Lake Waikare Low Enthalpy Geothermal Resource, New Zealand: Initial Field Study

Moises Oliver G. Balane[1], Katherine Luketina[2] and Sadiq J. Zarrouk[3*]

[1] Energy Development Corporation, Pasig City 1605, Philippines
[2] Waikato Regional Council, Private Bag 3038, Waikato Mail Centre, Hamilton, New Zealand
[3] Department of Engineering Science, The University of Auckland, Private Bag 92019, Auckland, New Zealand

[1] balane.mog@energy.com.ph, [2] katherine.luketina@ew.govt.nz, [3] s.zarrouk@auckland.ac.nz

Keywords: Silica sinter, geothermal reef, marine clastic sediments, greywacke, low temperature, Huntly coalfield, geothermometer

ABSTRACT

Lake Waikare, situated within the Huntly coalfield in North Waikato, is host to a small island (Punikanae Island) where a silica sinter-depositing spring is located. This is the only sinter depositing spring known outside the Taupo Volcanic Zone. The chemical analysis from the two spring samples complimented by geological information gathered during a short field visit and other technical data available in the literature are the sets of information used in this study. Based on the Cl-SO_4-HCO_3 ternary plot that was used to classify the geothermal waters with respect to major anion composition and the Na-K-Mg ternary plot to classify fluids according to the state of equilibrium at given temperatures, the origin of the geothermal system that feeds the spring is thought to be mature neutral chloride waters that probably originate from an up-flow zone beneath Punikanae Island with the Maungaroa Fault as its main conduit. Up-flow zones are generally characterized by silica sinter deposition of hot chloride springs on the surface. The relatively high chloride concentrations of the spring that resulted in the deposition of the silica sinters were possibly derived from reservoir waters composed of marine clastic sediments of the Te Kuiti Group. These clastic sediments unconformably overlie the Mesozoic greywacke basement rocks and these basement rocks probably supply the heat to the system. One of the spring samples lies just on the boundary line of the partially equilibrated waters region suggesting reservoir temperature of about 160°C that is typical for a low enthalpy geothermal system. The Na-K and Na-K-Ca geothermometers gave comparatively similar temperatures of 160.0 and 136.0°C, respectively.

1. INTRODUCTION

1.1 Background of the study

The Waikato Regional Council (WRC) manages Waikato region's geothermal resources, overseeing its sustainable development, utilization and implements monitoring programs towards the preservation of the thermal features around the region. In line with the thermal features monitoring program, a regular geochemical assessment is being conducted by WRC with the objectives of understanding the nature and vulnerability of the region's warm water resources to change in order to sustainably manage these resources and to determine the likely changes in the environmental impacts of these features/systems. In their 2012 assessment update which includes the 2009 monitoring data, the fluid behaviour of the 30 geothermal features through time were examined in detail. This includes some discussions on the Lake Waikare vent which is the subject of this study though very limited data of the feature is available.

1.2 Objective

Punikanae is a small island that lies within Lake Waikare. The island has a hot spring that deposits silica sinter as reported during the sampling which was carried out in 2004 and 2005. To our knowledge, this is the only sinter-depositing spring known in New Zealand outside the Taupo Volcanic Zone (TVZ).

However, research on the origin of this unique spring that lies on top of the Huntly coalfield has not yet been initiated. This study aims to proceed towards such initiative, to come up with an interpretation as to the origin of the geothermal system that feeds the spring, using the limited data available.

A one-day field visit to the Punikanae Island was conducted on September 6, 2013. One of the objectives of this visit was to sample the spring. It was unfortunate, however, not to find the spring in the same condition as in 2005 when the latest sampling activity was carried out because the spring is already submerged/flooded by less than a foot of water where bubbles of warmed lake water were observed. We also observed sinter deposits within the island and a distinct sinter deposit near the island that looks like a reef formation just above the lake water level which will be called "geothermal reefs" in this work.

1.3 Project location, accessibility, topography and drainage

Punikanae Island is a small island in Lake Waikare that measures around 75 meters × 35 meters. Lake Waikare is part of the Lower Waikato Lowland in North Waikato, a geomorphological feature within the Auckland Region (Edbrooke, 2001). Figure 1 below is a topographic relief model map showing the location of the lake.
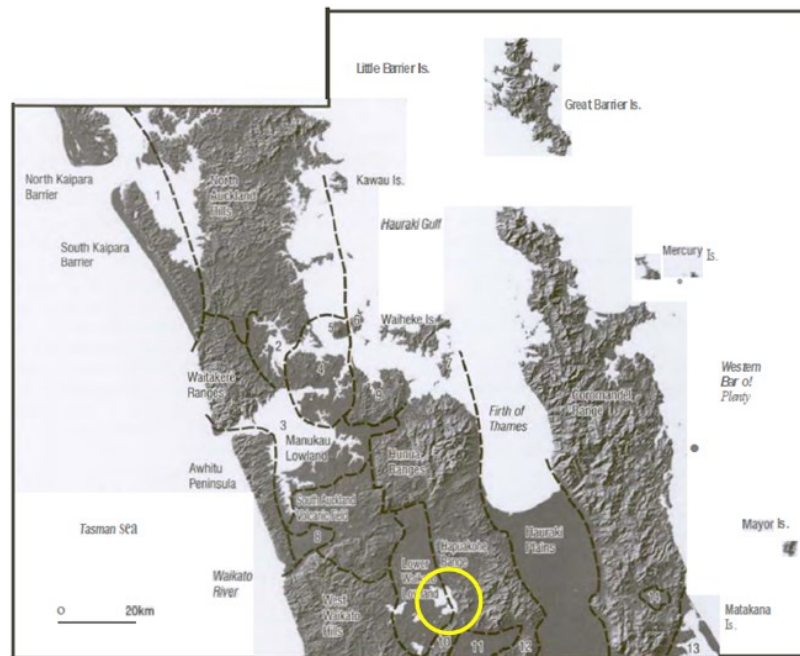
Figure 1. Hill·shaded topographic relief model of the Auckland area showing the geomorphological features (Edbrooke, 2001). Lake Waikare is encircled in yellow.

A closer view of the lake is shown below (image courtesy of Google Earth).

Figure 2a.Punikanae Island   Figure 2b.Waikare Lake

Small growth trees and shrubs abound the area which is a favourite resting place for licensed game bird hunters.

Rangiriri township is the nearest populated center located west of Lake Waikare. Punikanae Island, on the other hand, is accessible from Rangiriri via a 5-km asphalted road towards northeast to southeast and by boat towards south within the lake.

The topography is generally flat in the direction of the Ohinewai area to the west. High relief terrain of up to 281 meters characterizes the eastern side of the lake at Hapuakohe Range. Figure 3 below shows the route to the lake via the nearest population center (Rangiriri) and the contrast in topography from east to west.

Figure 3. Route A-B from the nearest population center, Rangiriri, towards the lake (map courtesy of Google Earth)

Lake Waikare is the largest lake in the lower Waikato catchment, with 34.42 km² of open water. It has an average depth of 1.5 meters and a maximum depth of 1.8 meters. Due to its shallow nature (its depth is never more than two meters) as the result of heavy use of fertiliser in the surrounding farming district, the waters of the lake are in poor condition with large amounts of pollutants. There are no submerged aquatic plants growing in the lake. The lake level was lowered by one meter in 1965. This was in accordance with the Lower Waikato Waipa Flood Control Scheme which followed the construction of an outlet gate. Lake Waikare discharges to the Whangamarino Wetland from the artificial Pungarehu Canal. The lake is managed under a strict seasonal fluctuation regime of approximately 0.3 metres.

2. GEOLOGY, STRUCTURES AND ALTERATION

The Lake Waikare area is overlain by 40 – 110 meter thick terrestrial deposits of the Tauranga Group that were formed during the Neogene epoch (here taken to include Late Miocene, Piocene and Quaternary). The Tauranga Group is lithologically highly variable, ranging from clays to gravels, and includes peats and pyroclastic deposits. This sequence is unconformably underlain by 200 meter thick Eocene – Oligocene coal measures and marine mudstones of the Te Kuiti Group (Nelson et al, 1988). The basement rock in the area is the Mesozoic greywacke which is also exposed as high-standing rocks (Hapuakohe Range) in the eastern part of the area with elevations up to 281 masl. The high elevations represent the upthrown block of Maungaroa Fault (Nelson et al, 1988), a normal fault that cuts across the eastern side of Lake Waikare and passes through Punikanae Island. This structure played a major role in the sinter deposition as it serves as the main conduit of the flow of the Punikanae spring to the surface. In many cases the hot springs are related to faulting such as in Lake Waikare (Edbrooke, 2001). Other structures west of the lake towards Ohinewai area are also shown in the geologic map below (Figure 4).

Huntly township is host to a coalfield that is part of the 200-meter thick Eocene-Oligocene Te Kuiti Group (Nelson et al, 1988). The Huntly coalfield has significant coal deposits in New Zealand that are targeted by mining. The coal deposits contain biogenically-sourced methane with relatively low to moderate measured gas (CH_4) contents (2-4 m^3/ton) (Zarrouk and Moore, 2009). The coal beds were also studied for CH_4 production and CO_2 sequestration sites. The reservoir model of enhanced coal bed methane (ECBM) developed by Zarrouk and Moore (2009) indicates that methane production can be significantly improved to nearly 90% through injection of CO_2 (CO_2 holding capacity is relatively high at 18.0 m^3/ton).
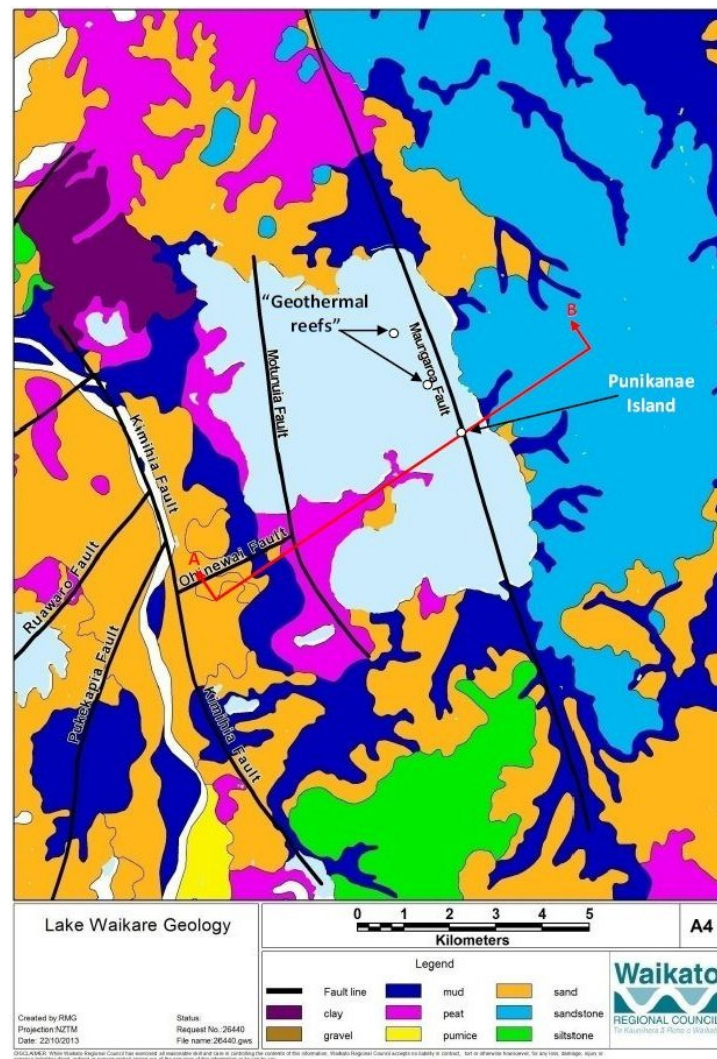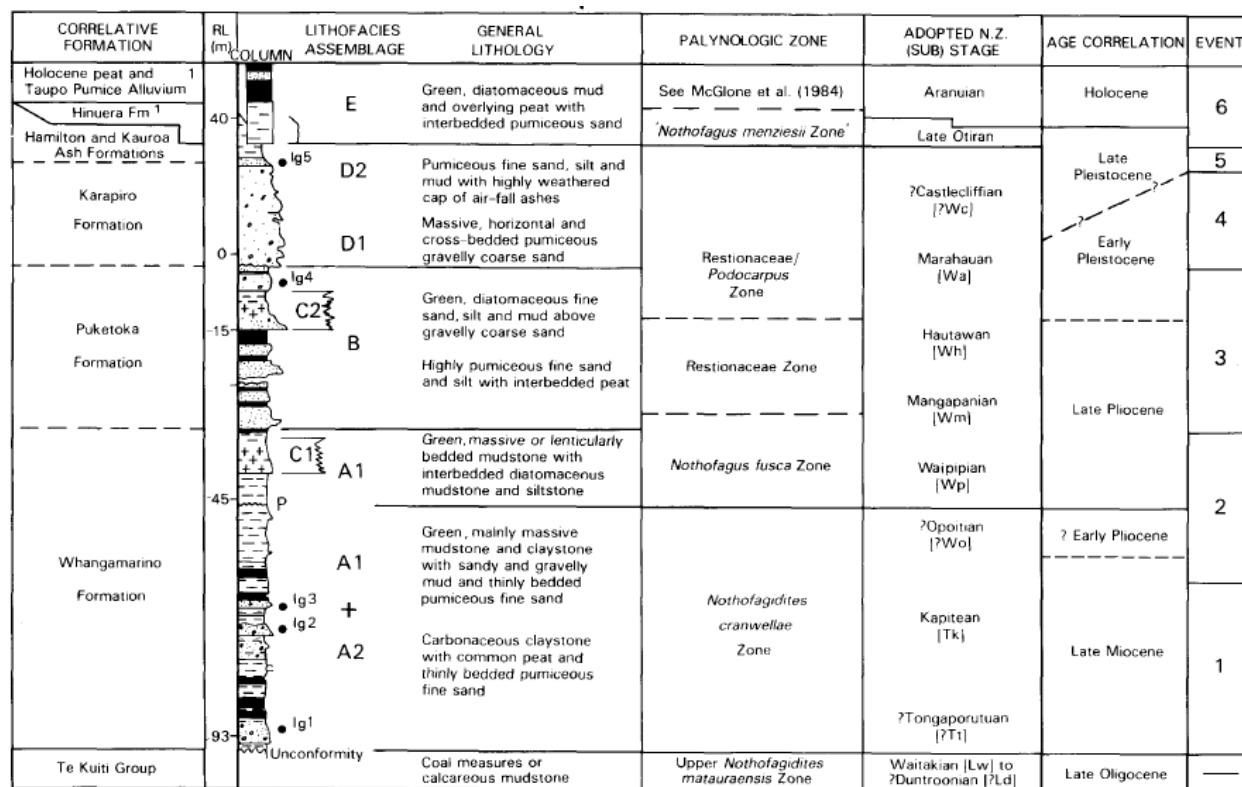

Figure 4. Geologic map of the Lake Waikare area (map courtesy of Waikato Regional Council)

Figure 5 below is the general stratigraphy of the area showing the Tauranga Group of sedimentary deposits overlying the Lake Waikare area (from Nelson, et al .(1988).

CORRELATIVE FORMATION	RL (m)	COLUMN	LITHOFACIES ASSEMBLAGE	GENERAL LITHOLOGY	PALYNOLOGIC ZONE	ADOPTED N.Z. (SUB) STAGE	AGE CORRELATION	EVENT
Holocene peat and Taupo Pumice Alluvium [1]	40		E	Green, diatomaceous mud and overlying peat with interbedded pumiceous sand	See McGlone et al. (1984)	Aranuian	Holocene	6
Hinuera Fm [1]					*Nothofagus menziesii* Zone	Late Otiran		
Hamilton and Kauroa Ash Formations							Late Pleistocene	5
Karapiro Formation	0		D2	Pumiceous fine sand, silt and mud with highly weathered cap of air-fall ashes	?Castlecliffian [?Wc]			
			D1	Massive, horizontal and cross-bedded pumiceous gravelly coarse sand	Restionaceae/ Podocarpus Zone	Marahauan [Wa]	Early Pleistocene	4
Puketoka Formation	-15	Ig4 / C2	B	Green, diatomaceous fine sand, silt and mud above gravelly coarse sand		Hautawan [Wh]		3
				Highly pumiceous fine sand and silt with interbedded peat	Restionaceae Zone	Mangapanian [Wm]	Late Pliocene	
		C1	A1	Green, massive or lenticularly bedded mudstone with interbedded diatomaceous mudstone and siltstone	*Nothofagus fusca* Zone	Waipipian [Wp]		2
Whangamarino Formation	-45	P	A1	Green, mainly massive mudstone and claystone with sandy and gravelly mud and thinly bedded pumiceous fine sand	*Nothofagidites cranwellae* Zone	?Opoitian [?Wo]	? Early Pliocene	
		Ig3 / Ig2	+ A2	Carbonaceous claystone with common peat and thinly bedded pumiceous fine sand		Kapitean [Tk]	Late Miocene	1
	-93	Ig1				?Tongaporutuan [?Tt]		
Te Kuiti Group		Unconformity		Coal measures or calcareous mudstone	Upper *Nothofagidites matauraensis* Zone	Waitakian [Lw] to ?Duntroonian [?Ld]	Late Oligocene	—

1.Collectively named here the Waikare beds

Figure 5. General stratigraphy of Lake Waikare area showing the Tauranga Group (from Nelson et al., 1988)

Punikanae Island, however, is overlain by an approximately one-meter thick grayish chalcedonic silica layer already broken to cobble-boulder size angular fragments which are scattered all over the island. The silica exhibits conchoidal fracturing, has Fe stains and some vesicles caused by the leaching of clay clasts in the silica. It is possible that the chalcedonic silica layer is a product of a total silica replacement of a fine-grained sedimentary unit during the hydrothermal alteration process. Figure 6 below is a hand specimen of the chalcedonic silica.

White porous silica (sinter) on top of massive silica

Figure 6. Sample of the silica with white incrustation of porous silica (sinter) on top.

A 2-4 mm whitish porous silica incrustation on chalcedonic silica represents the silica sinter that was deposited from the hot spring. In the paper by Nicholson (1993), thick sinters only form around springs which discharge water at, or close to, boiling point (i.e. about 80-100°C), their presence therefore indicates reservoir temperatures in excess of about 200°C; but for even minor amounts of amorphous silica to deposit, the reservoir temperature must be at least ~110°C.

The silica layer lies on top of a soft-moderately hard clay-altered/argillized tuffaceous sandstone which is the same rock material found in the adjacent "geothermal reefs". Figure 7 below shows the tuffaceous sandstone outcrop in Punikanae Island.

Figure 7. Tuffaceous sandstone outcrop in Punikanae Island

Figure 8 below shows pockets of "geothermal reefs" in Lake Waikare.

Figures 8. "Geothermal reef" in Lake Waikare

The suite of hydrothermal alteration products in Punikanae Island as described above show that this area is in the upflow zone of a liquid-dominated hydrothermal system. The rocks are pervasively altered by the neutral-chloride water that upflows from the system. The manifestation of its fluid composition is the silica sinter deposits earlier found in the spring. The chalcedonic silica layer represents the massive silica cap of the system. The host sedimentary rock (tuffaceous sandstone) lying below the massive silica cap has undergone argillization or clay (kaolinite) alteration that can represent the clay cap of the system. The pockets of "geothermal reefs" shown in Figure 8 protruding a few centimeters on the surface of the lake measuring around 1-5 m^2 located northwest of the island and aligned sub-parallel to the Maungaroa Fault can be correlated to the clay-altered/argillized sedimentary unit in the island. Localized flow along Maungaroa Fault of hydrothermal fluids coming from underneath might have caused the alteration and formation of these unique geothermal reefs.

A simplified geologic cross section of the Lake Waikare area is constructed and shown in Figure 9 below.

Figure 9. Simplified geologic cross section of Lake Waikare area along line A-B of Figure 4 (geologic map); vertical scale exaggerated to ~350 %

3. GEOCHEMISTRY

The Lake Waikare vent in Punikanae Island is the only thermal feature that provided geochemical data for the evaluation of the Lake Waikare geothermal resource. However, only two samples from the spring collected in 2004 and 2005 are available for this initial assessment. A third sample was also collected in 2005 at the epilimnion of the lake around a possible "geothermal reef" located 1 km northwest of Punikanae Island. But discussions on its chemistry will not be done in detail in this study. An attempt to collect additional samples during the recent field visit in September 2013 failed because the spring is already submerged in lake water.

Nicholson (1993) gave a discussion on the origin of low temperature type geothermal systems. The source of heat that feeds the Lake Waikare system can be classified as coming from tectonic uplift of the hot greywacke basement rocks where fluids are circulating through the Maungaroa Fault. The relatively high chloride concentrations of the spring that resulted in the deposition of the silica sinter possibly came from the waters of a reservoir composed of marine clastic sediments of the Te Kuiti Group that unconformably rest on the basement rocks. Based on the cross-section (Figure 9), the probable depth of the reservoir is around 200-300 meters.

Elevated Boron and CO_2 concentrations are also common in these types of reservoirs (Nicholson, 1993). Some low enthalpy systems around the area, such as in Ohinewai where the fluids flow along several faults namely Motunuia, Ohinewai, Kimihia, Ruawaro and Pukekapia (Figure 4), may have the same type of heat source since the area stands on the same basement rocks. Because of the lateral and vertical extent of Maungaroa Fault that cuts across Lake Waikare and deep down to the greywacke basement rocks, it is possible that a large portion of the heat coming from the basement rocks and flowing through the fault is being discharged into the lake. A warm water area more than twice the size of the Punikanae Island was mapped by WRC in Lake Waikare some years back (Figure 10). This map would somehow attest to this perception.
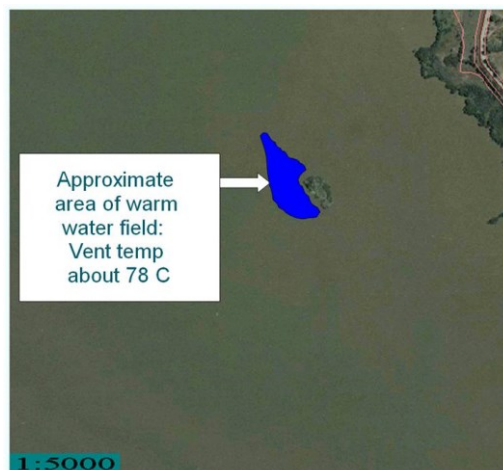

Figure 10. Area of warm water field in Lake Waikare (map courtesy of Waikato Regional Council)

The tri-linear or ternary diagram is the commonly used method to determine the correlations among three independent variables. These key correlations provide valuable insights and act as indicators to sub-surface conditions and processes. The variable combinations that will be discussed in this study are Cl-SO$_4$-HCO$_3$, Na-K-Mg and Cl-B-HCO$_3$. The first two diagrams were plotted using the spreadsheets of Powell and Cumming (2010) and the last one was adopted from the report of Cheptum (2012). Na-K and Na-K-CA geothermometers were also used to derive the inferred reservoir temperatures of the Lake Waikare vent and some representative TVZ springs. A short discussion on elevated mercury values is also given in the later part of this section.

The table below shows the analytical results of the Lake Waikare water samples that were used in this study (Webster-Brown and Brown, 2012).

Table 1. Geothermal Water Analytical Results of Lake Waikare water samples

Sample code	LW05	LW04	LWep*
Easting	2707137	2707137	2706400
Northing	6415506	6415506	6416700
Date sampled	30/08/2005	23/04/2004	30/08/2005
Sample Name	326.45 Vent	326.45 Vent	326.4 Lake
Temperature (°C)	64.5	79.8	15.7
Lab No	388423/1		388423/2
pH (pH units)	8.9	8.2	9.6
Electrical Conductivity (mS/m)	115		16.5
Salinity	0.3		< 0.1
Total Alkalinity (g/m^3 as CaCO$_3$)	66		31
HCO$_3$	40	43	19
Dissolved Calcium (g/m^3)	12	5.4	9.76
Dissolved Magnesium (g/m^3)	1.3	1.53	3.67
Dissolved Sodium (g/m^3)	201	129	15.5
Dissolved Potassium (g/m^3)	7	5.84	3.84
Dissolved Lithium (g/m^3)	0.473	0.275	0.0218
Dissolved Rubidium (g/m^3)	0.018		0.0074
Total Ammonia cal-N (g/m^3)	0.87		< 0.01
Chloride (g/m^3)	299	168	19.9
Fluoride (g/m^3)	1.74		0.17
Dissolved Bromine (g/m^3)	0.6		0.068
Sulphate (g/m^3)	7.3	19	13.6
Total Sulphide (g/m^3)	2.93	0.122	0.002
Un-ionised hydrogen sulphide(g/m^3)	0.013		< 0.002
Dissolved Boron (g/m^3)	16.1	8.46	0.118
Silicon (g/m^3)	36.2		6.7
Total Dissolved Silica (g/m^3 as SiO$_2$)	77.6	216	14.3
Dissolved Iron (g/m^3)	2.9		0.25
Dissolved Aluminium (g/m^3)	0.81		0.134
Dissolved Arsenic (g/m^3)	< 0.02		0.006
Dissolved Caesium (g/m^3)	0.019		0.0002
Total Mercury (g/m^3)	0.00254	0.557	< 0.00008
Dissolved Antimony (g/m^3)	< 0.004		< 0.0002
Dissolved Thallium (g/m^3)	< 0.001		< 0.00005

*Epilimnion

3.1 Cl-SO4-HCO3 ternary diagram

The Cl-SO$_4$-HCO$_3$ diagram is a ternary plot that is used to classify the type of geothermal waters based on the relative proportions of chloride, sulphate and bicarbonate ions. The types include deep chloride water, dilute Cl-HCO$_3$ waters, mixed Cl-SO$_4$ waters/volcanic condensates and steam-heated waters/steam condensates (Ellis and Mahon, 1977). This simple plot is preferred among others in literature as it permits the identification of the above water types, and therefore some degree of genetic interpretation (Nicholson 1993).

Figure 11 shows the two spring samples fall under the mature waters region which indicates that the neutral chloride fluid originates from a highly permeable upflow zone beneath. The main conduit of the spring is the Maungaroa Fault.
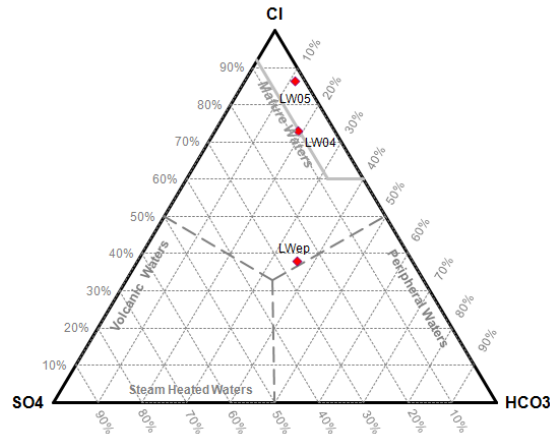
Figure 11. Cl-SO$_4$-HCO$_3$ ternary plot (Lake Waikare thermal area)

3.2 Na-K-Mg ternary diagram

The Na-K-Mg ternary diagram is used to classify waters according to the state of equilibrium at given temperatures (Giggenbach, 1988). They involve minerals of the full equilibrium assemblage after isochemical re-crystallization of an average crustal rock under conditions of geothermal interest. Fully equilibrated waters are normally selected as geothermometers.

Giggenbach et al. (1983) showed that the field of partial equilibrium suggests either:
a) a mineral that has dissolved, equilibrium reactions have set in but equilibrium has not been reached,
b) or a mixture of water that has reached equilibrium with a dilute unequilibrated water, e.g. cold groundwater.

Points close to the √Mg apex usually suggest a high proportion of relatively cold groundwater but not necessarily "immature". Lack of equilibrium is likely to be reflected in Na-contents of the waters being too low (Giggenbach, 1988).

The plot in Figure 12 shows the LW05 spring sample reaching partial equilibration with estimated subsurface temperature of 160°C. The sample was also used as an ionic solute geothermometer although it lies in the boundary of immature and partial equilibration line that could likely have some degree groundwater dilution. The other two samples, however, fall on the immature waters region nearer the √Mg apex.

Figure 12.Na-K-Mg ternary plot (Lake Waikare thermal area)

3.3 Na-K geothermometer
An experimentally-derived geothermometry equation based on the Na/K ratio was derived by Giggenbach (1988) and expressed as follows:

T (°C) = 1390/[log (Na/K) + 1.750] – 273 (Giggenbach, 1988 in Nicholson, 1993)

Using the above equation to get the temperature of sample no. LW05 that lies in the boundary of the partial equilibrium line of the Na-K-Mg ternary diagram, the resulting temperature is 160.28°C.

3.4 Na-K-Ca Geothermometer
An empirical method of estimating the last temperature of water-rock interaction has been devised by Fournier and Truesdell (1973). It is based upon molar Na, K and Ca concentrations in natural waters from temperature environments ranging from 4 to 340°C and expressed in the following equation:

$$T\ (°C) = 1647/\{log\ (Na/K) + β[log(Ca^{1/2}/\ Na) + 2.06] +2.47\} - 273$$

where

T > 70°C

Na, K and Ca = concentrations of sodium, potassium and calcium (mg/kg)

$\beta = 4/3$, if T < 100°C

$\beta = 1/3$, if T > 100°C

The procedure in using the above equation is as follows (concentrations in mg/kg) (Fournier and Truesdell, 1973 in Nicholson, 1993):

1. Calculate [log ($Ca^{1/2}$/Na + 2.06]; if this is positive, calculate the temperature, T (°C), using $\beta=4/3$.
2. If T < 100°C use this temperature.
3. If however, T > 100°C or [log ($Ca^{1/2}$/Na + 2.06] is negative, then use $\beta=1/3$ to calculate the temperature.

The computed temperature using the above equation for Na-K-Ca geothermometer is lower at 136.0°C confirming that the source of fluids of the Lake Waikare vent came from a low enthalpy system.

Table 2 below summarizes the results of geothermometer calculations for the Lake Waikare vent that are typical for a low enthalpy geothermal system.

Table 2. Inferred reservoir temperatures in °C using the Na-K-Mg ternary plot and the Na-K and Na-K-Ca geothermometers for Lake Waikare vent

Sample no.	Na-K-Mg (Giggenbach, 1983)	Na-K (Giggenbach, 1988)	Na-K-Ca (Fournier and Truesdell, 1973)
LW05	160	160.28	136.0

3.5 Cl-SO₄-HCO₃ and Na-K-Mg ternary plots for TVZ springs

The major element analyses of representative TVZ springs from Henley and Hedenquist (1986) were used in the following Cl-SO₄-HCO₃ and Na-K-Mg ternary plots (Figures 13 and 14) for comparison with the results in Lake Waikare vent.

In Figure 13, the Champagne and Ohaaki pools with high Cl values of 1898 and 1060 ppm respectively, plotted within the mature waters region of the Cl-SO₄-HCO₃ diagram, though there were no values given for HCO₃.
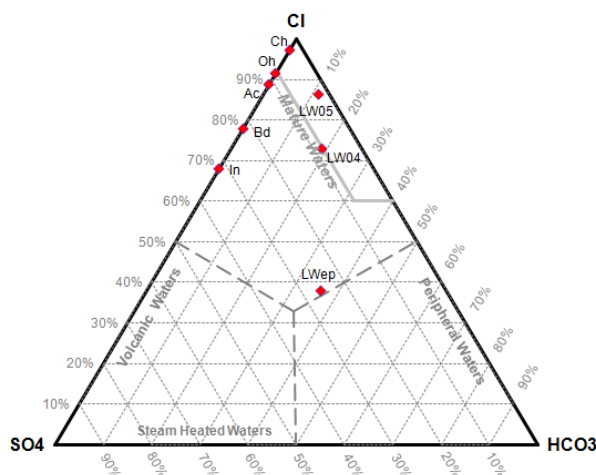

Figure 13. Cl-SO₄-HCO₃ ternary plot (representative TVZ springs and Lake Waikare thermal area). Note: Ch – Champagne Pool; Oh – Ohaaki Pool; Ac – Acid Spring; Bd – Birdnest Terrace; In – Inferno Crater; Dv – Devil's Ink Pot; LW05 – Lake Waikare vent, 2005 sample; LW04 – Lake Waikare vent, 2004 sample; LWep – Lake Waikare @ epilimnion, 2005 sample

The inferred reservoir temperatures of the Champagne and Ohaaki pools registered values of 260 and 230°C, respectively, (Figure 14) suggesting that the source of geothermal fluids that feed the springs originated from high temperature systems.
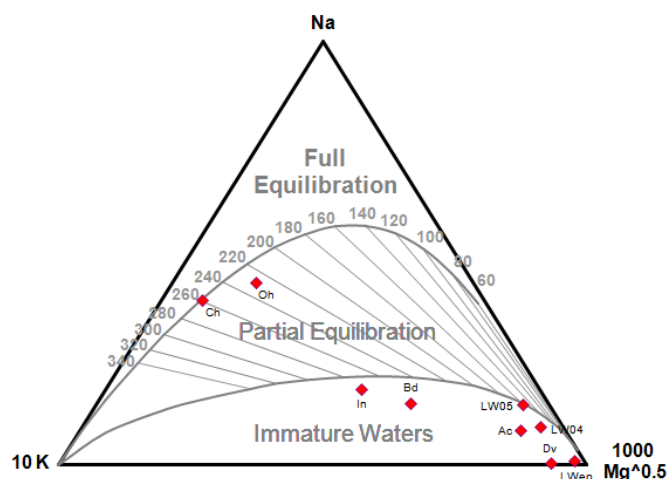
Figure 14. Na-K-Mg ternary plot (representative TVZ springs and Lake Waikare thermal area)

The rest of the TVZ springs (Devil's Ink Pot, Birdnest Terrace, Inferno Crater and Acid Spring) that generally fall within the immature waters plot are mostly acidic with elevated SO_4 concentration.

The high Cl, Na and K values of TVZ springs (up to 1898, 1102 and 151 ppm, respectively) that came from high temperature systems are several magnitudes greater than that of the Lake Waikare vent (only up to 299, 201 and 7 ppm, respectively). Relative Cl, Na and K contents of thermal waters derived through water-rock processes are therefore directly proportional with the reservoir temperature, i.e. the higher the chemical concentrations, the higher the reservoir temperature. The relatively lower Cl, Na and K contents in Lake Waikare vent corresponds to low reservoir temperature which were validated by results of computed temperatures for Na-K and Na-K-Ca geothermometers in Table 2 above.

3.6 Cl-B-HCO$_3$ ternary diagram

A Cl-B-HCO$_3$ ternary plot was adopted in order to determine the likely origin of the fluids of the Lake Waikare system. Based on the plot in Figure 15, the two samples from the Lake Waikare vent clustered towards the Boron apex which would indicate the origin of the fluids from the greywacke basement rocks underneath. Zarrouk and Moore (2007) have verified from well test analysis of bores in Huntly coalfield that the greywacke basement is the source of the geothermal fluid that is of significant interest for low enthalpy heat production and development in the Waikato region. The local temperature gradient of the Huntly coalfield is quite high at 55°C/km, and the two wells which have penetrated the basement rocks showed significant increase in temperature gradient in proximity to the greywacke basement which is possibly the result of convective behaviour (Zarrouk and Moore, 2007). The Champagne and Ohaaki pools, however, plotted very close to the Cl apex suggesting that the chloride waters came from deeper high temperature environment, though there were no values given for HCO$_3$. The rest of the TVZ springs that plotted in the Cl apex (Birdnest Terrace, Inferno Crater and Acid Spring) have high SO_4 values implying that these are mixed Cl-SO$_4$ waters/volcanic condensates from shallow origin.
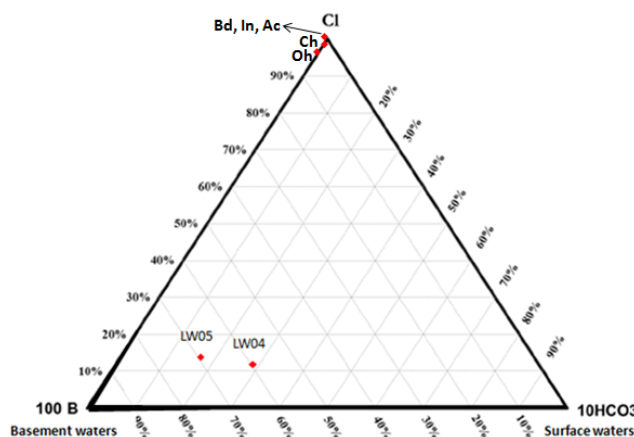

Figure 15. Cl-B-HCO$_3$ ternary plot (Lake Waikare thermal area and representative TVZ springs)

3.7 Elevated mercury concentrations

Surface enrichments in mercury are common around geothermal areas, and in some instances deposits of mercury minerals such as cinnabar have been formed. At high sub-surface temperatures of geothermal systems, mercury strongly partitions into the vapour phase and is transported to the surface largely as elemental mercury vapour. This vapour is adsorbed onto organic matter and, to a lesser extent, clay minerals in the upper, low-temperature soil horizons, to create elevated concentrations of mercury (Nicholson, 1993). EPRI (1987) indicated that the higher the H$_2$S concentrations, the lower the amount of soluble mercury in the reservoir fluid and the less formation of mercuric sulphide (HgS). But for H$_2$S concentrations <30 ppm, precipitation of HgS (cinnabar) and other metallic sulphides such as FeS$_2$ (pyrite) and As$_2$S$_3$ (orpiment) are likely to occur. The 2004 sample in Lake Waikare vent yielded a

high mercury value of 557 ppb. In 2005, analytical results for H_2S is only 0.013 ppm but with relatively low mercury value of 2.54 ppb (Table 1).

In general, the low H_2S concentrations would characterize the high level of mercury discharges in the Lake Waikare vent affecting the surrounding area with as much as 2.2 ppm mercury in the sediments (WRC collected mercury data). Figure 16 illustrates the level of mercury in the lake sediments centered around the Punikanae Island. The lake sediments close to the island exceeded the threshold value of 150 ppb by a mean value of 500 ppb mercury. An area of around 80 hectares ($0.8 km^2$), has a median probable effects level of 1000 ppb (1 mg/kg) as shown in Figure 17 below.
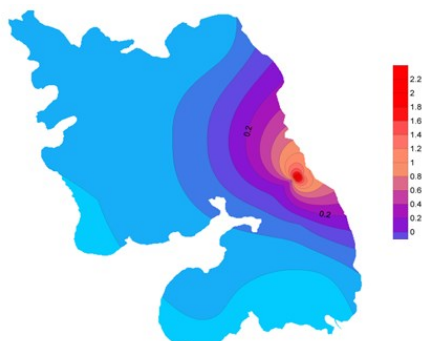

Figure 16. Levels of mercury in sediments in Lake Waikare
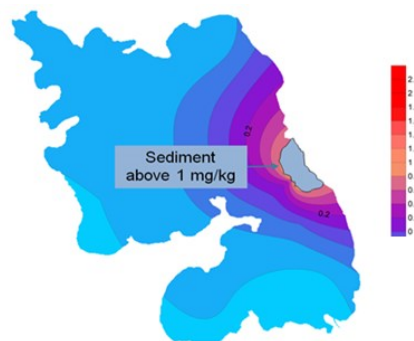
Figure 17. Median level in sediments with 1000 ppb (1 mg/kg) mercury in Lake Waikare

The potential issues related to high mercury levels include toxicity to plants with the following symptoms:

- Stunting of seedling growth & root development
- Inhibition of photosynthesis
- Inhibition of potassium uptake
- Reduction in yield
- Observed at nutrient concentrations down to 1 ppb

Another issue is the risk of human exposure related to the intake of lake fish (eels and catfish) that are contaminated by mercury.

In summary, Lake Waikare sediments are contaminated with mercury with the source of contamination associated with the geothermal resource. The mercury levels in sediments exceeded the threshold value where plant growth and lake fishes may be affected.

4. POTENTIAL USES OF THE GEOTHERMAL RESOURCE

Geothermal direct use application is the use of heat in geothermal fluid to provide energy for any end use other than electricity generation. This includes traditional uses common in many countries such as bathing, cooking (including industrial processes), heating, agriculture (greenhouses and drying) and mineral extraction.

In the Waikato Region, the current direct heat applications consist of growing tomatoes, capsicums, native plants, orchids and gerberas in geothermally-heated glasshouses, space and water heating for commercial facilities, aquaculture (prawns), timber drying and production of wood products and provision of water or heat for bathing pools (Barns and Luketina, 2011).

About 70 per cent of New Zealand's geothermal resources are in the Waikato region making the region not only the primary source of geothermal energy in New Zealand but also a geothermal tourism area attractive for both domestic and international tourists. Geothermal tourism in the Waikato Region, where an average of 2.5 million visits are made to geothermal attractions per year, is a growing business in the region that directly contributed $63 to $121 million to the Waikato regional economy in 2009, providing around 2,500 jobs in the tourism sector (Barns and Luketina, 2011). The popular geothermal attractions frequented by tourists in the region which use direct geothermal heat are as follow:

- Bathing as part of travel accommodation facilities (23 sites)
- Pay bathing (9 sites)
- Free informal bathing (10 sites)

Other geothermal attractions include:

- Pay nature tourism (4 sites)
- Free nature tourism (1 site)
- Technology-related sites (3 sites; Wairakei Terraces, a tourist attraction mainly comprising artificial geothermal features, the Wairakei Power Station borefield and the Prawn Park)

The fluid temperatures for several direct use applications in the Waikato Region range from 23 to 93°C (Zarrouk and Moore, 2007). The Lake Waikare resource with its inferred reservoir temperature between 136 to 160°C may be tapped for direct use. A detailed study as to what type of direct use application is viable has to be initially undertaken with several factors enumerated below that have to be considered:

- Site location of a deviated shallow production well (about 400-500 meters depth) that will be drilled along the eastern shoreline of the lake and directed towards west-southwest to the island to target Maungaroa Fault.
- The reinjection system to include site location of a reinjection well with almost the same direction and target depth.
- Option to use well for electricity generation (small-scale binary plant) subject to the fluid temperatures for self-sufficiency with the used geothermal fluid going to the intended heating system.
- Direct use facilities should be constructed within the vicinity of the production well.
- Assurance for market of the produce for a greenhouse project or projected tourist arrivals for hot pool or pay bathing facilities.
- Source of funding since quite a large amount of investment (possibly >NZ$ 1 million) maybe required.

5. CONCEPTUAL MODEL

Figure 18 illustrates the conceptual model of the Lake Waikare area showing the upflow zone along the Maungaroa Fault and fluid flow path at the formational or lithological contact between the marine mudstone and basement rocks. The marine mudstone with coal measures serves as the reservoir rocks while Mesozoic greywacke basement rocks supply heat to the system. Inferred low temperature isotherms are drawn in the model.
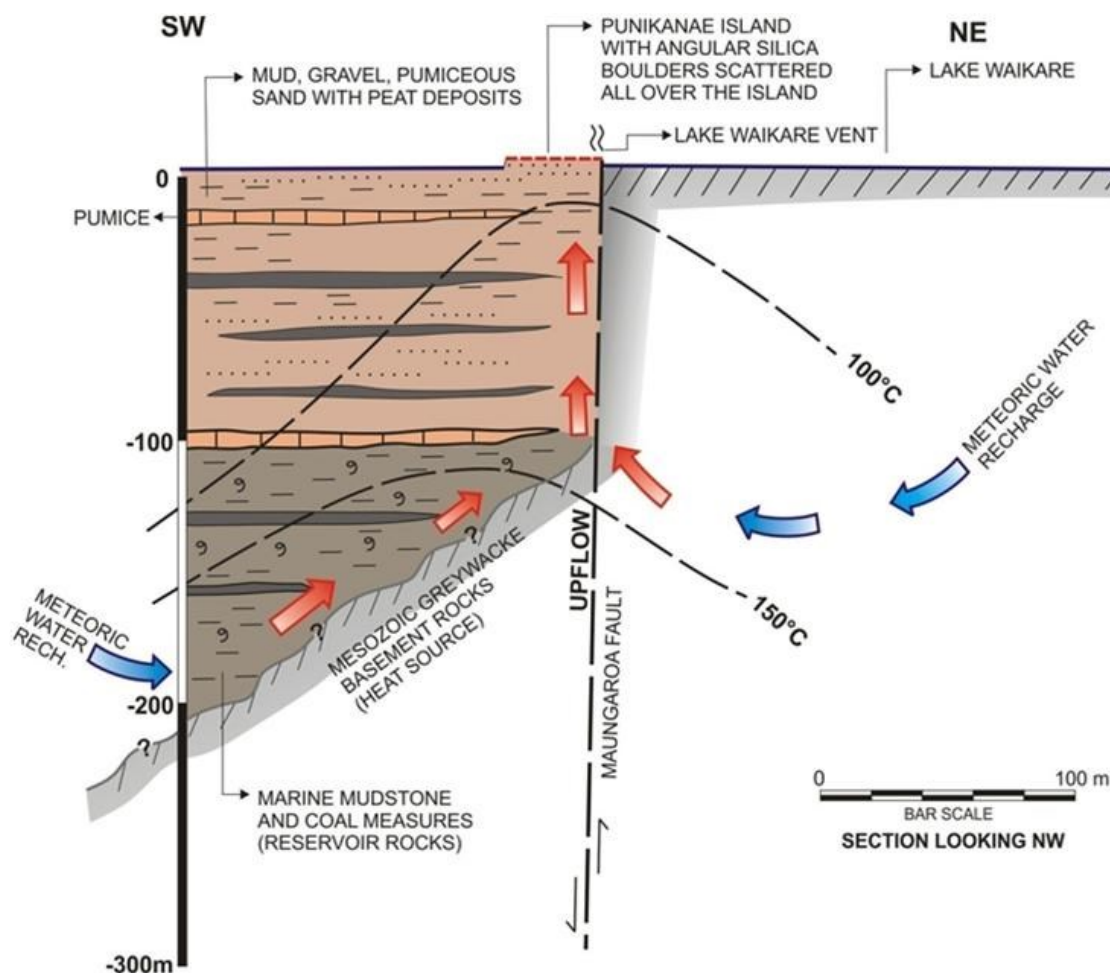

Figure 18. Conceptual model of the Lake Waikare geothermal system (section along line A-B of Figure 4)

6. CONCLUSIONS

The Lake Waikare geothermal waters are mature neutral chloride waters that likely originate from an upflow zone beneath the Punikanae Island with the Maungaroa Fault as its main conduit. Upflow zones are generally characterized by silica sinter deposition of hot chloride springs on the surface. The presence of a massive silica cap is also a manifestation that the island is the center of the geothermal activity in the area. The relatively high chloride concentrations of the spring that resulted in the deposition of the silica sinters possibly were derived from waters from reservoir composed of marine clastic sediments of the Te Kuiti Group. These clastic sediments unconformably overlie the Mesozoic greywacke basement rocks and these basement rocks probably supply the heat to the system as indicated in the Cl-B-HCO$_3$ ternary plot. The dilution by the cold groundwater is possible because one of the spring samples plotted near the $\sqrt{Mg}$ apex of the Na-K-Mg ternary diagram. The other sample lies just on the boundary line of the partially equilibrated waters region suggesting reservoir temperature of about 160°C that is typical for a low enthalpy geothermal system. This temperature was validated by results of computed temperatures of 160.3°C and 136.0°C using Na-K and Na-K-Ca geothermometers, respectively. The system is possibly recharged by meteoric waters that permeate through the Hapuakohe Range

to the east and the sediments to the west along structures and formational contacts. Lake Waikare sediments are contaminated with mercury with the source of contamination associated with the geothermal resource.

7. RECOMMENDATIONS

A petrographical study of the alteration assemblages in Punikanae Island as well as that of the "geothermal reefs" in the lake has to be initiated in order to establish a more detailed conceptual model that would give a clearer picture of the real system. This would compliment the megascopic analysis earlier done in the rocks as well as the very limited geochemical data used in this study.

A resampling of the spring is really necessary and finding a way on how to sample an underwater spring would be a good idea that could augment the present set of geochemical data.

REFERENCES

Barns, S. and Luketina, K.M.: Valuing uses of the Waikato regional geothermal resource. Waikato Regional Council, Document #: 1994613, (2011).

Cheptum, I (2012) Preliminary Assessment of Low Enthalpy Geothermal system at Ohinewai, Post Graduate Certificate Project in Geothermal Energy Technology, The Department of Engineering Science, The University of Auckland and Waikato Regional Council.

Ellis, A.J. and Mahon, W.A.J.: Chemistry and geothermal systems. Academic Press, New York, (1977), 392 pp.

EPRI : A theory on mercury in geothermal fluids. Research Project 1525-6, final report AP-AP-5111. Electric Power Research Institute, California, USA, (1987).

Fournier, R.O. and Truesdell, A.H.: An empirical Na-K-Ca geothermometer for natural waters. Geochim. Cosmochim. Acta, **37** (1973), 1255-1275.

Henley, R.W., and Hedenquist, J.W., 1986, Introduction to the geochemistry of active and fossil geothermal systems, Chapter 1 in Henley, R.W., Hedenquist, J.W., and Roberts, P.J., eds., 1986, Guide to Active Epithermal (Geothermal) Systems and Precious Metal Deposits: Mineral Deposits, Monograph 26, p. 211.

Giggenbach, W.F.: Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators. Geochim. Cosmochim. Acta, **52** (1988), 2749-2765.

Giggenbach, W.F., Gonfiantini, R., Jangi, B.L., and Truesdell, A.H.: Isotopic and chemical composition of Parbati Valley geothermal discharges, NW-Himalaya, India. *Geothermics,* **12**, (1983), 199-222.

Edbrooke, S.W.:Geology of the Auckland area, 1:250000 geological map 3. Institute of Geological and Nuclear Sciences Limited, Lower Hutt, New Zealand (2001).

Nelson, C.S, Mildenhall, D.C., Todd, A.J., Pocknall, D.T. : Subsurface stratigraphy, paleoenvironments, palynology, and depositional history of the late Neogene Tauranga Group at Ohinewai, Lower Waikato Lowland, South Auckland, New Zealand, New Zealand Journal of Geology and Geophysics, **31**, (1988),1, 21-24.

Nicholson, K.: Geothermal fluids: Chemistry and exploration techniques. Springer-Verlag, Berlin Heidelbarg, (1993).

Powell, T. and Cumming, W.: Spreadsheets for Geothermal Water and Gas Geochemistry. PROCEEDINGS, Thirty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, (2010), SGP-TR-188.

Webster-Brown, J.G. and Brown, K.L.: 2010 interpretation of geochemical data (REGEMP II) and recommendations for further monitoring. Waikato Regional Council Technical Report 2012/07, Document #: 1739611, (2012).

Zarrouk, S.J. and Moore, T.A.: Preliminary assessment of the geothermal signature and ECBM potential of the Huntly Coalbed Methane Field, New Zealand. Proceedings 29th NZ Geothermal Workshop, Auckland, New Zealand, (2007).

Zarrouk, S.J. and Moore, T.A.: Preliminary reservoir model of enhanced coal bed methane (ECBM) in a sub-bituminous coal seam, Huntly Coalfield, New Zealand. International Journal of Coal Geology, **77**, (2009), 153-161.