THE WAITOA LOW ENTHALPY GEOTHERMAL SYSTEM, NEW ZEALAND

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Keywords: *Waitoa, Waikato, low enthalpy, geothermal system, direct use.*

ABSTRACT

Waitoa is a small locality situated about 30 km from the city of Hamilton, New Zealand (Figure 1). It is in the heart of the Waikato dairy land which generally has low lying rolling landscapes, making it ideal for dairy farming. Geologically, Waitoa is located in the Hauraki Rift in the North Island of New Zealand. It is a broad rift valley bounded on the western side by Jurassic greywackes (forming the Hunua Range and its southern continuation, the Hapuakohe Range), and on the eastern side by the tertiary volcanic of rock of the Coromandel Range.

Thermal activity and manifestations are moderate in Waitoa. The spring temperatures rarely exceed 60 ^{o}C and the normal range is from 30-40 ^{o}C. Most of the springs in Waitoa area are associated with the active Kerepehi Fault and its associated structures. During a feasibility study of the area three springs and two boreholes were sampled. Data from previous studies in the area were also used to complement this study. The study has revealed that the thermal fluids have a common origin. Using the Cl-SO_4-HCO_3- ternary diagram, we were able to classify the fluids as peripheral waters. The Na-K-Mg diagram revealed that most of the waters are immature, therefore, not suitable for solute geothermometry. Nonetheless reservoir temperatures were estimated using the SiO_2 vs Log K^2/Mg and the Log K^2/Mg vs K^2/Ca plots, which indicated reservoir temperatures ranging from 80-100 ^{o}C. The temperatures pointed out a low enthalpy resource that could be developed for direct use applications. Temperature as high as 200 ^{o}C could be encountered, if a deep (>3 km) exploration well is drilled in the field; this should be sufficient to run a binary power plant.

1. INTRODUCTION

1.1 Background of the study

Geothermal energy accounts for 17% of the electricity generated in New Zealand, most of it coming from the north Island and more than 75% coming from the Waikato region which hosts most of the Taupo Volcanic Zone (Ministry of Economic Development, 2010b). Luketina and Barns (2011) say that "Geothermal resources are important to the people of the Waikato region. They contribute to economic, social, cultural and environmental wellbeing through a broad range of values." The geothermal resources of Waikato are managed by the Waikato Regional Council, which has the responsibility of overseeing sustainable development, utilization, implementation of monitoring programs and setting policies aimed at preservation of thermal features. New-Zealand geothermal systems are grouped into low and high enthalpy geothermal systems. Generally low enthalpy geothermal system are considered to have temperatures <150^{o}C and high enthalpy geothermal systems have temperature systems are considered to have temperatures >150^{o}C.

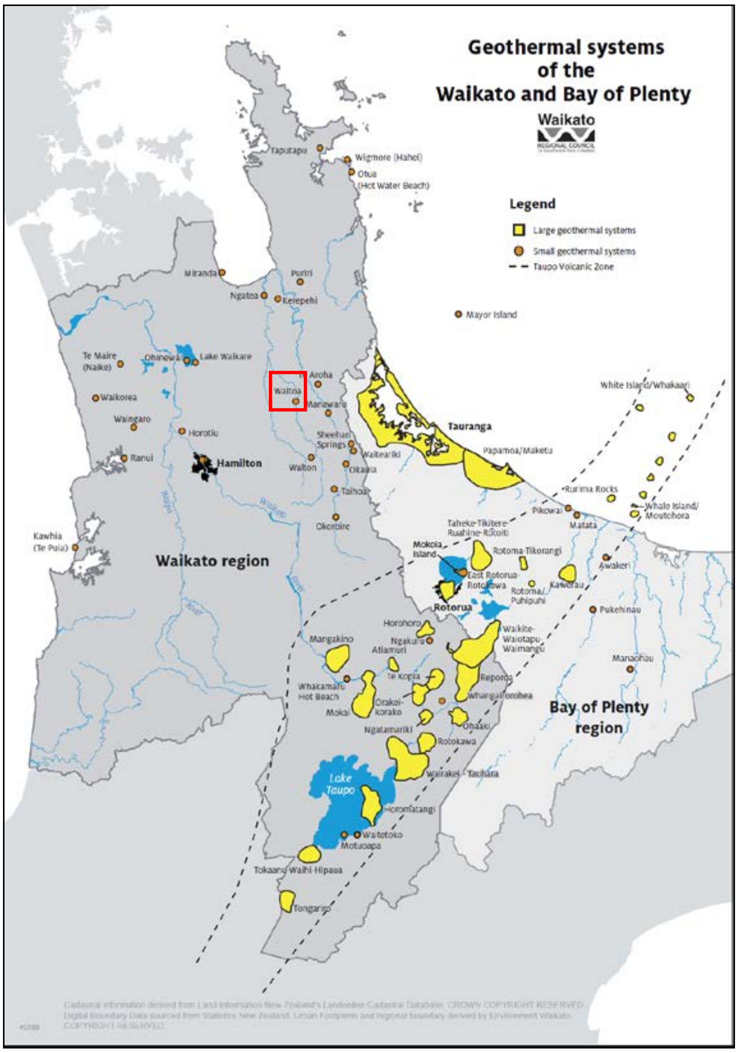

Figure 1: Geothermal resources in Waikato and Bay of Plenty regions. The red square indicates the location of the study

Proceedings 37th New Zealand Geothermal Workshop
18 – 20 November 2015
Taupo, New Zealand

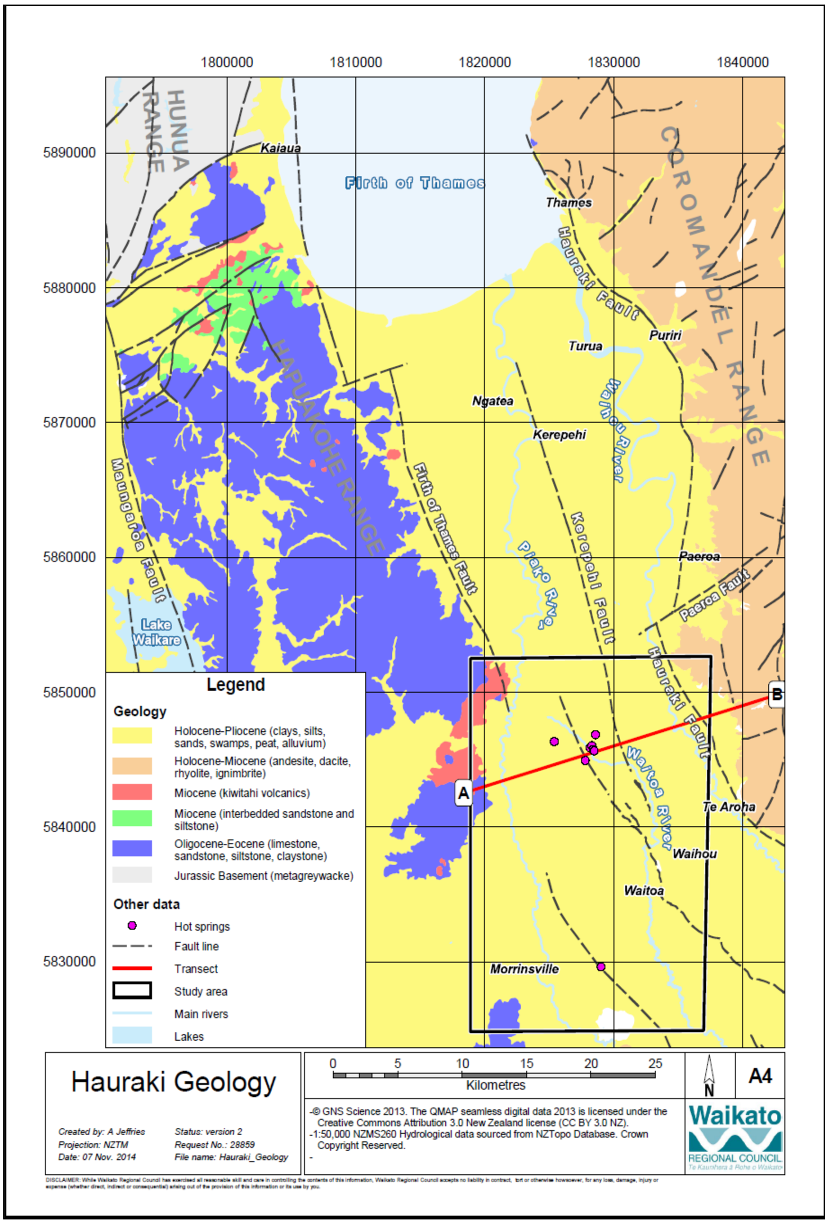

Figure 2: General geological and structural map of the Hauraki depression modified from Hochstein and Nixon (1979) and Jenkinson (1994)

1.2 Location

Waitoa is small town within the Waikato region with a population of about 400 people. Waitoa is located at about 30 km from both Hamilton and Tauranga (Figure 1). The main economic activity is dairy farming; the area has generally flat rolling landscapes.

1.3 Objectives of the study

A field visit to Waitoa was carried out on 4th Sept 2014, with the main objective to sample hot springs and boreholes with above ambient temperatures and evaluate the geomorphology. This would assist with the assessment of the Waitoa low enthalpy geothermal system. Samples were collected from two thermal springs and two local boreholes.

The specific objectives of the study included:

- To evaluate the viability of Waitoa low enthalpy geothermal system for power generation, using samples collected and existing data.
- Identify geothermal direct use applications that could be commercially viable and give recommendations.

2.0 GEOLOGY

In New Zealand, the geothermal resources have geological settings related to volcanism and tectonism. This is attributed to its location in a subduction zone where the Pacific plate is subducted under the Australian Plate, resulting in volcanic and tectonic activity. A result is the formation of the Coromandel and Taupo Volcanic Zones, associated with andesitic and rhyolitic volcanism and extensional normal faulting (Rowland and Sibson, 2001). In many places around the world, geothermal systems will be found in or adjacent to young volcanoes. In these areas, water is heated by shallow magma chambers and rises by buoyancy, coming in contact with cold groundwater as it rises, sometimes emerging kilometres away from the heat source due to the topography (Thain, 2006). Rain water and seawater percolating in zones of active faults may be heated by the natural thermal gradient and sometimes rise along fractures or faults emerging at the surface as warm springs. Figure 1 illustrates the distribution of high temperature geothermal systems in the Taupo Volcanic Zone.

Reyes et al. (2010) noted that thermal water in the North Island is discharged over a wide range of settings, which include:

- Active subduction in the east of the North Island –Holocene subduction, rifting or intraplate-related volcanism in the Taupo Volcanic Zone, Auckland, Western Waikato, Northland and Taranaki.
- Miocene to Pleistocene volcanism in the Coromandel region, Northland, and western Waikato.
- Continental back arc rifting in the Hauraki rift zone, extending to parts of Northland.
- A shear zone behind the accretionary prism along the North island axial ranges; an ancient accretionary prism in Northland; and sedimentary basins in Wanganui, Taranaki and western Waikato.

2.1 Waitoa geology and tectonic setting

Waitoa is located in the southern part of the Hauraki depression, which is associated with plate tectonics. It is thought to overlie an inferred active subduction zone which is part of the Indian-Pacific Plate boundary 200 km below the surface. Hochstein (1978) suggested that the rift belongs to a group of back arc rifts or basins, which are a result of extensional forces within the crust with resultant shallow earthquakes (>20 km). Rifting often results in bending of the earth crust which is accompanied by upsurge of hot deep mantle material. Basalt extruded over the flanks of the rifts indicates that sporadic melting occurs within these anomalously hot rocks. Basaltic and andesitic volcanic rocks are often found over back arc rifts; these rocks occur also on either side of Hauraki rift. The result is a crust with elevated temperatures contributing to high heat flows.

According to Hochstein and Nixon (1979), the Hauraki depression is a broad valley about 25 km wide extending from Matamata to the Hauraki Gulf over a distance of at least 250 km (Figure 2). It is bounded on the western side by Jurassic greywackes forming the Hunua Range and its southern continuation; the Hapuakohe range, with summit heights of up to 700 m. These greywackes constitute the basement of the region. On the eastern side it is bounded by tertiary volcanics of the Coromandel Range in the north and the Kaimai Range in the south with summit heights of 500-800 m.

The geology (Figure 2) of the area was summarised by Schofield (1967) and Healey (1964) as cited in Hochstein and Nixon (1979), and Jenkinson (1994). In the south (around Waitoa) the most dominant formation is the Mamaku Ignimbrite plateau which merges with the low lying Hauraki plains mainly composed of the Hinuera Formation which consists of cross-bedded fluviatile, rhyolitic and ignimbrite gravels to muds. These sediments progressively thin out horizontally and are commonly intercalated with peats, silts and clays. The maximum sediment thickness is estimated to be 2.5 km in the central region of the depression. The basement greywacke occurs at depths as shallow as 200 m in some areas within the rift (Hochstein, 1978).

The shallow Firth of Thames, with water depths up to 35 m, occupies the northern part of the Hauraki depression; and the Hauraki plains occupy the southern part. The Hauraki plains, between the Firth of Thames foreshore and Waitoa are a flood plain, which stands only a few metres above sea level. South of Waitoa, the mean elevation increases to a few tens of metres and the plain changes to a partly eroded deposition surface, the southern end of which is covered by terminal flows of a Pleistocene ignimbrite sheet. Upwelling mantle material is thought to be responsible for volcanic activity during the evolution of the Hauraki depression, which resulted on the uplift of its flanks.

“The Hauraki depression is a rift structure” according to Hochstein and Balance (1993) as cited in Reyes et al. (2010). It is an intra-continental rift zone (Figure 2) characterised by several half grabens. It is believed to have developed in Miocene in a back arc region parallel to the now extinct Coromandel Arc and is presently oriented at about 60 ^{o}C to the Tonga Kermadec Ridge (Hochstein and Nixon, 1979, Lowe and De Lange, 1990). It is characterised by normal faults dipping 70^{o}-80^{o}. The structure from west to east is made up of a fault angle depression, a median horst (the Kerepehi Fault) and a graben (Figures 2 and 3). It is bound by the Hauraki Fault in the east and the Wairoa Fault in the west. Also, it is crossed by incipient transform faults whose offsets have gradually increased during the tectonic history of the depression.

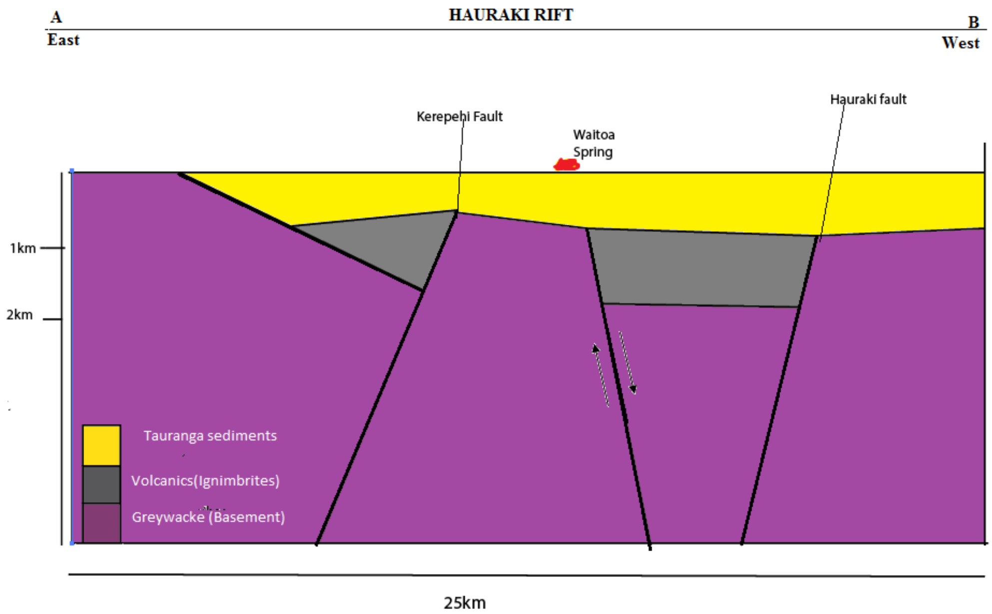

Figure 3: Cross section A-B (Figure 2) across the southern part of the Hauraki rift (Waitoa) after Healy et al. (1964), Schofield (1967) and Houghton and Cuthbertson (1989).

Present-day rifting is indicated directly by active faulting in the south along the southern extension of the Kerepehi Fault and indirectly by shallow earthquake activity (De Lange and Lowe, 1990). Kerepehi Fault bounds thehorst that occupies the middle position of the Hauraki depression; it has an upthrow to the east (Figure 3). Most of the hot springs occur in the southern part of the rift and are associated with horst and grabens (as illustrated by cross-section A-B in Figure 3), bounded by steeply dipping normal faults trending NNW-SSE. Kerepehi Fault to the south of Waitoa (Figures 2-4) is tectonically active as indicated by earthquakes with focal depths of less than 12 km (Hochstein, 1978) and cores taken on both sides of it through the peat, which contained preserved tephra layers that had been displaced by the fault movement (De Lange and Lowe, 1990).

3.0 GEOCHEMISTRY

Sampling was carried out on 4th September 2014. Several thermal springs and boreholes were visited (Figure.4) and samples collected and temperature and conductivity measurements carried out on site. The samples were taken to the laboratory for total fluid analysis. Five sets of sampleswere collected in the five different sampling sites and recorded. From each batch, one sample was acidified for cation analysis. The rest of the samples were left untreated for union analysis. In the analysis of the untreated samples, zinc acetate was added to a 50 ml bottle for sulphate analysis. Within 24 hours of sample collection the sample were filtered.

All the samples collected during the field work were analysed for Potassium (K^+), Sodium (Na^+), Calcium(Ca^{+2}), Lithium(Li^+), Bicarbonate (HCO_3^-), Fluoride (F^-), Aluminium (Al^{+3}), Boron (B^-), Sulphate (SO_4^{-2}), Magnesium (Mg^{+2}), Chloride (Cl), Silica ($SiO_{2)}$ among other ions (Table 1).

Sampling points in this area were limited; therefore data from other workers (Reyes et al., 2010; Jenkinson, 1994) in this area was used to complement data collected during this study. No surface deposits such as sinters and travertine deposits were observed during the field work.

3.1 Preliminary Observations

The thermal springs considered in Waitoa are closely associated with the Kerepehi Fault (Figure 3) Surface temperatures recorded were mainly in the range of 30-40 ^oC; the highest temperature recorded was 50 ^oC for spring No. 72_4291 (Table 1).

To a large extent the waters have very similar chemistry with the major ions being Na^+ and HCO_3-. These waters generally exhibit high concentrations of K, F, Cl, SO_4 and B, which is characteristic of waters with some thermal input. SiO_2 concentrations are also quite high in the sampled fluids. The presence of silica in natural water is controlled by the

Table 1: Sample collected during the field trip and the results of chemical analysis.

System or Locality	Map Co-ordinates		NZMS260	Located	source	Max Temp. (^0C)	pH	ppm												
	Easting	Northing						Al	K	B	Ca	Fe	Li	Mg	Na	Cl	F	SO_4^{2-}	SiO_2	HCO_3^{2-}
Waitoa	1825584	5846414	T13:357-079	72_2190	Bore	23	7.3	0.011	3.9	0.56	12.9	1.16	0.131	10.5	65	15	0.31	0.5	96	225
Waitoa	1828315	5846026	T13:386-076	72_2189	Bore	38	7.5	0.003	26	4.3	18.7	0.73	0.27	14	230	44	0.35	0.5	125	114
Waitoa	1828220	5845910	T14:386-073	72_4291	Spring	50	7.1	0.003	45	4.5	30	0.25	0.25	16.9	220	46	0.21	2.6	187	690
Waitoa	1828281	5845829	T13:388-072	72_2178	Spring	40.8	7.1	0.003	44	4.5	30	0.25	0.25	16.9	220	46	0.21	2.6	187	786
South Waitoa	1828865	5829522	T14:393-912	64_469	Bore	30.9	7.0	0.006	10.9	7.9	10.1	0.45	0.115	4.2	72	73	0.67	0.5	125	823

rock type and the fluid temperature with which it comes into contact. The high concentrations could be attributed to volcanic rocks, especially the pyroclastic ignimbrites that cover large areas of this area, and also contact with thermal fluids, which liberates SiO_2 from the rocks.

The ion balance calculation was carried out to determine the suitability of the data for further analysis. Data with an ion balance of >±5% is considered unsuitable for further analysis, and hence was not considered in the following discussion.

3.2 Classification of waters

An attempt was made to classify the thermal waters of Waitoa and its environs using the major ions i.e. Na^+, Ca^{2+} Mg^{2+}, HCO_3^-, SO_4^-, and Cl^-.

Using the SO_4-Cl-HCO_3 diagram we are able to illustrate how proportions of the anions present in geothermal water in a format based on Giggenbach (1988) normally used to classify waters from different types of geothermal systems. Waters that plot on the chloride apex such as Ngatea, Miranda spring and Lake Waikare (Figure 2) were used to indicate outflow from a mature geothermal reservoir. The diagram indicated that thermal fluids of Waitoa are bicarbonate waters. They were interpreted to be peripheral ground waters because they plotted at the HCO_3^- apex. They had a very high percentage of bicarbonate ions between 80-100% (Figure 5).

The Na-K-Mg ternary diagram was used to provide a further assessment of the suitability of the Waitoa waters for the application of ionic solute geoindicators. While doing this we assumed that equilibrium does exist between the mineral suite for the application of cation geothermometers. The triangular diagram was used to distinguish between immature, partially equilibrated (including mixed waters) and fully equilibrated waters. Geothermometers could be applied with a greater degree of confidence to equilibrated and partially equilibrated waters such as Lake Waikare (L.W) waters (Figure 6). Waters that plotted on the immature regions of the Na-K-Mg diagram (Figure 6), such these of Waitoa were interpreted to mean that the waters had not yet equilibrated and could be mixing with cold ground waters. They plotted on the Mg apex and, therefore, were not suitable for solute geothermometry as they could lead to misleading interpretations.

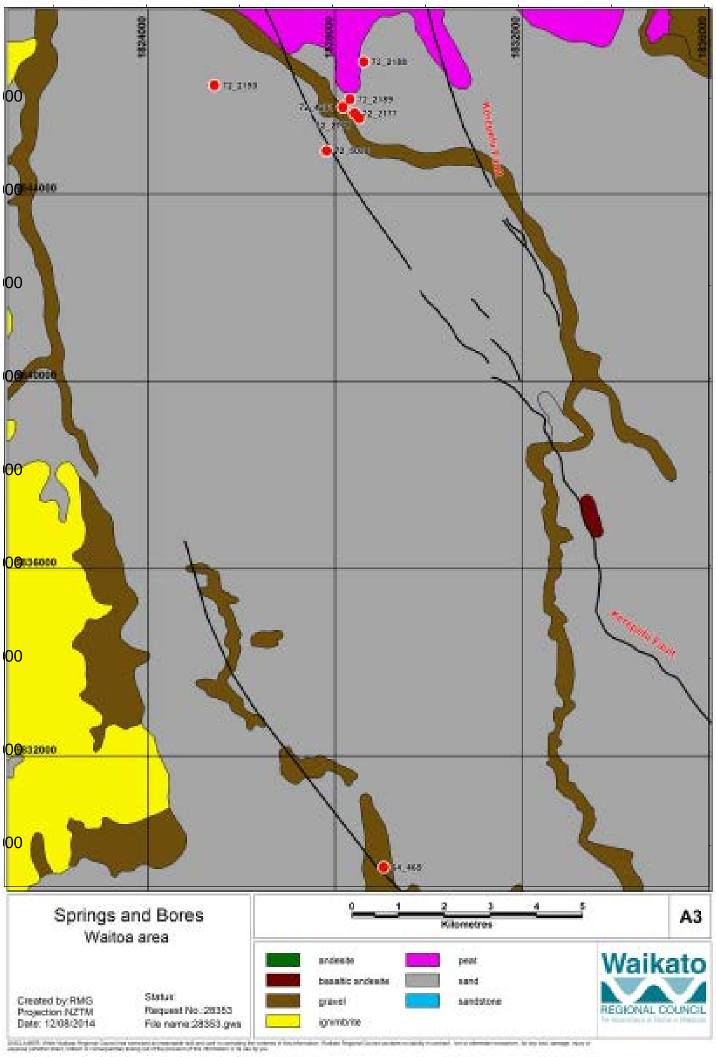

Figure 4: Waitoa Geology in relation to Kerepehi Fault and location of hot springs

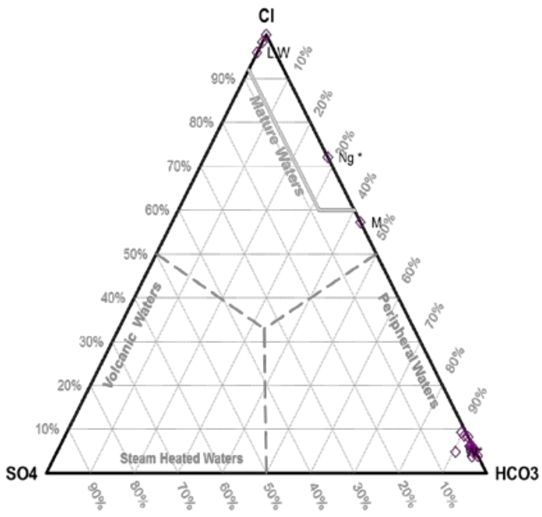

Figure 5: SO_4-Cl-HCO_3^- Ternary plot for Waitoa Waters

The Cl-Li-B diagram was used to distinguish fluids from different sources based on the fact that Cl, Li and B are conservative ions, being least affected by most secondary processes. They were used to provide information on processes affecting migration of fluids. The concentration of boron in thermal waters gave us an idea of the maturity of the hydrothermal system because boron is removed during the early heating stages due to its volatility. Fluids from older geothermal systems such as Ngatea and Miranda (Figure 9) had less boron content than younger geothermal systems.

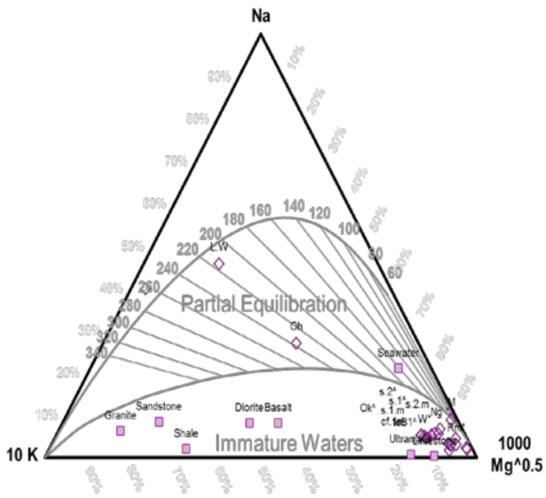

Figure 6: Na-K-Mg Ternary plot for Waitoa thermal fluids.

Most of the Waitoa water samples plot around the B apex (Figure 7). They have relatively high proportions of B compared to Li and Cl. This was interpreted to mean that most of the fluid in this area is from a relatively young geothermal system with high absorption of B/Cl magmatic vapor into the system. However, it is also important to note that the high concentrations of boron could come from the highly fractured greywacke. Some of the samples are also in between the old and the young hydrothermal systems (Figure 7), an indication that there was some mixing with ground water.

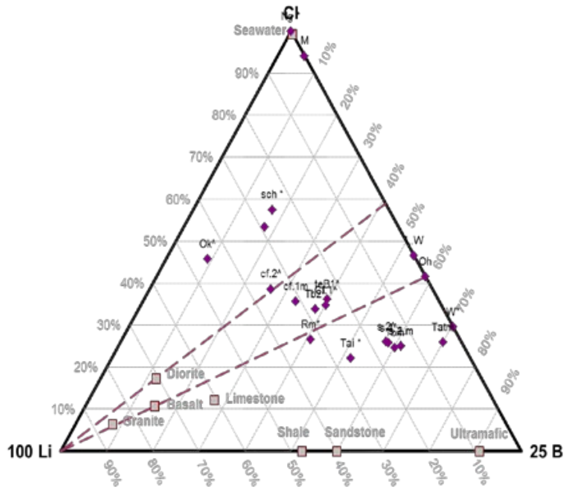

Figure7: Li-Cl-B Ternary plot for Waitoa thermal fluids

3.3 Geothermometry

Geothermometers are normally used to estimate reservoir temperatures based on the assumption that:

- Temperature dependent reaction and mineral fluid equilibria occur in the reservoir;
- No mixing takes places as fluids flow to the surface;
- There is an adequate supply of solid phases for the fluid to be adequately saturated with respect to solutes for geothermometry.

Some of the factors that may influence the outcome of geothermometry temperatures include;

- Boiling and condensation during up-flow;
- Different rates of equilibration between water and the dissolved minerals;
- Lack of equilibration with a particular mineral.

The waters in Waitoa and its environs are peripheral waters as indicated in the Cl-SO_4-HCO_3 diagram, and the Na-K-Mg diagram clearly indicates that they are immature waters. Therefore, they cannot be used for cation solute geothermometers (especially Na/K) because they could give misleading results.

Therefore, we used other means to estimate temperature. Giggenbach (1988) proposed a geothermometer adjusting with the speed similar to that of the K-Ca PCO_2 indicator can correlate the PCO_2 obtained with temperature. Giggenbach (1988) reiterates that CO_2 concentration of deep geothermal fluids is controlled by magmatic fluids, with pulses of magmatic fluids into CO_2 poor meteoric waters. "These fluids are expected to be reactive with respect to the conversion of Ca-Al-Silicates to Calcite which involves the formation of either acid clays or K mica" Giggenbach (1988) according the reaction below:

Ca-Al-Silicate + CO_2+H_2O → 2(H-Al-silicate) + Calcite or K-mica (1)

Ca-Al_2-Silicate+K-feldspar + CO_2 → K-mica + Calcite (2)

3k-Feldspar+ Ca^{2+} and CO_2 → K-mica + calcite+ 2 K (3)

whose equilibrium constant corresponds to Log (aK^{2+}/aCa^{2+}) - Log PCO_2 if the solid phases are assumed to be pure. The reaction is independent of temperature, since its equal to -1.66+/- 0.15 in the temperature range 50-300 ºC (Bowens et al., 1984). Therefore the K^2/Ca ratio acts as a PCO_2 indicator, as indicated by:

$$\text{Log}(K^2/Ca) \rightarrow \log PCO_2 + 3.0. \quad (4)$$

By assuming the K-Mg geothermometer, Giggenbach (1988) proposes to use two functions in a graphical method that permits the determination of both CO_2 contents and the than mineral-solute equilibrium water-rock interaction equilibrium. The full equilibrium line (Figure 8) denotes the coexistence of K-Feldspar, illite and chlorite. Data points below the equilibrium line have PCO_2 higher than full equilibrium PCO_2 and can promote Ca-Al-Silicates to calcite.

The fluids from Waitoa plot below the fully equilibrated line, which is the case for most bicarbonate waters with fluid source temperatures of 80-100 °C (Figure 8). This means there is a higher possibility of calcite scaling from these fluids as the reactions appear to be controlled by rock dissolution rather Giggenbach and Glover (1992) as cited in Reyes et al. (2010) note that silica and log K^2/Mg geothermometers record the most recent equilibrium between rock and water prior to discharge at the surface. A plot of dissolved SiO_2 concentration against log K^2/Mg (Figure 9) is based on the assumption that the geothermometers respond to temperature changes at the same rates to each other. The Waitoa thermal waters plot on the chalcedony or between chalcedony and the Beta Cristobalite solubility line (Figure 9). Only the 72_4291sample plotted on the 100 °C line. The rest of samples plotted at much lower temperatures.

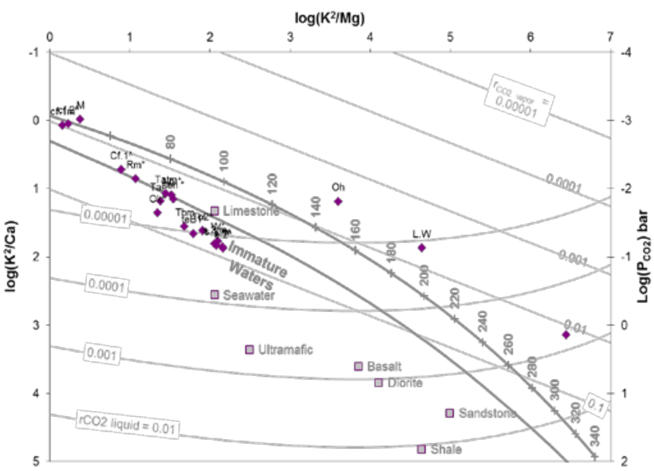

Figure 8: Plot of Log K^2/Mg Vs K^2/Ca plot for Waitoa waters showing geothermometry temperatures

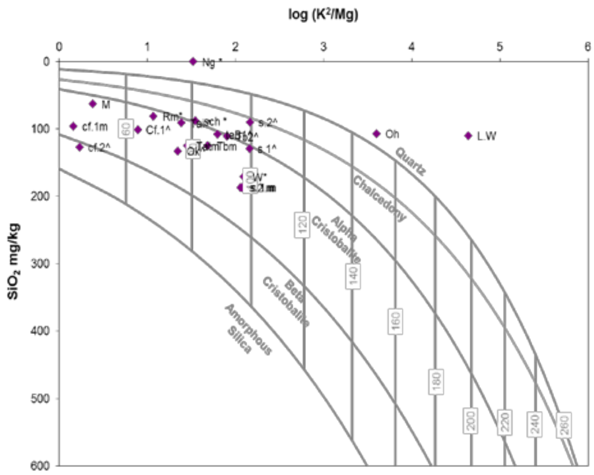

Figure 9: Plot of Log K^2/Mg Vs SiO_2 plot for Waitoa waters showing geothermomers

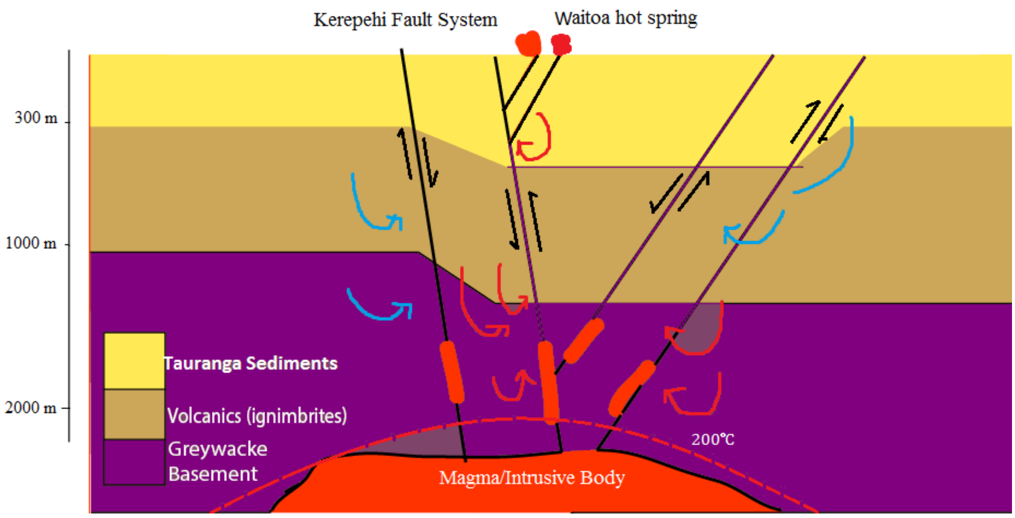

Figure 10: Conceptual model of the Fluid feed for the Waitoa Thermal Springs

5.0 SUMMARY AND CONCLUSIONS

In this area there are very few wells deeper than 100 m and the data available is scarce. It is difficult to make an informed judgment with respect to temperature gradient as at shallow levels ground-waters are subject to fluctuation and interference. Therefore, data from the spring water is more reliable given the assumption that leakage at ground surface is connected to deeper reservoirs.

Data from the springs indicates they are of a common origin are bicarbonate peripheral waters as indicated in the Cl-SO_4 -HCO_3 ternary plot (Figure 5) and are immature waters as shown by the Na-K-Mg ternary plot (Figure 6). Most of the Waitoa thermal waters plot around the B apex (Figure 7), an indication that most of the fluid in this area are from a relatively young geothermal system with high absorption of B/Cl magmatic vapor into the system. The Waitoa fluid concentrations affected by temperature-dependent mineral equilibria and additionally by kinetic rates of dissolution especially in mineral waters discharging from highly disintegrated rocks, as the case may be for Waitoa.

Suitable geothermometers for estimating the reservoir temperatures for low temperature geothermal systems include Chalcedony, SiO_2 and K-Mg geothermometers (Giggenbach, 1988). Silica and log K^2/Mg geothermometers record the most recent equilibrium temperatures between rock and water prior to discharge at the surface (Giggenbach and Glover 1992). In the plot of dissolved SiO_2 log K^2/Mg (Figure 8) the Waitoa thermal waters plot on the chalcedony or between and chalcedony and amorphous silica solubility line, indicating temperatures of 80-100 ^oC. This also agrees with the plot of Log K^2/Mg, Log K^2/Ca (Figure 8) which assists in the determination of both CO_2 contents and temperature of last water-rock interaction equilibrium which also lies between 80 and100 ^oC.

In the Waitoa area the main structure noted is the Kerepehi Fault and its associated faults, which are thought to be the main structures controlling fluid movement on the Hauraki rift floor. According to Hochstein (1978), the Kerepehi Fault is crossed by incipient transform faults whose offsets have gradually increased during the tectonic history of the depression, and average thickness of down faulted tertiary and quaternary terrestrial sediments is about 2.5-3.5 km. This implies that permeability of the reservoir has been greatly enhanced over time. A review by the consultants engaged by Fonterra of previous (East Harbour Ltd, 2009) gravity data undertaken for multiple cross sections revealed that deep permeability exists in the area. It is associated with multiple faults, some inferred and some clearly delineated. Therefore it can be assumed that multiple faults control the movement of groundwater that circulates deeply and conveys heat to the surface via surface discharge of hot springs (Figures 3 and 10). The conceptual model (Figure 10) illustrates that the greywacke basement rocks are highly fractured. The overlying sediments, which are approximately 1000 m thick, are also quite fractured inferring increased permeability. Given the inferred fractured nature of the rocks and circulating fluids, it is possible that higher temperatures could be encountered at depth than reflected in the spring chemistry, as springs may be affected by various processes at the surface. Zarrouk and Moore (2006) reported a temperature gradient of 52-55 ^oC/km in the Huntly coal field around the Ohinewai area, about 30 km from Waitoa (Figure 1). East Harbour Ltd (2009) suggests that there are temperatures of about 200 ^oC at just over 3.0 km depth, assuming a temperature gradient of 67 ^oC/km.

The temperatures in this study indicate a low-enthalpy resource that could be developed for the lower end of direct use applications which may include; pasteurization of milk, drying of grains, district heating, heating of greenhouses etc etc. However, deep drilling (≥3 km) into the greywacke basement could encounter higher temperatures, which could be used for more energy intensive industries (dairy factory) and possibly a small power generation binary pant. However, at least one deep exploration well would be needed to investigate this possibility. However, such a well (7” production casing) would come at a cost of about $1000/metre (private communications with Mr. Bruce McKeown, Drill Force, New Zealand Ltd). The drilling cost along with the exploration risk (uncertainty) is the main challenge for the future development of low enthalpy geothermal systems in New Zealand.

ACKNOWLEDGEMENTS

To my PGCert Fellows 2014 and all my friends at the University of Auckland thank you for your support. A special thank goes to my family (Thiru, Edel, Norah, Fedelma, Lonah, Mum & Dad) for their support and encouraging words throughout the course. Last but not least I would like to express my gratitude to the Government of Kenya who through Geothermal Development Company (GDC) granted me study leave to attend the course. Finally I would like to thank the Government of New Zealand through NZAID for awarding me the scholarship study in Auckland.

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