Investigating the Geothermal Signature of the Kaimai Tunnel, New Zealand

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ABSTRACT

The Kaimai Tunnel passes through the Kaimai Ranges in the North Island, which mark the boundary between the Waikato and the Bay of Plenty Regions. The existence of the hot springs in the tunnel has been known for some time, but these springs have not been sampled or studied before. The objectives of this study is to sample the springs and determine the natural setting of the Kaimai tunnel springs and assess the type of geothermal system.

Six water samples from seepages in the tunnel have been analyzed for the water chemistry, and the results used to classify the water source, characteristic and geothermometry. In addition, the Cl-B-HCO_3 diagram applied in this method can distinguish the water source from different aquifers. Results indicate that the springs have the same shallow groundwater source. The water is shown to be immature water, that has not reached equilibrium. There is no indication that the springs come directly from a deep reservoir.

The springs in Kaimai Tunnel are interpreted not to be related to geothermal activity, their slightly elevated temperatures are related to the natural temperature gradient inside the tunnel.

1. INTRODUCTION

1.1 Location and Objective

The Kaimai rail tunnel runs through the Kaimai ranges in the North Island of New Zealand, entering near Armadale Rd, Waikato Region, and exiting near Wright Rd, Bay of Plenty Region. The existence of hot springs in the tunnel have been known, but these springs have not been sampled or studied before. There are several nearby areas of hot springs at Te Aroha, Miranda-Kaiaua, Lake Waikare, and Ohinewai that may have originated from the Tertiary Coromandel Volcanic Zone (CVZ) and are identified as being low temperature geothermal systems.

In 2016 the surface geological data, the Kaimai Tunnel borehole logs, and the chemistry of the tunnel springs were used to investigate the possibility of a geothermal system underneath the Kaimai tunnel in 2016.

In this study we have sampled the springs and provide the water chemistry to determine the nature of Kaimai tunnel springs and the geothermal system.

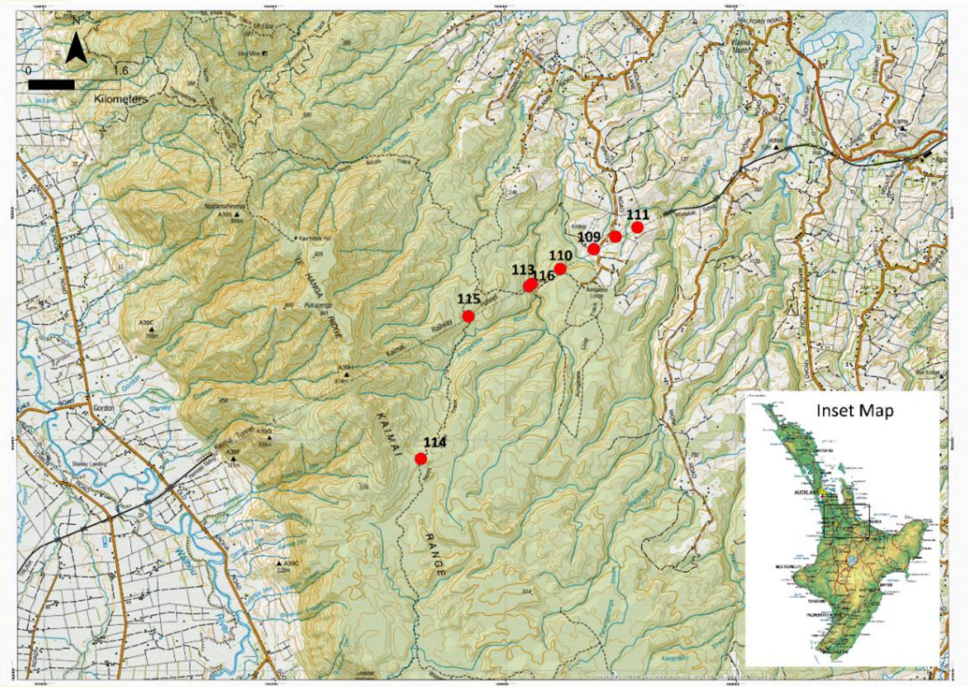

Figure 1: A topography map of the Kaimai Range and the surrounding area (see Inset Map) showing the tunnel location as a black dashed line that crosses the Kaimai Range. The red dot line with numbers represent the borehole locations.

1.2 Thermal Manifestations Around Coromandel Volcanic Zone

The appearances of the geothermal system in the Coromandel Volcanic Zone can be seen from the distribution of the springs around this area, there are isolated sets of low-temperature geothermal springs occur at on the Western edge of the Kaimai ranges, and on the adjacent Hauraki Plains at Te Aroha, Miranda, Lake Waikare and Ohinewai (Figure 2). There are also hot springs along the Eastern edge. Although this system is older than the Taupo Volcanic Zone, there are small thermal activities indicating a signature of a low enthalpy geothermal system in the area.

According to Booden (2011) and Turner (2011), the springs in the Coromandel Volcanic Zone are heated from a Mesozoic greywacke basement of Manaia Hill group conserved in the sediment or Miocene to Quaternary Volcanic layers.

The volcanic activity began further north at approximately 25 Ma ago and gradually shifted to the southward during the Miocene and Pliocene (Turner, 2011). Then the latest volcanism 1.9 Ma formed in the Coromandel Volcanic Zone in parallel with the arc subduction and was shifted from Coromandel to the Taupo Volcanic Zone 1.6 Ma ago. During this time, the magma composition changed from basaltic in the Coromandel Volcanic Zone to more felsic in the Taupo Volcanic Zone.

While the geochemistry shows mature chloride water at Lake Waikare and Ohinewai, Te Aroha and Miranda-Kaiaua (Figure 2) are more dominated with bicarbonate water that indicates shallow groundwater mixing, as seen in the Cl-SO_4-HCO_3 ternary diagram.

The Cl-B-HCO_3 diagram also suggests that the spring water is derived from clastic sediment which uncomformably overlies the Mesozoic greywacke basement rock as the heat source (close to B apex) in the Lake Waikare and Ohinewai and the diluted groundwater in Te Aroha and Miranda-Kaiaua (close to Bicarbonate apex).

The Cl-Li-B ternary diagram indicates that the Te Aroha domain springs are formed in a young geothermal system because they lie close to the B apex while the rest of the springs are likely formed from an older geothermal field since they lie close to the Cl apex.

The Na-K-Mg diagram shows that the springs in Lake Waikare are immature water, still not in equilibrium, while the rest of the springs are partially equilibrated, indicating that the water has a stable interaction with the surrounding rocks. Particularly, the Te Aroha springs are almost fully equilibrated, indicating that the water has a fast flow and is stable at the surface with less water rock interaction.

The temperature indication for these springs may be inaccurate due to the fluid mostly being diluted with groundwater. However, based on the geothermometry from chemistry content, the heated fluid at greater depths can reach around 60-122 °C in Ohinewai and Miranda-Kaiaua, and 136-170 °C in Lake Waikare and Te Aroha.

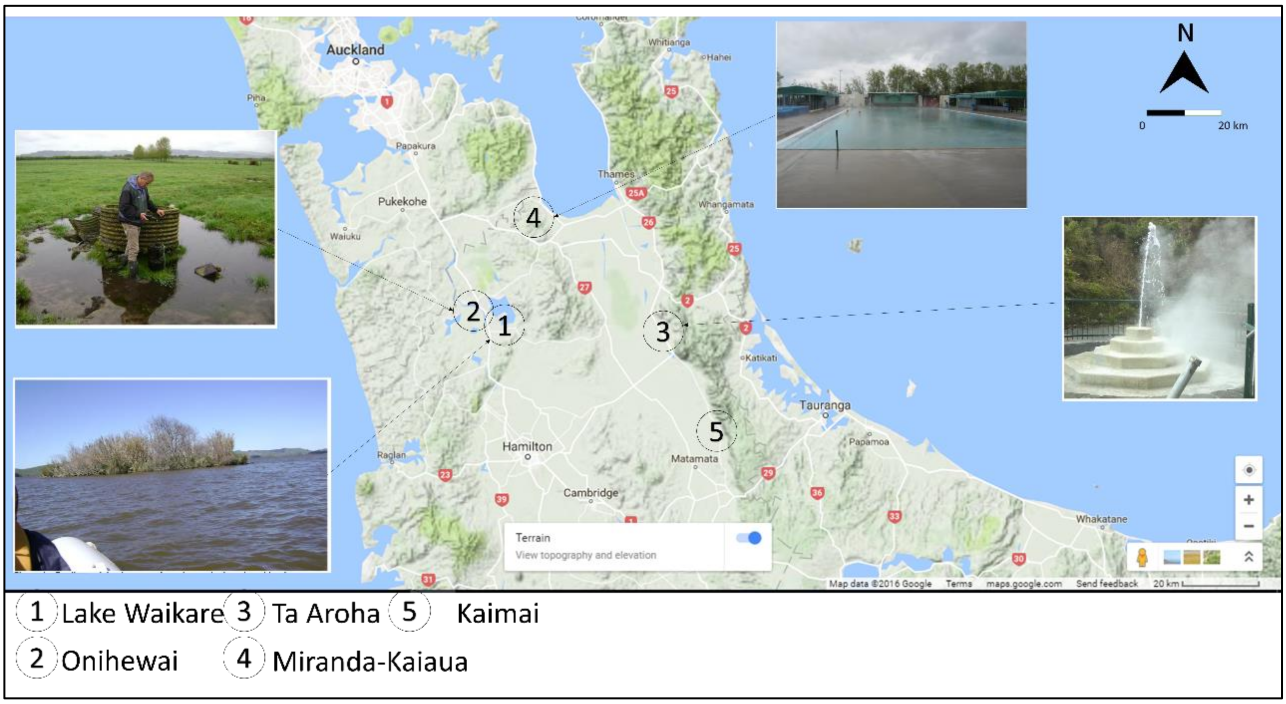

Figure 2: The location of the thermal springs around the Coromandel Volcanic Zone compiled from Waikato Regional Council reports (map taken from Google map, 2016).

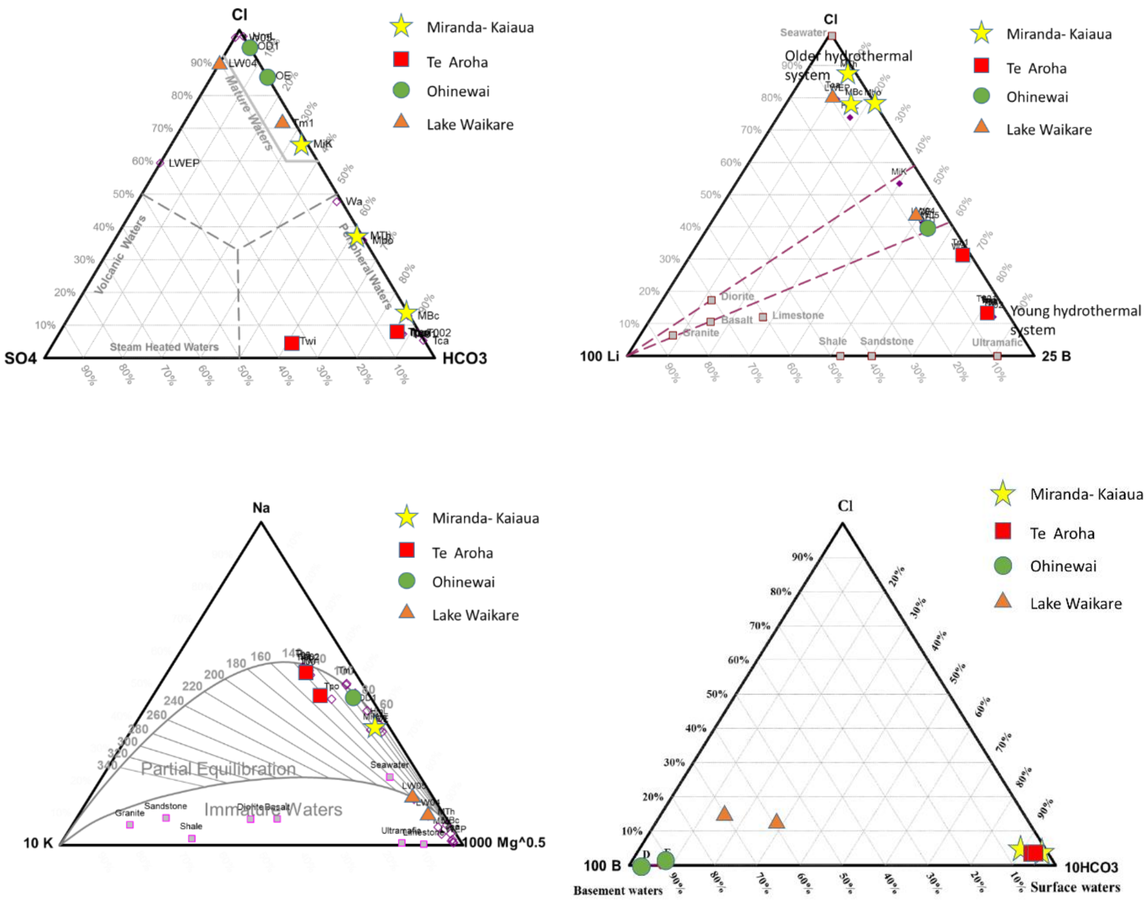

Figure 3: Cl-SO$_4$-HCO$_3$ (above left), Cl-LI-B (above right), Na-K-Mg (below left) and Cl-B-HCO$_3$ (below right) ternary diagram from springs in TVZ.

2. KAIMAI TUNNEL SPRINGS

2.2 Geological Background

The Kaimai Tunnel is located underneath the Kaimai-Aongatete Mountain with moderate to steep terrain. The highest elevation in the surrounding area is around 800 masl.

The stratigraphy in the Kaimai Tunnel is described in the geology report of Hegan (1973). The geology map is shown in Figure 4. From oldest to youngest units consist of: Waitakere Ignimbrite or ignimbrite unit, dominated with welded lenticulite ignimbrite and basal lava interbedded with soft tuff; Aongatete volcanics or andesite unit, dominated with sequence of pumice breccia and andesite rock; and lastly the Beeson's Island volcanics or younger andesite unit, dominated with breccia with andesitic fragments and grey crystalline andesite.

The structural geology seen on the surface is the NNW- SSE trend of the Hauraki Fault (Figure 4). This fault becomes a boundary of the sedimentary Hauraki rift on the western side and the andesitic/dacitic deposits of the Kaimai Ranges on the eastern side. Nevertheless, observations from the borehole log and the tunnel wall as written in Hagen (1973) and Kiwi Rail (2013) clearly show some minor faults with offset rocks, fault breccia and fracture zones which may act as a channel for the fluid flow in the tunnel. The average strike for the fracture trend is NNW- NNE with the dip range from 60 to 900. Besides that, primary joints are developed particularly in andesite, breccia and welded lenticulites with similar trends.

The groundwater in the tunnel is isolated from each layer from Aongatete volcanic, Waiteariki ignimbrite, and upper tuff breccia showing an impermeable layer with average permeability from 10^{-4} to 10^{-5} cm/s (Hegan, 1973). The groundwater temperature in the tunnel ranges from 15 to 40 °C (see Kaimai Tunnel cross-section in Figure 5). The water inflow is concentrated in several spots with a range from 380 to 1900 l/min. These concentrated spots and temperatures become a reference for the water sample (Figure 5).

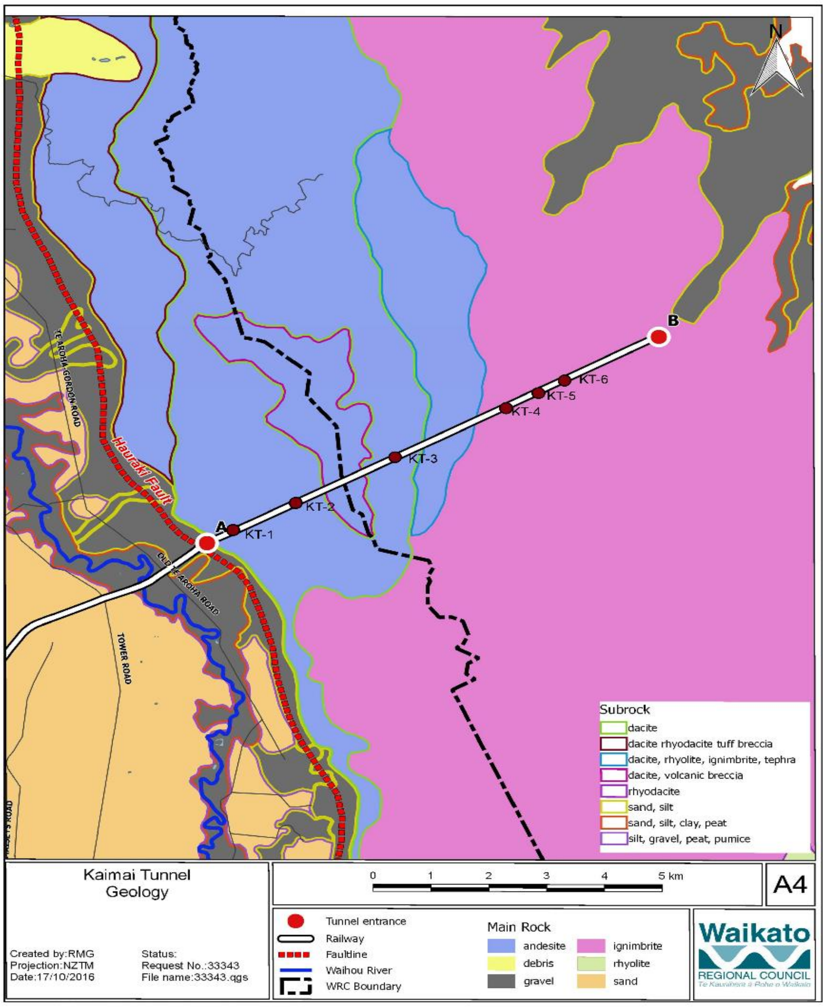

Figure 4: Geology map of the Kaimai Tunnel, showing the stratigraphy units and structure fault developed in this area

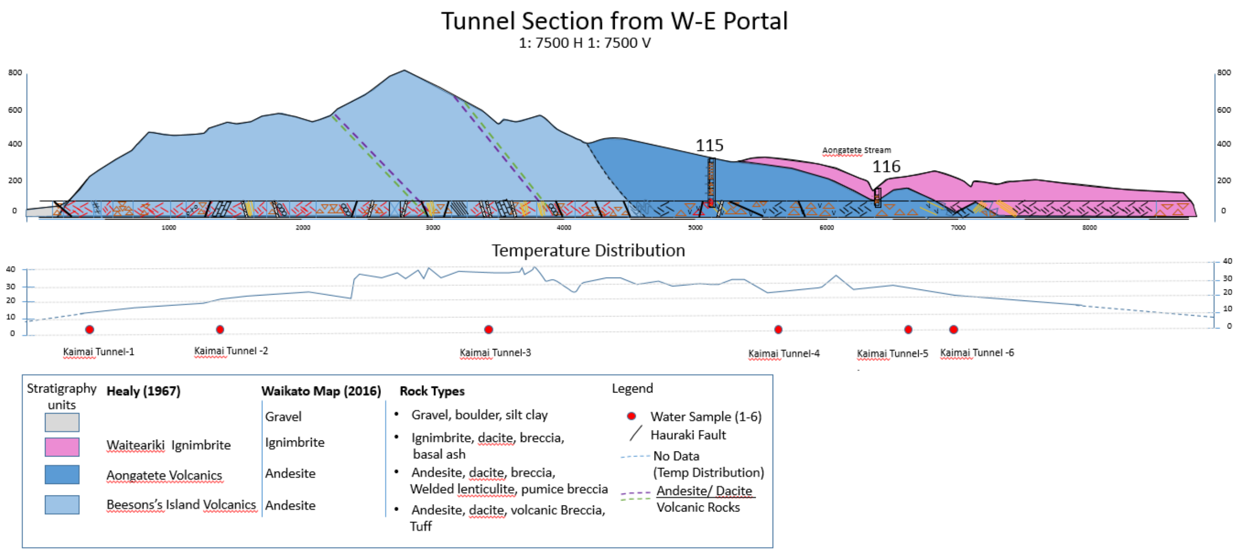

Figure 5: W-E Cross Section along the tunnel, showing the lithology distribution, air temperature and water inflow measurements during construction (data from Kiwirail, 2013).

2.3 Thermal Manifestation Inside Kaimai Tunnel

The thermal manifestations inside the Kaimai tunnel consist of seepages from the tunnel wall, ceiling, and e floor. During the tunnel construction, the temperature in the seepage had increased from an ambient temperature of 15 °C to 20 °C then to 30 °C and the flow was concentrated in five different areas, being the locations for water samples (400, 1350, 3350, 6600, 6950 m from the west portal end). However, when the water was sampled in 2016, the temperature ranged from 15 °C to 28 °C.

Figure 6: The West Portal Location before entering the Kaimai Tunnel (from Kiwirail, 2013).

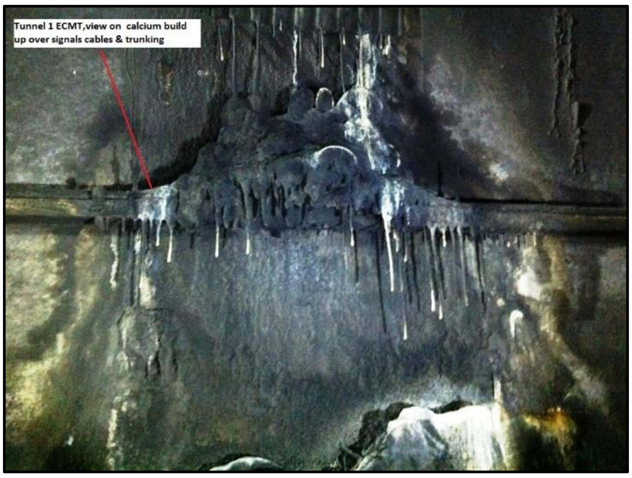

Figure 7: Travertine sinter that deposited near the wall seepage (from Kiwirail, 2013).

Figure 8: Seepage in the walls (left) and the floor (right) of the tunnel (from Kiwirail, 2013)

2.4 Geochemistry and Hydrogeology

Six water samples have been analysed for chemistry, while a cold groundwater from Te Aroha (Murithi, 2013), a Basement water from Huntly (Abu Bakar and Zarrouk, 2016), and a high temperature Wairakei well (Powell and Cumming, 2010) are used for reference and comparison. Before undertaking the analysis and interpretation, the water needed to be checked with an ion-balance or charge balance equation for the quality of the sample. Based on Nicholson (1993), the adequate sample must have a balance between anions and cations or have a deviation not more than 5 percent. The results are shown in Table 1.

These thermal water samples have characteristics of slightly basic pH while the conservative marker boron has slightly higher values than the cold-water background. Meanwhile, the reactive constituents have various values except bicarbonate which have higher values than the other constituents. Typically, a geothermal fluid from the reservoir has characteristics of rich chloride, high silica and potassium, while the magnesium and bicarbonates are low, as can be seen in the well chemistry in Table 1 (derived using calculations from Powell and Cumming (2010).

The Cl-SO_4-HCO_3 diagram classifies high temperature geothermal waters using the major anion concentrations (chlorides, sulphates and bicarbonates) (Giggenbach, 1988) and also helps to distinguish the waters as mature, peripheral, volcanic and steam-heated waters. Mature water indicates that the source fluid comes directly from a deep reservoir while sulphate water is formed by condensation of geothermal gases into the near-surface and has been oxygenated by groundwater. Lastly, the bicarbonate water is derived from the peripheral waters with rich CO_2 condensation and mixed with the groundwater (Nicholson, 1993). The degree of separation between data points for high-Cl and HCO_3 waters gives an indication of the degree of interaction of CO_2 charged fluids at lower temperature, bicarbonate content increasing with time and distance travelled underground (Giggenbach, 1988).

Based on Figure 9, all the springs originated from bicarbonate water, their water source is derived from a peripheral or groundwater. Therefore, indicating no communication between the geothermal reservoir water when compared with the geothermal well fluids from Wairakei wells (WK) or basement water wells (B1), which are typically higher in chloride content and a mature water type.

The Cl-B-HCO_3 ternary plot applies three independent chemical constituents of produced water to indicate the source of fluid at different subsurface conditions (Abu Bakar and Zarrouk 2016). The diagram shows the correlation between the deep basement water, coal bed methane water (intermediate aquifer) and shallow groundwater. Application of the ternary diagram on the low temperature geothermal system indicates whether the water source is related to deep geothermal source, groundwater or only basement source.

The cluster towards the boron apex would indicate the origin of deep basement water. High concentrations of Boron are associated with organic-rich sedimentary rocks (Nicholson, 1993). The source of Boron could be from the leaching of evaporitic sequence, while bicarbonate water shows the shallow groundwater. The bicarbonate water is formed from dissolved CO_2 and mixed with groundwater. Finally, there is a correlation between chloride water and deep geothermal source since higher chloride mean minimal mixing with other constituents.

Based on the ternary diagram for the Kaimai Tunnel in Figure 10, all the springs have trends close to the HCO_3 apex, meaning that the water source mainly is derived from the shallow groundwater flow with no relation with the reservoir, similar with the Cl-SO_4-HCO_3 ternary diagram. For comparison, the geothermal fluid from Wairakei stands in the middle of the chloride and boron apex, meaning that the characteristic of water is similar to the geothermal reservoir as wells as to basement water from the Huntly coal field. It shows the high boron ratio compared with chloride and bicarbonate contents.

The Cl/B ratio in Cl-Li-B ternary diagram indicates a common reservoir source for the water. Caution should be taken in applying this interpretation because water from the same reservoir can show differences in Cl/B ratio due to changes in lithology at depth in a field (e.g. sedimentary horizon), or by the absorption of boron into clays during lateral flow. Lithium is taken up into chlorite, quartz and probably clays in near-surface reactions causing an increase in the B/Li ratio with increasing lateral flow (Nicholson, 1993). These elements attain greatest concentration (of the order of 1 to 10 mg/kg) in areas with host rocks of rhyolitic and andesitic composition (including sedimentary environments with similar rock chemistry), and are significantly lower (- <0.1 mg/kg) in fluids from basaltic areas (Ellis & Mahon, 1977).

In the ternary diagram in Figure 11, the springs are mostly located close to the chloride apex because water has very low levels of boron. This means that the fluid is in lateral flow with clay absorption. While the lithium concentration at less than 0.1 mg/kg indicates that the host rock in the deeper zone is more basaltic environment. In the meantime, these clustered Kaimai springs also indicate that the water may have been derived from the same source, which is the groundwater in this case.

Lastly, The Na-K-Mg ternary diagram classifies types of water as fully equilibrated, partially equilibrated or immature. It is also used to predict equilibrium temperature and the suitability for application of solute geothermometers. Geothermometers are suitable only for the fully equilibrated and partially equilibrated waters. Data points plotted on the full equilibrium on the diagram indicate attainment of water-rock equilibrium. Plotting on the partial equilibrium indicates whether a mineral that has dissolved but has not attained equilibrium, or geothermal water that has reached equilibrium with diluted unequilibrated cold water. Immature water indicates initial dissolution of minerals before the equilibrium reaction begins. Data points plotted close to the Mg corner usually indicate a high proportion of cold groundwater, not necessarily immature waters.

This type of plot organizes the data points in a manner that not only illustrates the evidence which supports the interpretation of equilibrated water at high temperature, but also the influence of shallow processes and possible equilibration at lower temperature. Giggenbach therefore called it a geo-indicator (Powell & Cumming, 2010).

Based on the ternary diagram in Figure 12, the Kaimai Springs are included on immature water due to high concentrations of Mg. It means that the water is not on equilibrium phase since the water type comes from shallow groundwater seen from the high Mg ratios. Therefore, no reservoir temperature can be predicted using the Na-K-Mg ternary diagram.

Table 1: Chemistry data from the water sample in Kaimai Tannel and some reference water samples

Sample Name	Code	T ^0C	TDS	pH	Li g/m^3	Na g/m^3	K g/m^3	Ca g/m^3	Mg g/m^3	SiO_2 g/m^3	B g/m^3	Cl g/m^3	F g/m^3	SO4 g/m^3	HCO3 g/m^3	NH4 g/m^3	Charge Balance
Kaimai Tunnel-1	KT-1	15.2	74	7.8	0.0022	9.8	1.84	5.5	3.8	46	0.012	9.8	0.05	1.6	45	0.01	1%
Kaimai Tunnel-2	KT-2	25.1	115	8.6	0.0087	37	1.48	4	0.83	38	0.017	8.2	0.05	1.5	88	0.014	6%
Kaimai Tunnel-3	KT-3	26	-	8	0.0029	14.6	2.1	7.6	2.2	56	0.013	6.8	0.05	1.2	59	0.01	3%
Kaimai Tunnel-4	KT-4	23.5	95	7.4	0.0187	15.8	3.5	6.8	4	82	0.015	8.1	0.07	1.4	71	0.01	1%
Kaimai Tunnel-5	KT-5	25.9	98	7.4	0.0183	21	3.7	5.9	3.4	94	0.025	9	0.1	1.6	72	0.01	4%
Kaimai Tunnel-6	KT-6	27.8	106	7.4	0.0189	23	4.3	6	2.7	97	0.03	9.4	0.12	1.5	79	0.01	1%
Basement Huntly Water	B1	-	-	-	-	1100	-	220	0.45	-	15.5	430	-	18	83	-	62%
Te Aroha	T08	15.5	-	-	0.03	110	3.4	24.5	13.1	44	3	31	0.38	35	320	-	2%
Wairakei well	WK	240	-	8.5	10.7	1170	167	20	0.01	590	26	1970	-	35	5	-	1%

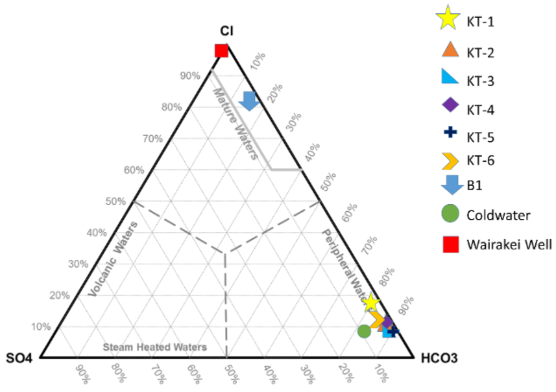

Figure 9: The Cl-SO₄-HCO₃ ternary diagram from Kaimai Springs, showing the diluted groundwater type of water with CO₂ gases.

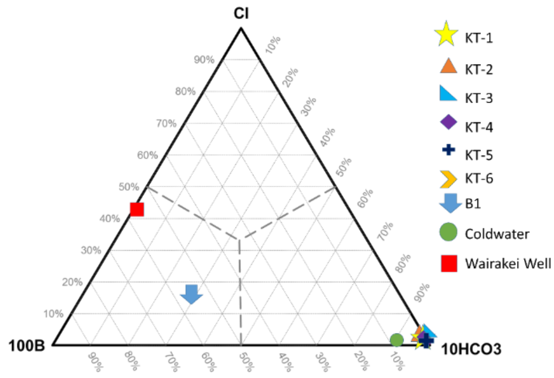

Figure 10: The Cl-B-HCO₃ ternary diagram from Kaimai Springs, showing the shallow groundwater origin without any connection from deep reservoir.

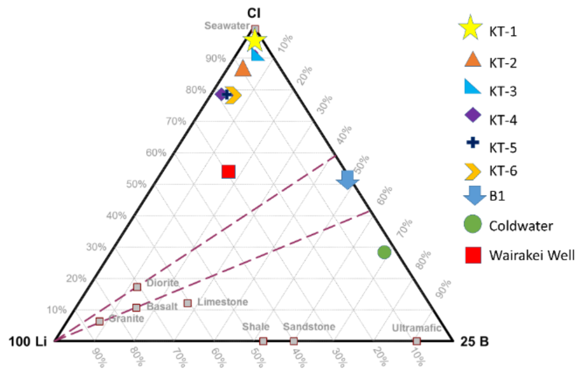

Figure 11: Cl-Li-B ternary diagram from Kaimai Springs, showing the clustering near Cl apex that indicate from the same source (groundwater).

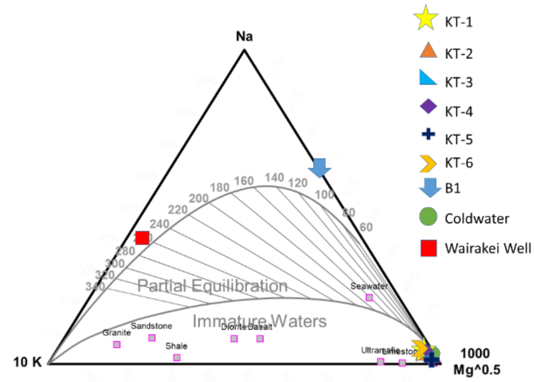

Figure 12: Na-K-Mg ternary diagram from Kaimai Springs, showing the clustering near immature water due to high Mg concentration.

2.5 Geothermometry

To calculate the reservoir temperature, chemical geothermometers can be used for predicting a subsurface temperature based on the chemical composition. Instead, the method relies on the fluid chemistry being preserved as the fluid flows from depth to the surface. Referring to Nicholson (1993) there are five assumptions for geothermometry ideally to be used: the concentration is controlled only by a temperature-dependent mineral-fluid reaction, there is an abundance of minerals and/or dissolved species in the fluid system, the reaction attains equilibrium in the reservoir, there is a rapid flow to the surface with no re-equilibration after the fluid leaves the reservoir, and there is no mixing or dilution.

There are two common geothermometries used in geothermal work: mineral solubility from quartz geothermometer (Elis and Mahon, 1973) and cation geothermometer which consists of a Na/K geothermometer for slow equilibrium (Giggenbach, 1988), Na-K-Ca for water for high Ca concentration (Fournier, 1973), K-Mg geothermometer for fast equilibrium (Giggenbach, 1983), and Na-K-Mg for the combination of slow and fast equilibrium (Giggenbach, 1983). In addition, since the geothermal system may be included on low temperatures, Na/Li geothermometery will be effective when used in sedimentary and volcano hosted reservoir conditions (Kharaka, 1982; Nicholson, 1993).

To calculate the geothermometry, an Excel spreadsheet is available from Powell and Cumming (2010) except for the Na/Li equations. The results can be seen in Figure 13. However, since the springs are not directly fed from the reservoir, this geothermometry will only show the temperature at greater depth and not the reservoir condition. Based on K-Mg, Na-K-Ca with Mg correction geothermometry, which is more suitable for low reservoir temperature, the temperature from Kaimai Springs shows around 42 to 65 °C, while the Na/Li ratio shows the temperature from 82-156 °C. These values are similar to the temperature from the cold groundwater Te Aroha. Thus, the temperature become questionable for reference and therefore cannot be used for the geothermometry.

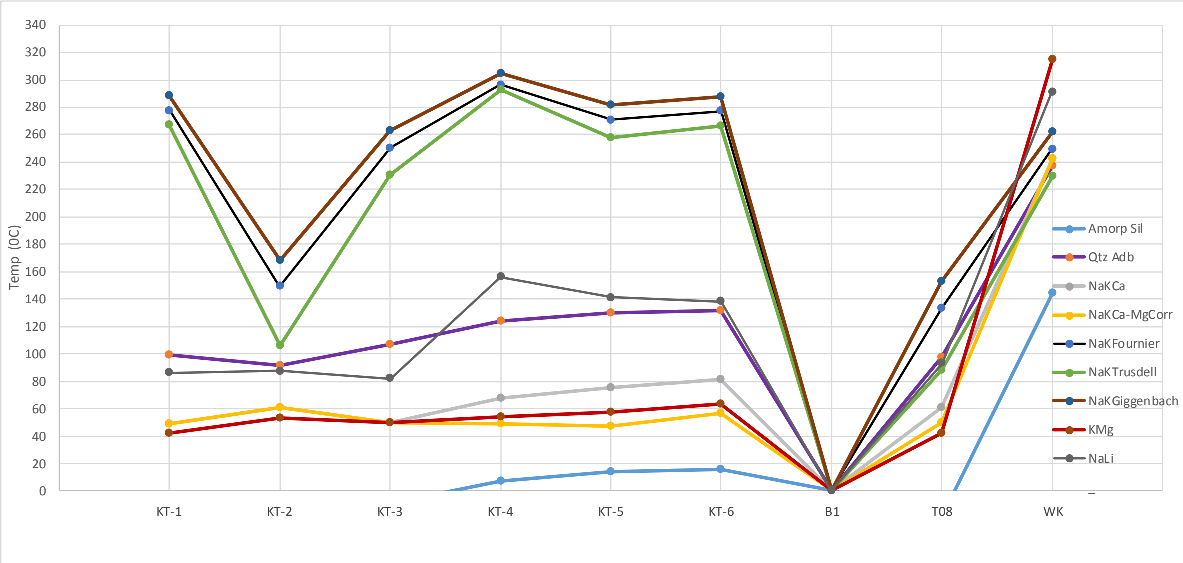

Figure 13: Comparison between the different geothermometers using samples from the Kaimai Springs and some reference wells.

3. CONCEPTUAL MODEL

The geothermal system in the Kaimai Tunnel can be described from the potential heat source and reservoir rock, the permeability distribution, the fluid characteristic with the reservoir temperature and the up-flow and outflow of the system.

The occurrence of the andesite and dacite lavas clearly indicates that there is a remnant of magma system presented in the deeper depth in this area which can potentially act as a heat source (Figure 14). The intrusion rock in the Kaimai Ranges is older than that of the Taupo Volcanic Zone (2.1-2.9 Ma) (Turner 2011) which might have an impact on reducing the conductive heat transfer. The rocks that act as the reservoir rock are interpreted from the greywacke basement (regional data) or the fractured intrusion around the Kaimai Ranges that are assumed to have some porosity and permeability.

The fluid characteristic in the Kaimai Tunnel indicates that the fluid source originates from shallow groundwater based on CL-B-HCO_3 and Cl-SO_4-HCO_3 ternary diagrams. Based on Cl-Li-B ternary diagram these cluster springs, indicate it has the same source of fluids. The Na-K-Mg ternary diagram shows that the water is of immature water type, meaning that there is less interaction and still in-equilibrium with host rock. Lastly, no valid geothermometry can be used to indicate the temperature in deeper depth.

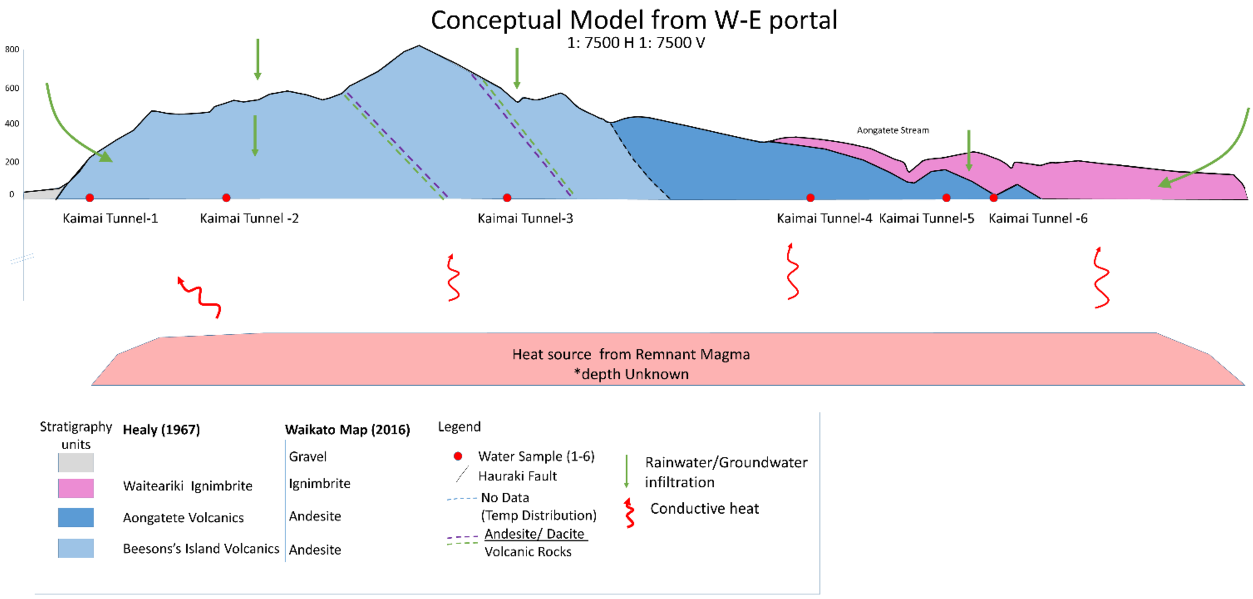

Figure 14: Cross section from W-E portal of Conceptual Model in the Kaimai Tunnel.

4. CONCLUSIONS AND RECOMMENDATIONS

There is a low possibility of forming a geothermal system within the Kaimai Tunnel area even though it is located in a volcanic zone with some warm springs inside the tunnel. Based on chemistry and age, the system is older than the Taupo Volcanic Zone and hence have lower geothermal potenial. It is simply meteoric rain water colectted on the Kaimai rainges that finds its way down into the tunnel. The 10-15 °C increase in water temperature is related to the natural thermal gradient in the area given that the tunnel is few hundreds of meeters underground. This thermal gradient is also responsable for the increase in the air temepratures in the tunnel (Figure 5).

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REFERENCES

Bakar, H.A & Zarrouk, S.J. 2016. Geochemical Multiaquifer assessment of the Huntly Coalfield. New Zealand, using a novel Chloride-Bicarbonate-Boron ternary diagram. International Journal of Coal Geology (2016). Doi: 10.2016/j.coal.2016.09.017

Booden, M.A. 2011. Late Cenozoic Arc Volcanism in Northland and the Coromandel, and Implications for Geochemical Exploration in the Hauraki Goldfield. Master Thesis of Doctor of Philosophy in Geology, University of Auckland Publication.

Ellis, A.J, Mahon W.A.J. 1977. Chemistry and geothermal systems. New York, Academic Press.

Fournier, R.O, Truesdell, A.H. 1973. An empirical Na-K-Ca geothermometer for natural waters. Geochimica et Cosmochima Acta, 37(5):1255-1275.

Giggenbach, W.F. 1988. Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators. Geochimica et Cosmochima Acta, 52(12):2749-2765.

Hegan, B.D., 1973. Easter Site Geological Investigation Kaimai Tunnel, Kaimai Railway Deviation. NZ Geological Survey, Engineering Geology Section. New Zealand.

Kiwirail, 2013. Kaimai Tunnel As-built Tunnel Long Section with Asset Condition Ratings. Unpublished report and drawing from Kiwirail corporation.

Murithi, L. & Luketina, K. 2013. The Chemistry of Waters of Te Aroha Geothermal System. A Waikato Regional Council Report (Document# 2292573). Hamilton

Nicholson, K 1993. Geothermal fluids: chemistry and exploration techniques. Berlin, Springer.

Powell, T, Cumming, W. 2010. Spreadsheets for Geothermal Water and Gas Geochemistry. Proceedings: Thirty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 1-3, 2010. 10.

Turner, E.L. 2011. Near- and Sub-Solidus Magma/Fluid Reaction, Coromandel Volcanic Zone, and Implications for Deep Reservoir Conditions in Geothermal Systems. Maser Thesis of Master of Science in Geology. University of Auckland Publication.