

The Lake Waikare low enthalpy geothermal resource: An initial study of its origin

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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 complemented by some geological information gathered during the short field visit and other technical data available in the literature indicate that the Punikanae Island geothermal waters are mature neutral chloride waters that probably originate from an upflow zone beneath the Punikanae Island with the Maungaroa Fault as its main conduit. The relatively high chloride concentrations of the spring that resulted in the deposition of the silica sinters possibly were 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 as indicated in the Cl-B-HCO₃ ternary diagram. One of the spring 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 160.28 and 136.0°C using Na-K and Na-K-Ca geothermometers, respectively.

Executive summary

This report was prepared as a requirement for the University of Auckland's Postgraduate Certificate in Geothermal Energy Technology.

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 complemented by some geological information gathered during the short field visit and other technical data available in the literature are the sets of information used in this study. Although the sets of chemical analysis used in the evaluation are very limited, an interpretation on the origin of the geothermal system that feeds the spring was initially concluded. Based on the Cl-SO₄-HCO₃ 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 Punikanae Island geothermal waters are mature neutral chloride waters that probably 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 relatively high chloride concentrations of the spring that resulted in the deposition of the silica sinters possibly were 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 as indicated in the Cl-B-HCO₃ ternary diagram. One of the spring 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 160.28 and 136.0°C using Na-K and Na-K-Ca geothermometers, respectively.

1 Introduction

1.1 Background of the study

The Waikato Regional Council (WRC) manages Waikato region's geothermal resources, overseeing its sustainable development, and use, and implements monitoring programs towards the preservation of the thermal features around the region. In line with 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 (WRC TR.2012/07). 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 discussion on Lake Waikare vent which is the subject of this study though very limited data of the feature is available at hand.

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 done in 2004 and 2005. To our knowledge, this is the only sinter-depositing spring known outside the Taupo Volcanic Zone (TVZ).

However, a research on the origin of this unique spring that lies on top of the Huntly coalfield has not yet been initiated. And 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 is to sample the spring. It is unfortunate, however, not to find the spring in its similar condition as in 2005 when the latest sampling activity was carried out because the spring is already submerged by less than a foot of water where only bubbles of warmed lake water were observed during the visit. **Figures 1a** and **1b** show pictures of the bubbling features where the spring is located.

It is worthwhile though to observe the island, the sinter deposits, some geology, the other features in the lake such as the "geothermal reefs" and the local topography.



Figure 1a. Bubbles from the spring; warmed lake water



Figure 1b. Bubbles from the spring; warmed lake water

1.3 Project location, accessibility, topography and drainage

Punikanae Island is a small island in Lake Waikare that measures around 75 m x 35 m. Lake Waikare is part of the Lower Waikato Lowland in North Waikato, a geomorphological feature within the Auckland Region (GNS, 2012). **Figure 2** below is a topographic relief model map showing the location of the lake, and surrounding geomorphological features. Lake Waikare is encircled in yellow.

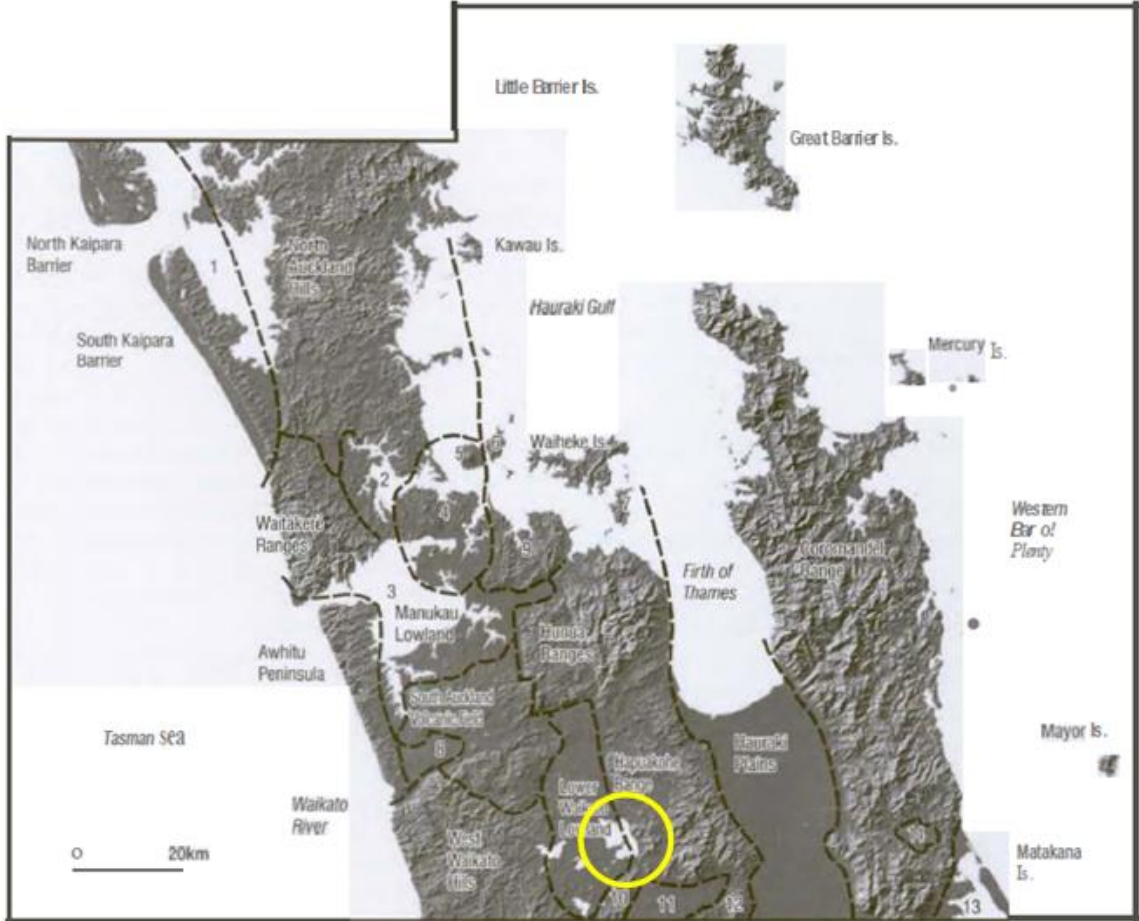


Figure 2. Hill-shaded topographic relief model of Auckland area (courtesy of GNS, 2001)

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

Small growth trees and shrubs around the area which is a favourite resting place for licensed game bird hunters. **Figures 4a** and **4b** are pictures of Punikanae Island.



Figure 3a. Punikanae Island



Figure 3b. Waikare Lake



Figure 4a. Punikanae Island as seen from the north aboard a rubber boat



Figure 4b. Inside the island

Rangiriri township is the nearest population centre 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 towards west to Ohinewai area. High relief terrain of up to 281 meters characterized the eastern side of the lake at Hapuakohe Range. **Figure 5** below shows the route to the lake via the nearest population centre (Rangiriri) and the contrast in topography from east to west.



Figure 5. Route A-B from the nearest population centre, 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) and the heavy use of fertiliser in the surrounding farming district, the waters of the lake are in poor condition with large amount 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 and 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 (<http://www.waikatoregion.govt.nz/Environment/Natural-resources/Water/Lakes/Shallow-lakes-of-the-Waikato-region/Riverine-lakes/Lake-Waikare/>).

2 Geology, structures and alteration

The Lake Waikare area is overlain by a 40 – 110 meter thick terrestrial deposits of the Tauranga Group that was formed during the Neogene epoch (here taken to include Late Miocene, Pliocene 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 a 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 (GNS, 2001). Other structures west of the lake towards Ohinewai area are also shown in the geologic map below (**Figure 6**).

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 that are targeted by mining. The coal deposits contain biogenically-sourced methane with relatively low to moderate measured gas (CH₄) contents (2-4 m³/ton) (Zarrouk and Moore, 2009).

Figure 7 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).

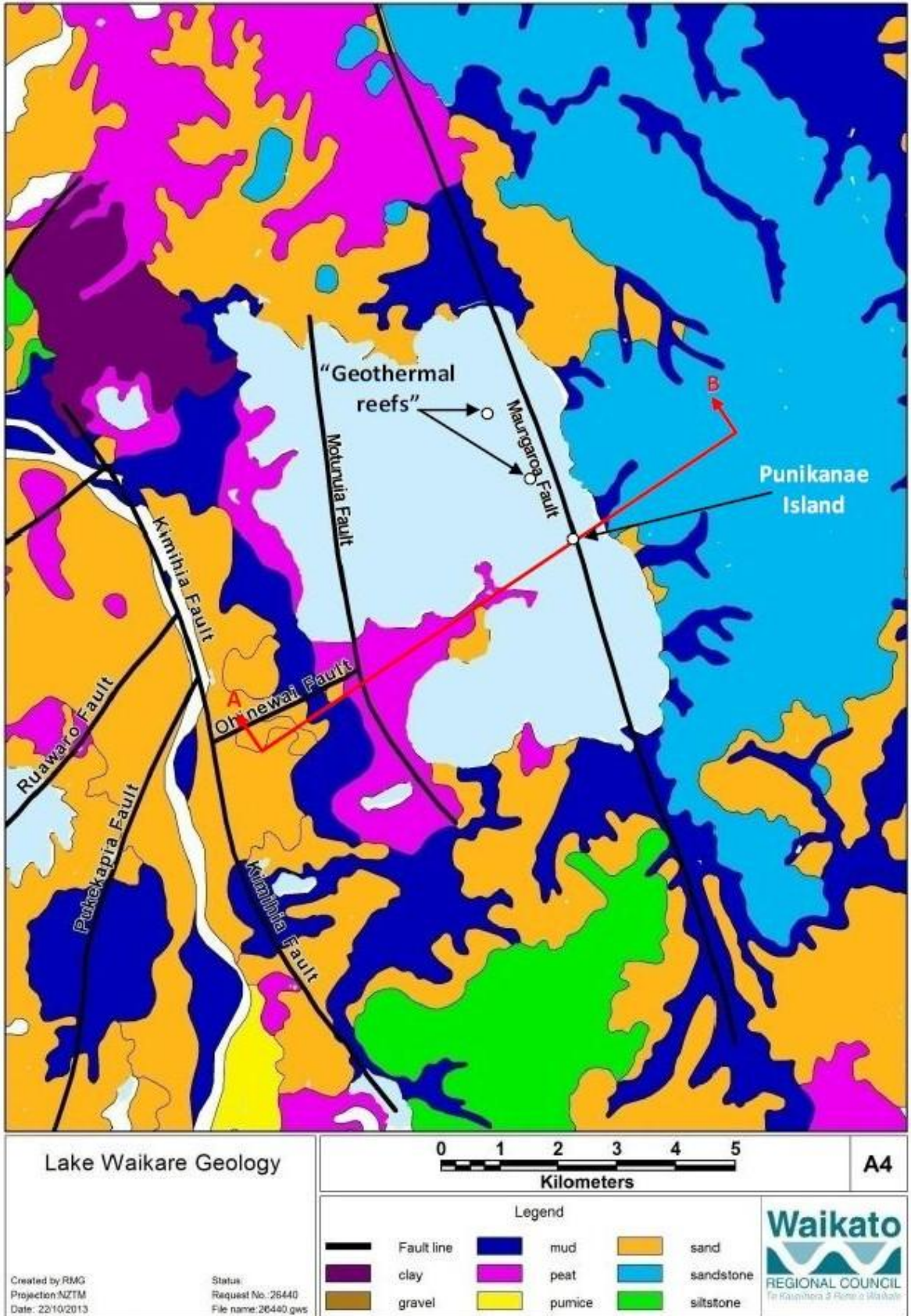


Figure 6. Geologic map of Lake Waikare area (map courtesy of Waikato Regional Council)

CORRELATIVE FORMATION	RL (m)	LITHOFACIES ASSEMBLAGE	GENERAL LITHOLOGY	PALYNOLOGIC ZONE	ADOPTED N.Z. (SUB) STAGE	AGE CORRELATION	EVENT
Holocene peat and Taupo Pumice Alluvium	1			See McGlone et al. (1984)	Aranuan	Holocene	6
Hinuera Fm ¹	40	E	Green, diatomaceous mud and overlying peat with interbedded pumiceous sand	<i>Nothofagus menziesii</i> Zone	Late Otiran		
Hamilton and Kairoa Ash Formations						Late Pleistocene	5
Karapiro Formation		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/ <i>Podocarpus</i> Zone	Marahauan [Wa]	Early Pleistocene	4
Puketoka Formation	0						
	-15	C2	Green, diatomaceous fine sand, silt and mud above gravelly coarse sand		Hautawan [Wh]		
		B	Highly pumiceous fine sand and silt with interbedded peat	Restionaceae Zone	Mangapanian [Wm]	Late Pliocene	3
	-45	C1	Green, massive or lenticularly bedded mudstone with interbedded diatomaceous mudstone and siltstone	<i>Nothofagus fusca</i> Zone	Waipipian [Wp]		
		A1					
Whangamarino Formation		A1	Green, mainly massive mudstone and claystone with sandy and gravelly mud and thinly bedded pumiceous fine sand	<i>Nothofagidites cranwellae</i> Zone	?Opoitian [?Wo]	? Early Pliocene	2
		A2	Carbonaceous claystone with common peat and thinly bedded pumiceous fine sand		Kapitean [Tk]	Late Miocene	1
Te Kuiti Group	93	Unconformity	Coal measures or calcareous mudstone	Upper <i>Nothofagidites matauraensis</i> Zone	Waitakian [Lw] to ?Dunroonian [?Ld]	Late Oligocene	—

1. Collectively named here the Waikare beds

Figure 7. General stratigraphy of the Lake Waikare area showing the Tauranga Group (from Nelson et al., 1988)

Punikanae Island, however, is overlain by approximately one-meter thick grayish chalcedonic silica layer already broken to cobble-boulder size angular fragments that 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. **Figures 8a** and **8b** below shows the angular silica boulders present in the island. **Figure 8c** is a hand specimen of the chalcedonic silica.



Figure 8a. Silica boulder showing banding



Figure 8b. Silica boulder



Figure 8c. 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 (**Figure 9**).

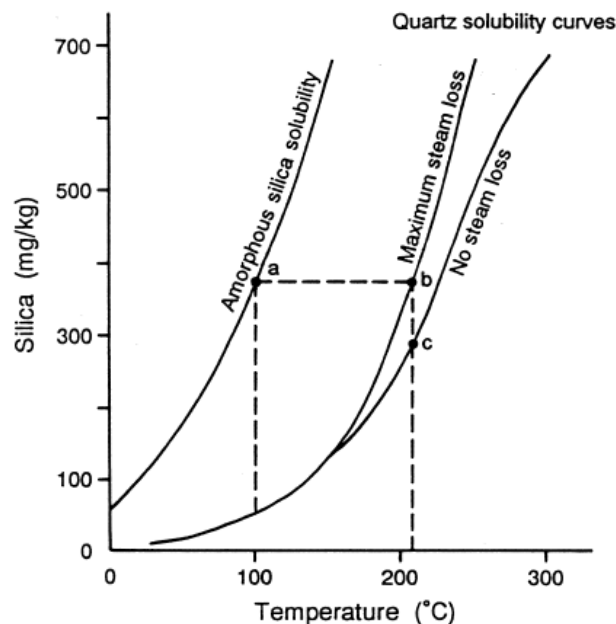


Figure 9. Solubilities of amorphous silica and quartz (curve Q_C) at the vapour pressure of the solutions with respect to temperature.

Curve Q_B is a correction to curve Q_C and shows the concentration of dissolved silica that would be present after flashing (boiling) to 100°C from the initial fluid temperature (i.e. from point c to point b). The dashed line (a-b-c) shows the concentration of silica in the reservoir, and the reservoir temperature of 210°C, for a spring boiling at 100°C and depositing silica. Springs depositing silica sinters must therefore discharge from a reservoir with temperatures in excess of 200°C (Nicholson, 1993).

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”. **Figures 10a, 10b** and **10c** show the tuffaceous sandstone outcrop in Punikanae Island.

Figures 11a, 11b and **11c** below are pockets of “geothermal reefs” in Lake Waikare.



Figure 10a. Tuffaceous sandstone outcrop in Punikanae Island



Figure 10b. Tuffaceous sandstone outcrop in Punikanae Island



Figure 10c. Tuffaceous sandstone outcrop in Punikanae Island.



Figure 11a. "Geothermal reef" in Lake Waikare



Figure 11b. “Geothermal reef” in Lake Waikare



Figure 11c. “Geothermal reef” in Lake Waikare



Figure 12 Specimen of the clay-altered/argillized tuffaceous sandstone.

Figure 12 above shows a picture of the argillized tuffaceous sandstone specimen.

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 11a, 11b** and **11c** protrude a few centimetres on the surface of the lake measuring around 1-5 m² 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 this unique geothermal reefs.

A simplified geologic cross section of the Lake Waikare area is constructed and shown in **Figure 13** below.

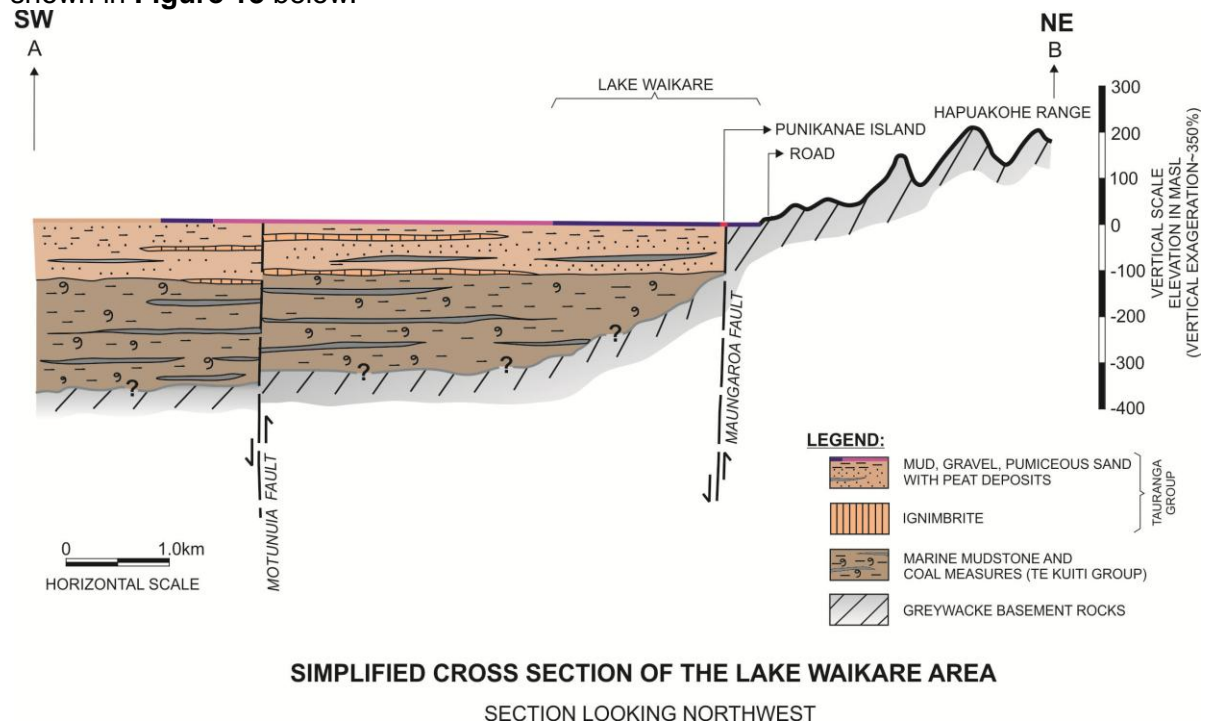


Figure 13 Simplified geologic cross section of Lake Waikare area along line A-B of Figure 6 (geologic map); vertical scale exaggerated to ~350%

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 (**Appendix 1**). 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 origin of low temperature type geothermal systems. The source of heat that feeds Lake Waikare system can be classified to come 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 waters from reservoir composed of marine clastic sediments of the Te Kuiti Group that unconformably rest on the basement rocks. Based on the cross-section (**Figure 13**), the possible depth of the reservoir is around 200-300 meters. Elevated Boron and CO₂ concentrations are also common in this type 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 6**) 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 discharge 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 14**). This map would somehow attest to this perception.

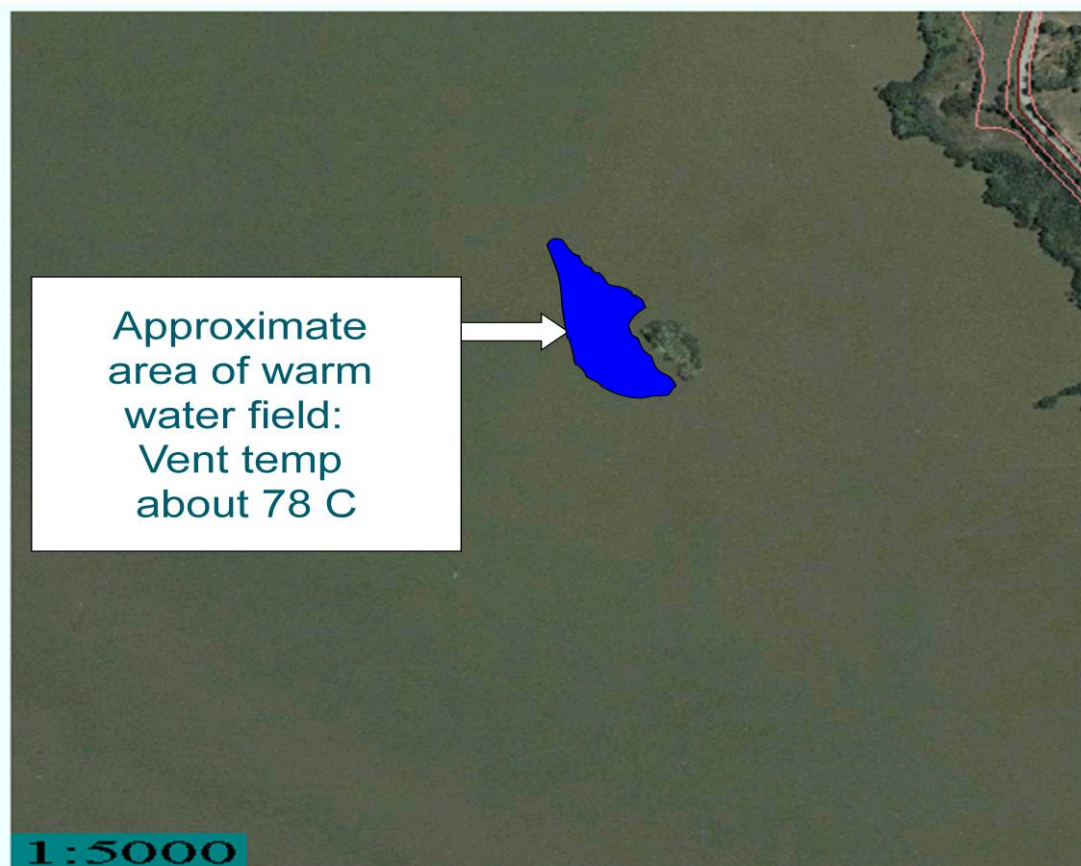


Figure 14. Area of warm water field in Lake Waikare (C) Waikato Regional Council)

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-SO₄-HCO₃, Na-K-Mg and Cl-B-HCO₃. 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 (2013). 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
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 CI-SO₄-HCO₃ ternary diagram

The CI-SO₄-HCO₃ diagram is ternary plot that is used to classify type of geothermal waters based on the relative proportions of chloride, sulphate and bicarbonate ions. The types include deep chloride waters, dilute CI-HCO₃ waters, mixed CI-SO₄ 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 15 shows the two spring samples fall under 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.

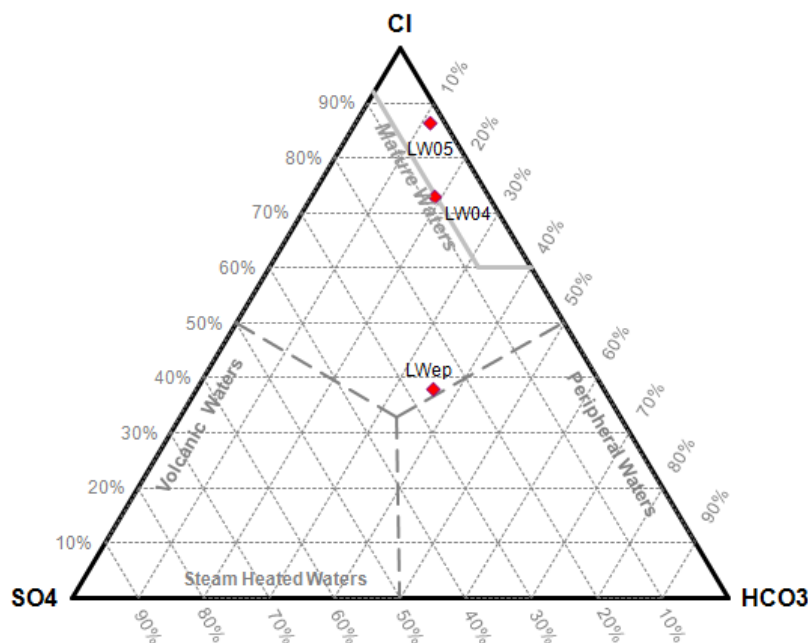


Figure 15. CI-SO₄-HCO₃ ternary plot (Lake Waikare thermal area)

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 $\sqrt{\text{Mg}}$ 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 16** 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 $\sqrt{\text{Mg}}$ apex.

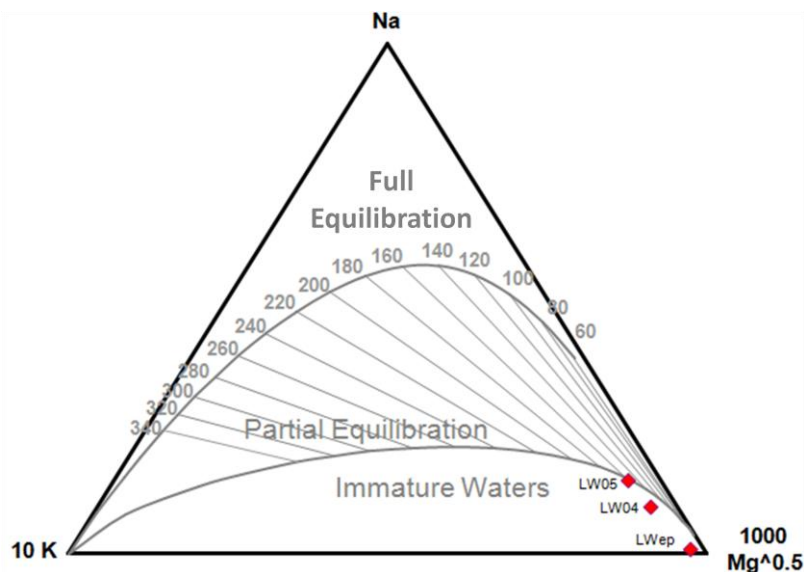


Figure 16. Na-K-Mg ternary plot (Lake Waikare thermal area)

3.3 Na-K geothermometer

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

$$t^{\circ}\text{C} = 1390 / [\log (\text{Na}/\text{K}) + 1.750] - 273 \text{ (Giggenbach, 1988 in Nicholson, 1993)}$$

Using the above equation to get the temperature of sample no. LW05 that lies in the boundary of the partial equilibration 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:

$$t^{\circ}\text{C} = 1647 / \{ \log (\text{Na}/\text{K}) + \beta [\log (\text{Ca}^{1/2} / \text{Na}) + 2.06] + 2.47 \} - 273$$

where

$$t > 70^{\circ}\text{C}$$

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

$$\beta = 4/3, \text{ if } t < 100^{\circ}\text{C}$$

$$\beta = 1/3, \text{ if } t > 100^{\circ}\text{C}$$

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

1. Calculate $[\log (\text{Ca}^{1/2}/\text{Na} + 2.06)]$; if this is positive, calculate the temperature, $t^{\circ}\text{C}$, using $\beta=4/3$.

2. If $t < 100^{\circ}\text{C}$ use this temperature.
3. If however, $t > 100^{\circ}\text{C}$ or $[\log (\text{Ca}^{1/2}/\text{Na} + 2.06)]$ 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 Na-K and Na-K-Ca geothermometer calculations for the Lake Waikare vent that are typical for a low enthalpy geothermal system.

Table 2. Inferred reservoir temperatures in $^{\circ}\text{C}$ using the Na-K-Mg ternary plot

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 $\text{Cl-SO}_4\text{-HCO}_3$ and Na-K-Mg ternary plots for TVZ springs

The major element analyses of representative TVZ springs in **Table 3** were used in the following $\text{Cl-SO}_4\text{-HCO}_3$ and Na-K-Mg ternary plots (**Figures 17** and **18**) for comparison with the results in Lake Waikare vent.

Table 3. Major element analyses of representative TVZ hydrothermal fluids (Henley and Hedenquist, 1986 and Giggenbach and Glasby, 1977 in Simmons et al., 1992)

Location	T $^{\circ}\text{C}$	Na	K	Ca	Mg	Cl	SO ₄	SiO ₂	B	CO ₂	H ₂ S
		<i>in mg/kg</i>									
Well discharges											
Wairakei 27	250	926	154	11.8	0.04	1543	20	484	20	348	9
Tauhara 1	253	891	156	10.0	<0.02	1553	21	507	27	475	25
Rotokawa 5	320	265	87	0.5	0.01	520	4	710	15	4495	345
Broadlands 6*	129	500	41	7.3	56	25	19	170	<2.5	12,888	
Broadlands 11	261	705	150	5.0	0.6	1238	7	556	34	4104	72
Waiotapu 6	220	434	78	5.0	-	732	102	238	11	1020	86
Mokai 3	300	900	293	10	0.02	2273	8	-	25	636	38
Orakeikorako 3	230	183	29	0.2	-	223	25	408	3	248	10
Springs											
Broadlands-Ohaaki Ohaaki Pool	95	860	82	2.5	0.1	1060	100	338	32	490	
Waiotapu Champagne Pool	75	1102	151	35.1	0.05	1898	53	445	25.4	250	
Devil's Ink Pot	65	4	6.2	2.5	0.80	<2	1047	151			
		<i>also contains 44 mg/kg Al and 2.5 mg/kg Fe</i>									
Waimangu Birdnest Terrace	99	495	89	24	4.09	760	215	413	7.5	11.5	
Inferno Crater	43	540	103	17	2.19	852	400	667	8.6		
White Island Acid spring	79	5910	635	3150	3800	38700	4870	360	160		
		<i>also contains 1610 mg/kg Al and 5720 mg/kg Fe</i>									

* Sample taken 850 m downhole

In **Figure 17**, the Champagne and Ohaaki pools with high Cl values of 1898 and 1060 ppm, respectively, plotted within the mature waters region of the $\text{Cl-SO}_4\text{-HCO}_3$ diagram, though there were no values given for HCO_3 .

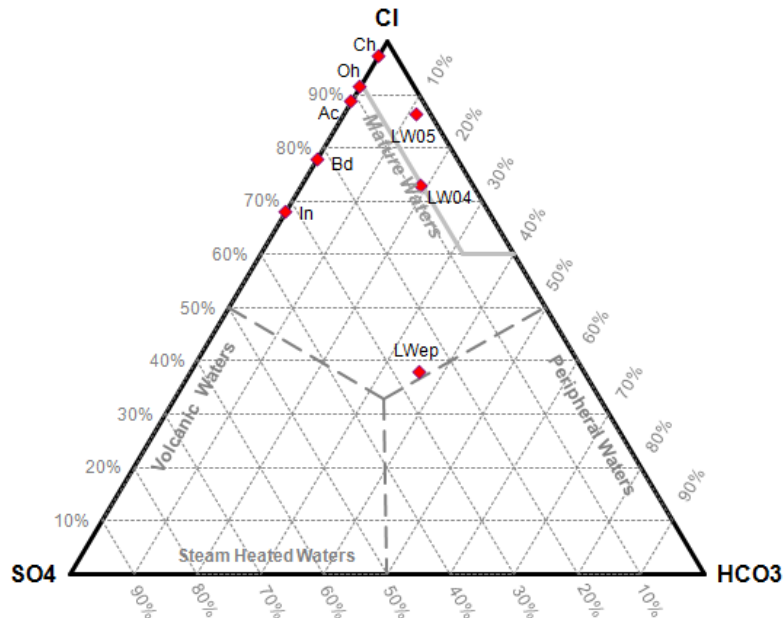


Figure 17 CI-SO₄-HCO₃ ternary plot (TVZ springs and Lake Waikare thermal area).

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 (**Figure 18**) suggesting that the source of geothermal fluids that feed the springs originated from high temperature systems.

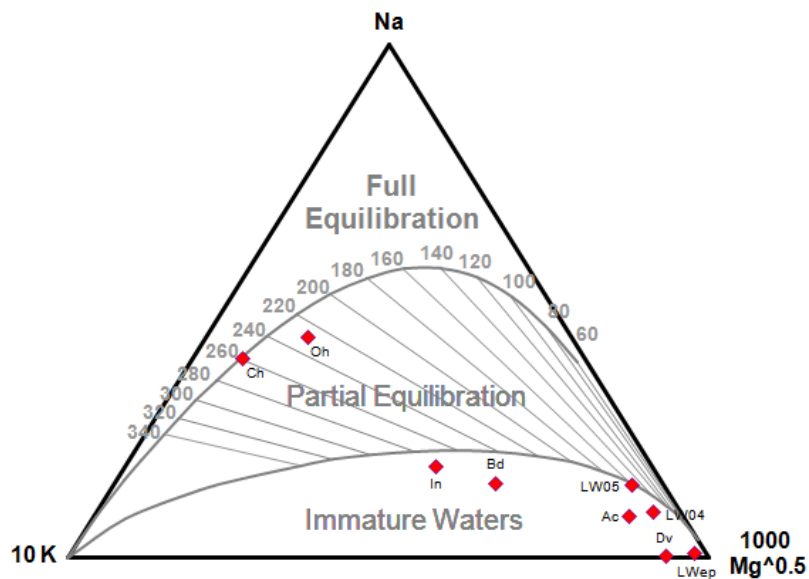


Figure 18 Na-K-Mg ternary plot (TVZ springs and Lake Waikare thermal area)

The high temperature values that yielded from Champagne and Ohaaki pools were confirmed using the Na-K and Na-K-Ca geothermometers and results are provided in **Table 4** below.

Table 4. Inferred reservoir temperatures in °C using the Na-K-Mg ternary plot and the Na-K and Na-K-Ca geothermometers for TVZ springs

Sample no.	Na-K-Mg (Giggenbach, 1983)	Na-K (Giggenbach, 1988)	Na-K-Ca (Fournier and Truesdell, 1973)
Ch (Champagne Pool)	260	258.91	231.69
Oh (Ohaaki Pool)	230	228.68	231.36

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 SO₄ values.

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 low 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-HCO₃ ternary diagram

The Cl-B-HCO₃ ternary plot was adopted from the report of Cheptum (2013) in order to determine the likely origin of the fluids of the Lake Waikare system. Based on the plot in **Figure 19**, 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 HCO₃. The rest of the TVZ springs that plotted in the Cl apex (Birdnest Terrace, Inferno Crater and Acid Spring) have high SO₄ values implying that these are mixed Cl-SO₄ waters/volcanic condensates from shallow origin.

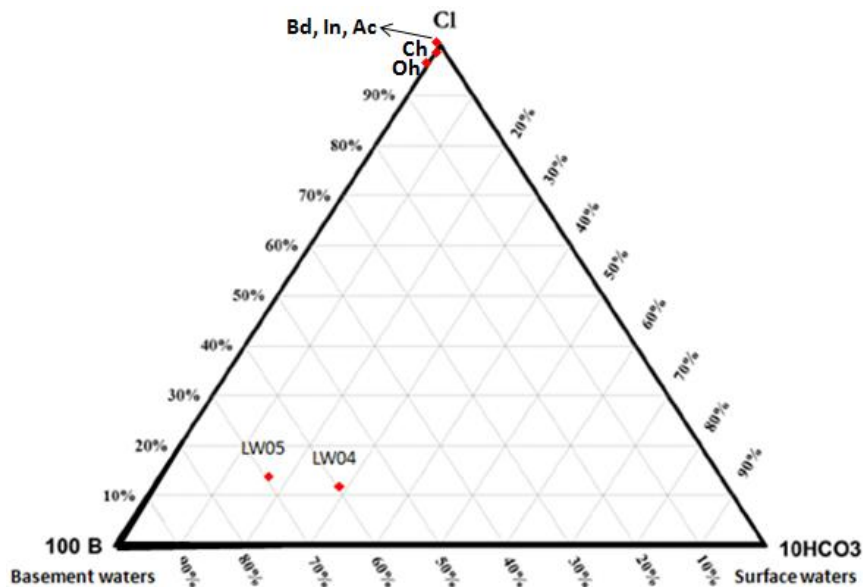


Figure 19. Cl-B-HCO₃ ternary plot (Lake Waikare thermal area and TVZ springs)

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 H₂S concentrations, the lower the amount of soluble mercury in the reservoir fluid and the less formation of mercuric sulphide (HgS). But for H₂S concentrations <30 ppm, precipitation of HgS (cinnabar) and other metallic sulphides such as FeS₂ (pyrite) and As₂S₃ (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 H₂S is only 0.013 ppm but with relatively low mercury value of 2.54 ppb (Table 1).

In general, the low H₂S 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 20** illustrates the level of mercury in the lake sediments centred around the Punikanae Island.

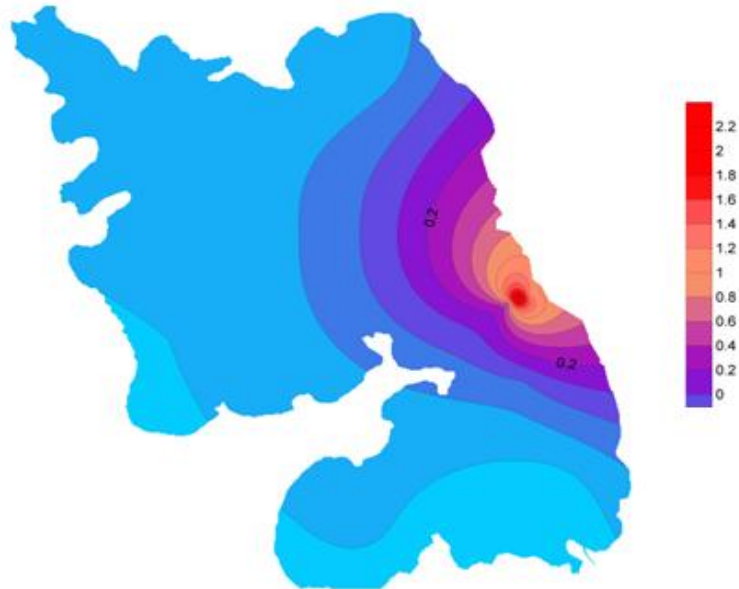


Figure 20. Levels of mercury in sediments in Lake Waikare

The lake sediments close to the island had a mean value of 500 ppb mercury. An area of around 80 hectares (0.8 km²), has a median probable effects level of 1000 ppb (1 mg/kg) as shown in **Figure 21** below.

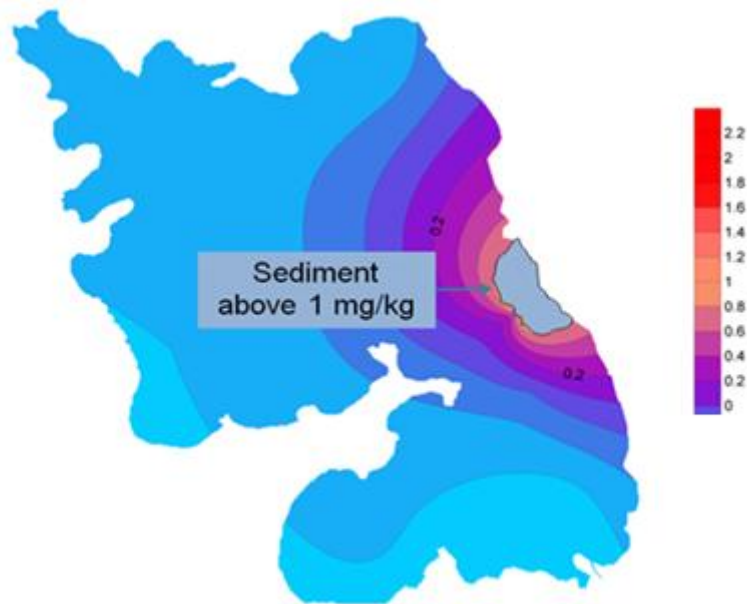


Figure 21. Median level in sediments with 1000 ppb (1 mg/kg) mercury in Lake Waikare

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 (Zarrouk, 2013, Geothermal Technology lecture hand-out).

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 22 illustrates the conceptual model of 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.

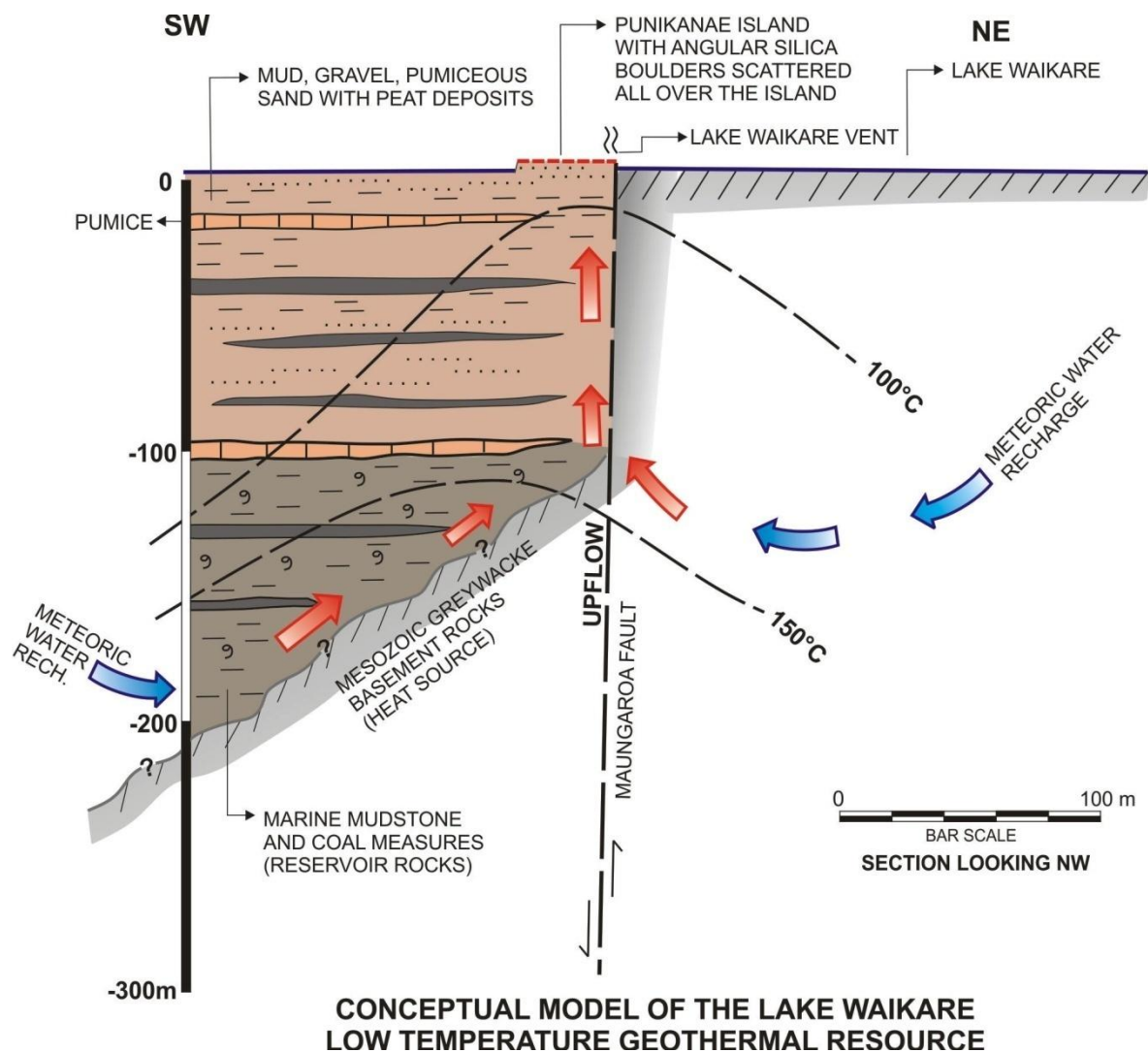


Figure 22. Conceptual model of the Lake Waikare geothermal system

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 centre 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-HCO₃ ternary plot. The dilution by the cold groundwater is possible because one of the spring samples plotted near the $\sqrt{\text{Mg}}$ 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 160.28 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 high in mercury concentrations, with the source of mercury 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 complement 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 necessary using a similar method as previously to conquer the challenge of sampling an underwater spring, to augment the present set of geochemical data.

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Appendix 1: 2005 analytical results from Hill Laboratories

Hill Laboratories

R J Hill Laboratories Limited

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Email:
mail@hill-labs.co.nz
Internet:
www.hill-labs.co.nz



Client: Environment Waikato
Address: P O Box 4010,
HAMILTON
Contact: Ian Buchanan

Laboratory No: 388423
Date Registered: 30/08/2005
Date Completed: 13/10/2005
Page Number: 1 of 3

Client's Reference: Geothermal Water Analysis

The results for the analyses you requested are as follows:

Sample Type: Water, Geothermal waters

Sample Name	326.45 Vent Temp 64.5°	326.4 Lake Temp 15.7
Lab No	388423/1	388423/2
pH (pH units)	8.9	9.6
Electrical Conductivity (mS/m)	115	16.5
Salinity*	0.3	< 0.1
Total Alkalinity (g.m-3 as CaCO3)	66	31
Dissolved Calcium (g.m-3)	12	9.76
Dissolved Magnesium (g.m-3)	1.3	3.67
Dissolved Sodium (g.m-3)	201	15.5
Dissolved Potassium (g.m-3)	7	3.84
Dissolved Lithium (g.m-3)	0.473	0.0218
Dissolved Rubidium (g.m-3)	0.018	0.0074
Total Ammoniacal-N (g.m-3)	0.87	< 0.01
Chloride (g.m-3)	299	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	13.6
Total Sulphide (g.m-3)	2.93	0.002
Un-ionised hydrogen sulphide* (g.m-3)	0.013	< 0.002
Dissolved Boron (g.m-3)	16.1	0.118
Silicon (g.m-3)	36.2	6.7
Total Dissolved Silica (g.m-3 as SiO2)	77.6	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	< 0.00008
Dissolved Antimony (g.m-3)	< 0.004	< 0.0002
Dissolved Thallium (g.m-3)	< 0.001	< 0.00005

* This test is not accredited.



This Laboratory is accredited by International Accreditation New Zealand (IANZ), which represents New Zealand in the International Laboratory Accreditation Cooperation (ILAC). Through the ILAC Mutual Recognition Arrangement (ILAC-MRA) this accreditation is internationally recognised. The tests reported herein have been performed in accordance with the terms of accreditation, with the exception of tests marked *, which are not accredited.

Sample Containers

The following table shows the sample containers that were associated with this job.

Container Description	Container Size (mL)	Number of Containers
Unpreserved (1L)	1000	2
Nitric washed, UNPRESERVED (250 mL)	250	2
Glass Mercury Sulphuric/Dichromate Pres (100 mL)	100	2
Zinc acetate preserved (sulphide) (100 mL)	100	2
Sulphuric Preserved Pottle	100	2

Details of sample bottle preparation procedures are available upon request.

Summary of Methods Used and Detection Limits

The following table(s) gives a brief description of the methods used to conduct the analyses for this job. The detection limits given below are those attainable in a relatively clean matrix. Detection limits may be higher for individual samples should insufficient sample be available, or if the matrix requires that dilutions be performed during analysis.

Substance Type: Water

Parameter	Method Used	Detection Limit
Sample filtration for general testing	Sample filtration through 0.45µm membrane filter.	N/A
Sample filtration for metals analyses	Sample filtration through nitric washed 0.45µm membrane filter. APHA 3030 B 20 th ed. 1998	N/A
pH	Saline sample. pH meter APHA 4500-H ⁺ B 20 th ed. 1998	0.1 pH units
Electrical Conductivity	Conductivity meter, 25°C APHA 2510 B 20 th ed. 1998	0.1 mS/m
Salinity*	Saline sample. Meter, temperature compensation. APHA 2520 B 20 th ed. 1998	0.2
Total Alkalinity	Saline sample. Titration to pH 4.5.	1 g.m-3 as CaCO ₃
Dissolved Calcium	Filtered sample, ICP-MS APHA 3125 B 20 th ed. 1998	0.05 g.m-3
Dissolved Magnesium	Filtered sample, ICP-MS APHA 3125 B 20 th ed. 1998	0.02 g.m-3
Dissolved Sodium	Filtered sample, ICP-MS APHA 3125 B 20 th ed. 1998	0.02 g.m-3
Dissolved Potassium	Filtered sample, ICP-MS APHA 3125 B 20 th ed. 1998	0.05 g.m-3
Dissolved Lithium	Filtered sample. ICP-MS APHA 3125 B 20 th ed. 1998	0.0002 g.m-3
Dissolved Rubidium	Filtered sample. ICP-MS APHA 3125 B 20 th ed. 1998	0.0001 g.m-3
Total Ammoniacal-N	Filtered sample. Phenol/hypochlorite colorimetry. Discrete Analyser. (NH ₄ -N = NH ₄ ⁺ -N + NH ₃ -N) APHA 4500-NH ₃ F (modified from manual analysis) 20 th ed. 1998	0.01 g.m-3
Chloride	Filtered sample. Ferric thiocyanate colorimetry. Discrete Analyser. APHA 4110-Cl E (modified from continuous-flow analysis) 20 th ed. 1998	0.5 g.m-3
Fluoride	Ion selective electrode APHA 4500-F ⁻ C 20 th ed. 1998	0.05 g.m-3
Dissolved Bromine*	Filtered sample. ICP-MS APHA 3125 B 20 th ed. 1998	0.005 g.m-3
Sulphate	Filtered sample. Ion Chromatography. APHA 4110 B 20 th ed. 1998	0.5 g.m-3
Total Sulphide	Gas diffusion, Automated Methylene blue colorimetry. APHA 4500-S ²⁻ E 20 th ed. 1998	0.002 g.m-3
Un-ionised hydrogen sulphide*	Calculation from total sulphide, EC, pH, temp. APHA 4500-S ²⁻ H 20 th ed. 1998	0.002 g.m-3
Dissolved Boron	Filtered sample. ICP-MS APHA 3125 B 20 th ed. 1998	0.005 g.m-3
Silicon	Analysed as received (filtration, if required), ICP-MS. APHA 3125 B 20 th ed. 1998	0.005 g.m-3
Total Dissolved Silica	Calculation: Silicon x 2.14	0.01 g.m-3 as SiO ₂
Dissolved Iron	Filtered sample. ICP-MS APHA 3125 B 20 th ed. 1998	0.02 g.m-3

- R J Hill Laboratories Ltd -