the lake floor and the geothermal aquifer (Grant-Taylor et al., 2001).

Stewart *et al*., (1992) draws somewhat different conclusions as their model was derived from isotopic and chemical data from water and gas samples which suggests that the east-west flow is of shallower origin. They favour a boiling primary upflow in the east, extending from

Whakarewarewa, through Ngapuna towards the lake. A portion of this outflow passes under the sediments that underlie the city, becoming diluted with bicarbonate-chloride water before mixing with cool ground water, and then discharging at Kuirau/Ohinemutu (Grant-Taylor et al., 2001).

Graham (1992) in his study of rock-water interaction in the field based on strontium isotope ratios, suggests a deep origin for the primary water (of at least 2km) with direct upwelling in the east, and a flow to the west which undergoes dilution by old ground water, and interaction with the country rock (Grant-Taylor et al., 2001).

Glover and Mroczek (1998), by examining silica chemistry and using only the most reliable temperature data, suggest that there are two diluting fluids one at 150ºC and a second at 15ºC. Their data lends weight to the shallow mixing model (Grant-Taylor et al., 2001).

Whatever the merits of the two models it is apparent that the two natural spring areas, in the west and in the east, are interconnected. With the east as the primary source, removal of geothermal fluid provides an alternate "exit" for the upwelling fluid, and provides fluid to the eastern natural features. For the natural features in the west, the mechanism is different, but the result is qualitatively the same. The shallow mixing model gives interception of the fluids supplying the western features, while the deep upwelling to the west model will result in the springs in the west being affected indirectly a reduction of the pressure at the deep source (Figure 1.1) (Grant-Taylor et al., 2001).

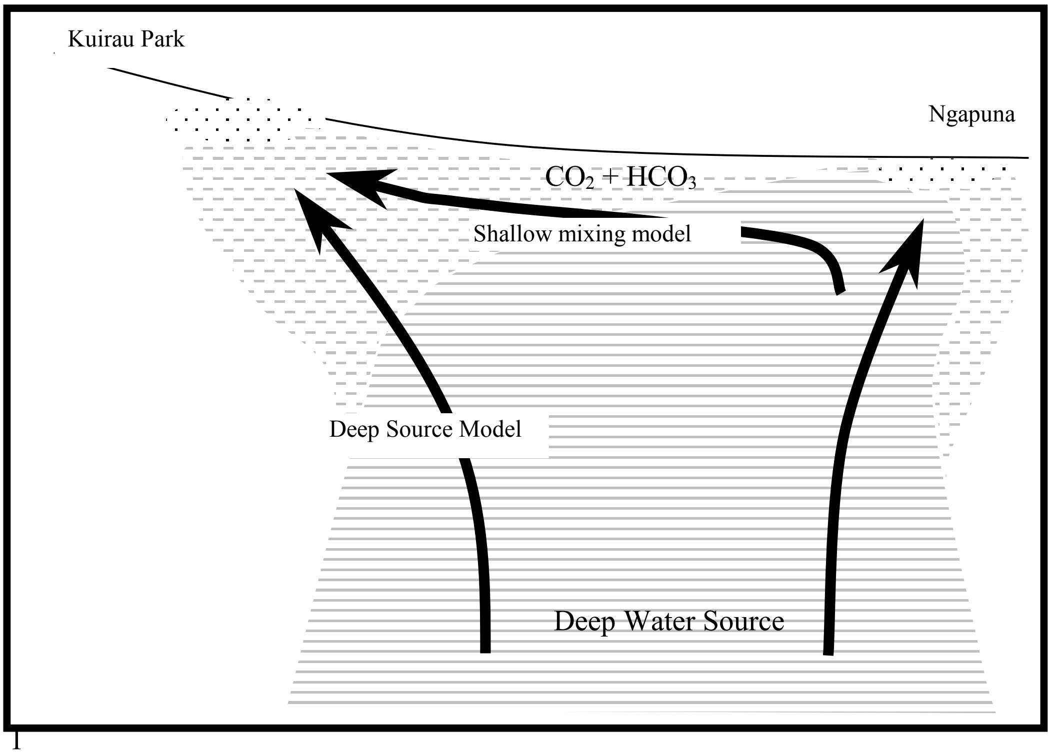


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Figure 1.1 Possible sources for near surface geothermal fluid in Rotorua – shallow mixing and direct deep source model.

2.2 Chemical Characteristics

The processes of boiling, mixing, oxidation and wall rock reaction control the chemistry of the fluid. The extent to which these processes affect the geothermal fluid depends on the rate of the process, and the residence time of the fluid in the reaction zone. In the east hot alkali-chloride fluid is typical of deep fluid in New Zealand geothermal systems.

To the south, Arikikapakapa and Whakarewarewa geothermal fluids contain some bicarbonate but appear to have been diluted by cold ground water before boiling. In the north underlying Rotorua City is an area high in bicarbonate. A secondary high bicarbonate source occurs to the northeast at Kuirau Park/Ohinemutu which represents the deep chloride fluids diluted by shallower possibly steam heated fluids near surface groundwaters. These intermediate depth waters undergo changes as the fluid moves to natural features at the surface. Boiling, dilution, and oxidation tends to reduce the total carbonate species, all chemical concentrations and pH, while sulphate increases as result of oxidation. The best overall representations of the major chemistry of the water are the maps of Stewart et al (1992). Modified versions of these are given (Figure 1.2).

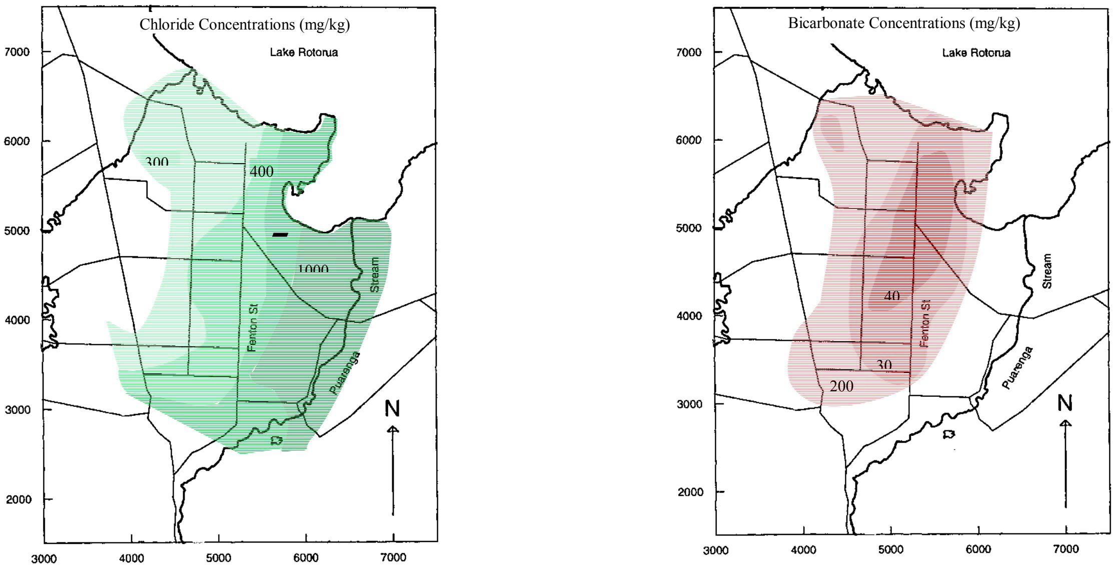

Figure 1.2 Chloride and bicarbonate levels in waters from geothermal bores in Rotorua (after Stewart et al, 1992).

3. Re-examining Chemistry and Geochemical Models of the Field

There has been unprecedented recovery of surface features and the observed slow rising trend in water levels across the field subsequent to bore closure that is beyond variations in rainfall and usage of the field. This has highlighted the issue of current and future field management with stakeholders and the greater community. It is therefore timely that Environment B·O·P undertakes limited chemical survey of the field to assess if there has been any change compared to geochemical data that was collected as part of the 1980's central government funded monitoring programme. Interpretation of this date may also indicate if changes are occurring to the deep upflows zones in the east (Whakarewarewa - Ngapuna) and a possible second zone in the west (Kuirau Park) depending on the geochemical model employed.

The recent major resurgence of springs and natural feature activity and hydrothermal eruptions in Kuirau Park together with water level rises suggests there has been some reheating of the shallow aquifer in the Kuirau Park area. One possible interpretation of this is the presence of a secondary heat source in the area, and this is important to consider this possibility in terms of hazard management, especially in an area where there is limited understanding of the underlying geological structure. The possibility of a second source also has implications for the model for the field and overall field management. Further interpretation of existing Geochemical data from the 1980's monitoring programme and new survey data may assist in reducing the uncertainty of the shallow aquifer system in the northwest and examining the possible presence of a deep secondary upflow.

4. Objectives

The two key tasks for the project are:

Task 1 Conduct a limited geochemical survey and compare to historical data and provide an overall assessment to highlight any changes.

Task 2 Conduct further interpretation of existing and new survey data to provide further insight into shallow aquifer relationships between east (Ngapuna-Whakarewarewa) and northwestern (Kuirau Park) parts of the field and examine the possibility of second deep upflow in the northwest.

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