INSIGHTS INTO THE CHEMISTRY OF WATERS BEYOND THE TE AROHA DOMAIN

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ABSTRACT

The Te Aroha geothermal system has been utilized for several direct use applications including balneology, bathing and swimming since 1889. Data has been collected on this historic area since that time. The low temperature geothermal system produces bicarbonate rich fluids.

The results from studies over the past three decades were used to gain further comprehension of the Te Aroha geothermal system. This project includes the geochemical analysis of the first private bores sampled beyond the Te Aroha Domain and focuses on the relation of those fluids to the fluids sampled in 1993 and 2012 from bores within the Te Aroha Domain. Some of the bores drilled within the domain exhibit geysering, this work will assess the mechanism behind that behavior. This work also seeks to assess the trends of the fluids in the Te Aroha region and the potential for sustainable utilization of the reservoir. Additionally, the present work provides insight into the geological setting of the system using the available data including stratigraphic bore logs.

1. INTRODUCTION

1.1 Location

The rural town of Te Aroha is in the Waikato Region of the North Island of New Zealand located 53km Northeast of Hamilton at the base of the 952 meter Mount Te Aroha, the highest point of the Kaimai Range (Figure 1). The Waihou River runs through the town and the low-lying, alluvial Hauraki Plains are to the north of Te Aroha. The small town has an area of 11.6 km2 and a population of 3,906 (2013 census).

Figure 1: Location of Te Aroha and the three bores sampled for this study (map adapted from Google Earth, 2017).

1.2 Geology

Te Aroha is part of the Hauraki Rift Zone on the western flank of Mount Te Aroha of the Kaimai Ranges. The surface geology of the Te Aroha area (Figure 2) is comprised of alluvial sediments, rhyolitic tuffs, horneblende dacites, ignimbrites, altered andesite breccias with an underlying metagraywacke basement (Moodie, 2016). The active Hauraki Rift Zone, 20-40km wide and 250km long, formed in the back-arc of the Hikurangi subduction margin (Persaud et al. 2016). The Hauraki Rift zone can be delineated into three sections from south to north: the Hauraki Depression, the Firth of Thames and the Hauraki Gulf. The Te Aroha study area lies within the Hauraki Depression section which has a western border marked by the minor hinge Firth of Thames fault.

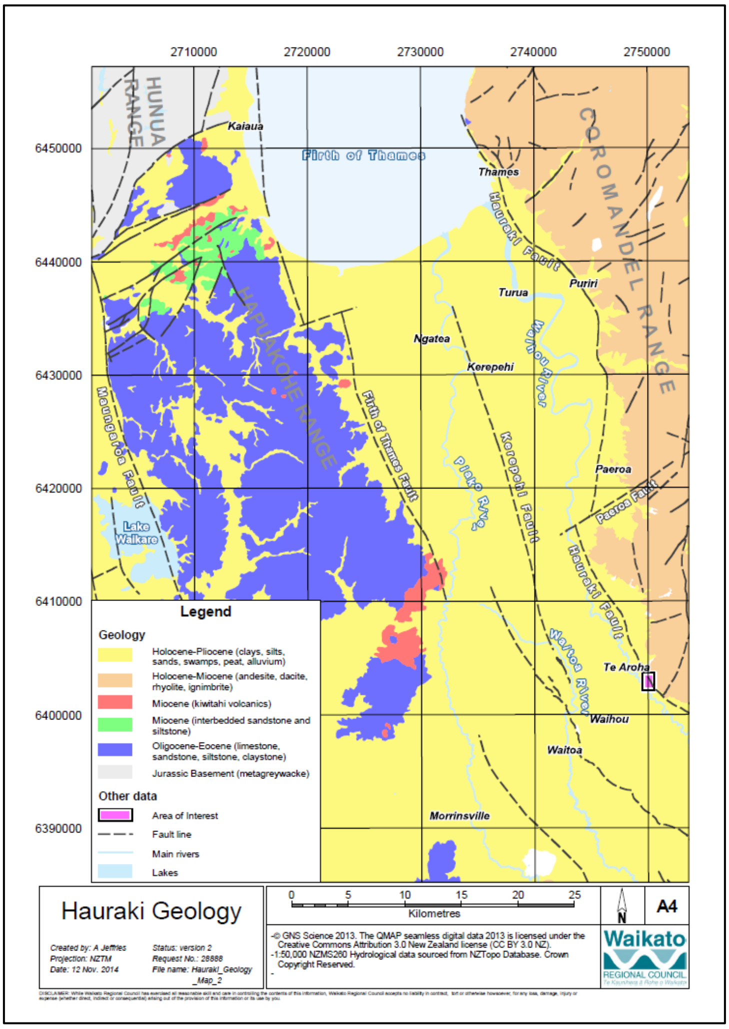

Figure 2: Surface Geology map of Hauraki Rift zone and the location of Te Aroha.

The normal Hauraki fault comprises the eastern border while the active, normal Kerepehi fault propagates through the center of the section (Persaud et al. 2016). Anomalously high heat flows exist below the Hauraki Depression which suggests there is an upper mantle swell indicating thinning crust in the region (Davidge, 1982). The high heat flows and permeability provided along the Hauraki fault yield the Te Aroha geothermal system.

1.3 Reservoir

Te Aroha is a small, low enthalpy, bicarbonate geothermal system located at the southeastern edge of the Hauraki rift valley depression. The thermal fluids of the reservoir have been studied and utilized in a direct use application for balneology and therapeutics since 1889. Previous studies suggest that the source of these fluids, which have a high CO_2 concentration, is at a depth of approximately 150 meters (Murithi, 2012). A complex of faults, including the Hauraki Fault, provide the main source of permeability and serve as conduits for the fluid to surface as springs. The expansion of the carbon dioxide drives the fluid upward and results in bubbling in some of the springs. This expansion of CO_2 is also the mechanism driving the intermittent eruptions of the Mokena geyser (Figure 3) which is a geysering well that sometimes erupts to heights of more than 10 meters.

Figure 3: Mokena geyser with discharge driven by expansion of CO_2.

2. PREVIOUS WORK

As part of his work on Hauraki Depression thermal waters, Jenkinson (1994) provided a detailed analysis of historical geochemical data. This work concluded Te Aroha is located over a bicarbonate outflow zone.

Michels et al, 1993 conducted analysis of discharge of thermal fluids at Te Aroha to report on the chemistry and measure the amount of CO_2 present in the Mokena wellbore. The study reports concentrations of 1.5-5.0 g/kg +/- 0.5 g/kg of CO_2 in the Mokena wellbore.

A comprehensive review of data relating to the Te Aroha system was conducted by Moodie, 2016. This study aimed to determine how the system has been affected by utilization, provided insights into the systems' geologic setting, fluid chemistry and interpreted wellbore pressure and temperature data. Moodie concluded Te Aroha is a low temperature bicarbonate rich resource with fluids typical of a young hydrothermal system. Additionally, utilizing the resource must be conducted carefully as the installation of new bores can result in springs in the surrounding area drying up or ceasing to discharge.

Data regarding the Te Aroha geothermal system was also collated by Murithi (2012) with the goal of mapping features and bores in the region, analyzing fluid chemistry data and determining the sustainability of the system. The study found that fluids of the Te Aroha domain are sodium-bicarbonate waters from a young hydrothermal system with strong vertical permeability.

The geologic structure of the Te Aroha region was provided by Persaud et al, (2016) by their analysis of the Hauraki Rift as part of their work on the activity of the Kerepehi Fault.

Yalniz (1997) conducted interference testing and measurements of two bores using the capillary tubing technique to investigate hydraulic connectivity and monitor pressure of the reservoir. The study concluded hydraulic connection existed between the Mokena wellbore and the Test and New Wilson Street wellbores.

By using Geokon vibrating wire pressure transducers and analyzing the data by Fourier, autocorrelation and wavelet analysis, Leaver et al. (1999) determined two wells within the domain were not in hydraulic communication with one another.

An effort to determine the feasibility of utilizing additional fluid from the reservoir was pursued by Woodward-Clyde (1993) by providing further insights and modeling the system. The work found indications of convective heat transfer from high permeability in multiple wellbores and determined hydraulic connectivity between the Mokena and Domain Trust wellbores.

3. GEOLOGY OF TE AROHA BORES

The stratigraphic logs, provided by Waikato Regional Council (Appendix A), of five bores offer further insights into the rock types underlying the Te Aroha region. The surface geology and locations of bores are provided by Figure 4. The five logs include three from bores located in the Te Aroha Domain and two of the three bores that were sampled for this study located west of the domain, beyond the Waihou River. The bore logs from within the Te Aroha Domain indicate that the main underlying rock types are alluvial sediments including clays, silts and sands overlying altered andesite and rhyolite. The andesite is highly altered and contains veins of quartz and calcite (Moodie, 2016). The quartz and calcite veins are an indication of boiling at that depth at some point in the history of the reservoir. The Newly Sampled Bores (RT, SRS and SRN) were completed to a maximum depth of 30m and thus the stratigraphic logs only indicate the shallow alluvium sediments. However, these formations are consistent with those encountered at similar depths by bores in the Te Aroha Domain.

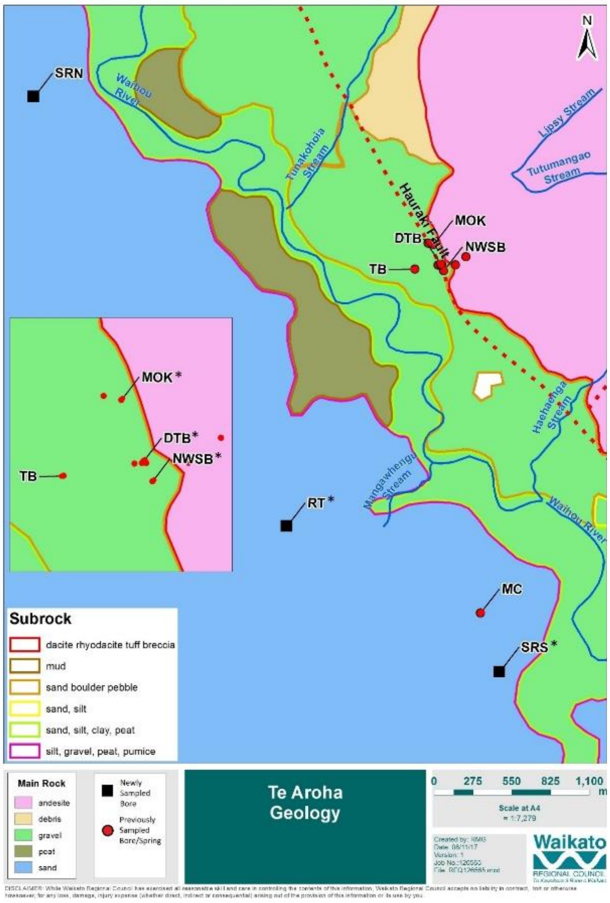

Figure 4: Map of Te Aroha surface geology with locations of bores (labeled) and springs (unlabeled).

4. GEOCHEMISTRY AND CLASSIFICATION OF THERMAL WATERS

4.1 Ternary Diagrams

The previous geochemistry data included in this study is from two data sets collected in 1993 (Michels, 1993) and 2012 (Murithi, 2012). These are identified as “Bores 1993” and “Bores 2012”, respectively. The data set identified as “Newly Sampled Bores” is from the sampling of three bores conducted on 14th September 2017 as part of the current study. These samples were collected following a period of intense rain in the area in a notably wet year in which rainfall had already exceeded the yearly average by 182mm at the time of collection, 14th September 2017. The laboratory analysis done by the Hill Laboratories was used to provide insights into the Te Aroha geothermal system. The chemistry of the previous fluids sampled and those sampled through this study were summarized with additional information (Table 1). Changes in sampling methods over time should be taken into consideration when assessing the accuracy of the data. Also, for some elements, concentrations were not determined and thus, particular analyses could not be pursued for all fluids in the data sets.

4.1.1 Cl-SO_4-HCO_3 Ternary Diagram

This diagram categorizes samples using relative anion concentrations into one of the three main types of geothermal fluids. The three end members (Chloride, Sulphate and Bicarbonate) each indicate a different fluid type. High concentrations of chloride (Cl) indicate mature waters from the deep reservoir. This fluid type is typically present in the up-flow zones of geothermal systems. High concentrations of sulphate (SO_4) indicate steam-heated waters. In low-relief terrain, this fluid type is associated with the boundary of a geothermal system. High concentrations of bicarbonate (HCO_3) indicate peripheral waters. These fluids are common in outflow zones of geothermal systems where thermal fluids have mixed and been diluted with meteoric waters that have high concentrations of CO_2.

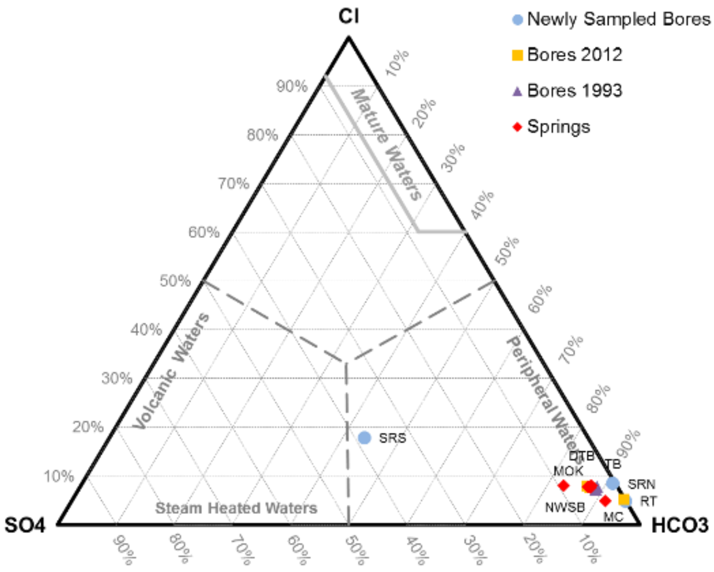

Figure 5: Cl-SO_4-HCO_3 ternary diagram for fluids in Te Aroha region between 1993 and 2017.

4.1.2 Na-K-Mg Triangular Diagram

Combining the Sodium-Potassium and Potassium-Magnesium geothermometers, this diagram classifies waters into fully equilibrated, partial equilibrated or immature. Though solute geothermometers are only suitable for fully and partially equilibrated waters, if data points plot consistently along the temperature lines on the diagram, the maximum temperature of the geothermal system can be inferred. Attainment of water-rock equilibrium is indicated by data points that plot in the full equilibrium section of the diagram. Geothermal water that has reached equlibrium with cold water or a mineral that has dissolved but not fully equilibrated is designated by data points that plot in the partial equilibration section. Initial dissolution of minerals and a high amount of dilution from cold groundwater is indicated by data points that plot in the immature waters section (Murithi, 2012).

Table 1 Chemistry data from Michels (1993), Murithi (2012) and Waikato Council (2017).

Description	Site	Label	Depth (m)	Temp (°C)	pH	All concentrations in mg/kg (ppm)									
						Li	Na	K	Mg	B	Br	F	Cl	SO_4	HCO_3
Waikato Regional Council, 2017	72_6518	RT	30	17.7	7.2	0.059	112	10	6.1	1.07	0.051	0.32	18.9	<0.5	365
	72_5788	SRS	9	17.2	6.9	0.003	17.0	7.8	5.4	0.018	0.033	0.07	16.7	36	41
	72_9618	SRN	13	17.2	6.6	0.007	17.3	4.4	5.2	0.023	0.025	0.16	9.6	0.5	103
Murithi, 2012	72_2227	MOK	105	90.0	8.5	1.97	3100	70	3.8	154	1.30	1.81	640	410	6940
	72_2951	MC	85	23.0	7.5	0.013	45	5	7.0	0.057	0.042	0.37	11.1	0.5	197
	64_512	NWSB	79	53.0	7.4	1.95	3100	69	4.3	148	1.10	1.74	580	380	6700
	72_2214	Spring	N/A	40.0	7.5	1.52	2400	53	5.7	117	0.90	1.41	490	320	5500
	72_2226	Spring	N/A	45.0	7.5	1.96	3200	70	3.6	157	1.20	1.77	630	390	7290
Michels, 1993	72_2252	TB	65	62.0	N/A	2.58	3066	66	22.2	140	N/A	1.03	610	273	7000
	64_276	DTB	105	67.0	7.9	2.10	3159	74	3.5	158	N/A	1.29	631	348	7700
	72_2116	Spring	N/A	N/A	7.2	1.84	2825	67	5.0	146	N/A	1.18	609	330	6600
	72_2225	Spring	N/A	55.0	7.3	0.48	2911	69	3.4	145	N/A	1.53	611	335	6700
	72_2248	Spring	N/A	17.5	6.3	0.26	663	20	27.5	28	N/A	0.25	111	81	2100
	72_2247	Spring	N/A	15.5	5.8	0.03	110	3	13.1	4	64.0	0.38	31	35	320
	72_2251	Spring	N/A	N/A	7	1.38	2176	53	7.8	99	0.37	1.01	433	273	4900

Table 2 Chemical compositions of end members used in Cl-Br-B ternary diagram and B-F cross plot. Adapted from Reyes (2010).

End Member	Abbreviation	Li	Na	K	Mg	B	Br	F	Cl	SO_4	HCO_3
400° C Meteoric water Andesite	Ma	1.8	150	31	0.35	5	N/A	14	125	73	N/A
Seawater	Sw	0.08	10870	504	1236	4.5	64	1.30	19406	2669	1118
Andesite	An	20	20550	13615	19900	15	0.41	190	190	N/A	N/A
Mean Crust	Rock	20	23000	21000	23000	10	0.37	950	130	N/A	N/A

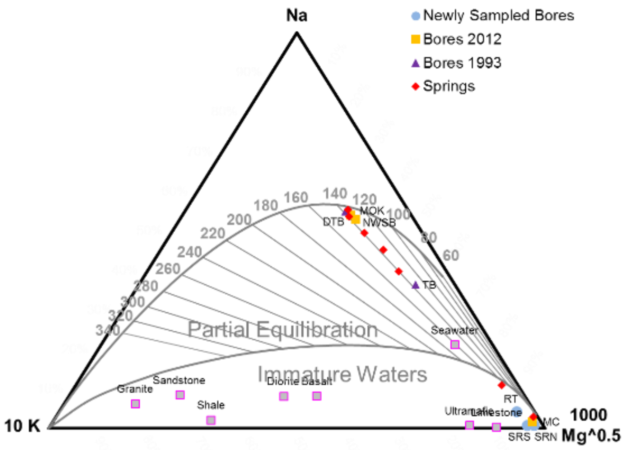

Figure 6: Na-K-Mg ternary diagram for Te Aroha region between 1993 and 2017.

4.1.3 Cl-Li-B Ternary Diagram

By assessing the relative concentrations of Chloride, Lithium and Boron, it is possible to determine the source of the sampled fluid and the rate at which the fluid traveled from the source. The rare alkali metal lithium (Li), being a conservative element, will remain unaltered as temperature and depth vary and is least affected by secondary processes relative to chloride (Cl) and boron (B). This allows lithium (Li) to be used as a reference for evaluating the possible origin of the chloride (Cl) and boron (B) constituents (Mnjokava, 2007). As fluids propagate both laterally and vertically farther from the source, the relative concentration of lithium (Li) will decrease from becoming incorporated into alteration minerals and/or diluted with groundwater. Due to its volatility, boron (B) is expelled from fluid during the initial stages of geothermal systems heating up. Therefore, fluids from younger geothermal systems have higher concentrations of boron (B). Concentrations of chloride (Cl) will be relatively stable as it is a much more conservative element than boron (B). Thus, older geothermal systems will have fluids with higher concentrations of chloride (Cl). The Cl/B ratio is often used to indicate a common reservoir source for the fluids. However, due to changes in lithology at depth over a reservoir and absorption of boron (B) into clays during lateral flow impacting this ratio, care must be taken in applying this interpretation (Murithi, 2012).

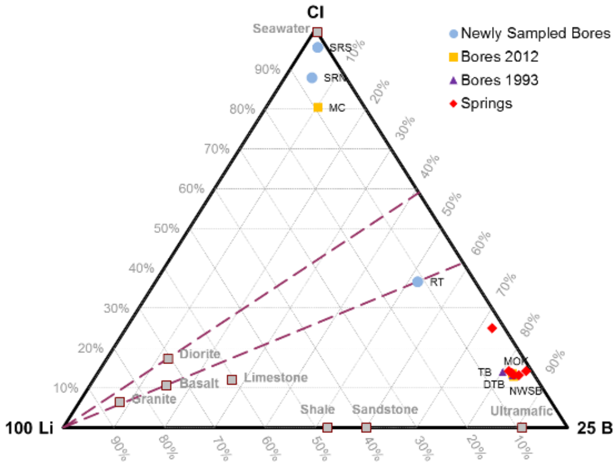

Figure 7: Cl-Li-B ternary diagram for Te Aroha region between 1993 and 2017.

4.1.4 Cl-HCO$_3$-B Ternary Diagram

This diagram correlates three chemical constituents of fluids to gain insights into subsurface conditions. The Cl-HCO$_3$-B diagram can assist with the geochemical assessment of fluids by classifying their source into shallow or basement/deeper formation water and can qualitatively infer the permeability of a reservoir. Data points that plot near the boron (B) apex indicate basement or deeper formation water. Boron (B) is rather volatile and is leached from rock as geothermal reservoirs begin to heat up. Therefore, fluids with a high boron (B) content are relatively young (Bakar and Zarrouk 2016). These fluids are indicative of low permeability formations that have stronger connection with basement/deeper formation water. Data points that plot near the bicarbonate (HCO_3^-) side designate shallow groundwater. Fluids with high bicarbonate (HCO_3^-) concentrations signify that there is moderate to strong communication with shallow/surface water and good permeability. Plots near the chloride (Cl^-) apex of the diagram indicate poor permeability that leaves water uncirculated (Rogers, 1994).

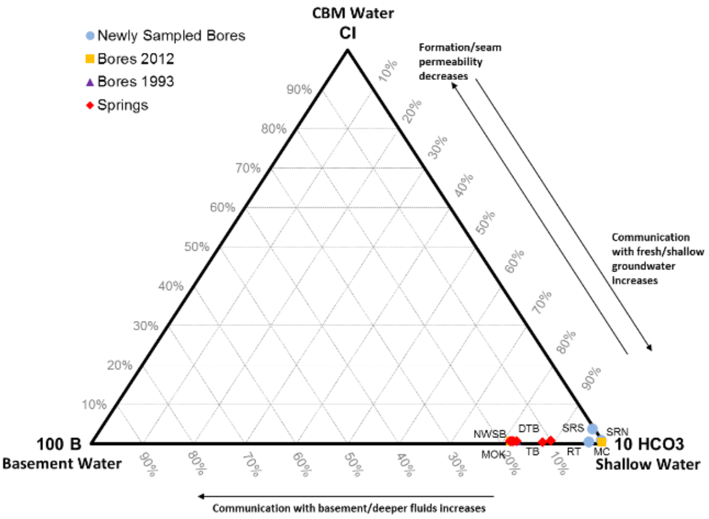

Figure 8: Cl-B-HCO$_3$ ternary diagram for Te Aroha region between 1993 and 2017.

4.1.5 Cl-Br-B Ternary Diagram

By plotting the relative concentrations of chloride (Cl), bromine (Br) and boron (B) and including the two end members (seawater and mean crust from Table 2), this ternary diagram provides useful insights into reservoir conditions. Bromine (Br) is quite reactive and highly soluble. Though not very abundant in the crust, due to the reactive and soluble nature of bromine (Br), it accumulates in seawater from long-term leaching. Fluids with a high Br/Cl ratio are common in high temperature hydrothermal systems affected by seawater influx (Reyes et al., 2010). As the proportion of the dissolved rock increases in a fluid, the Br/B ratio decreases. Therefore, fluids with high concentrations of boron (B) indicate a greater interaction with rock. Fluids with relatively high chloride (Cl) concentrations infer the influx of meteoric waters and mixing with heated seawater. The occurrence of Br/Cl ratios lower than seawater in fluids is probably the result of diagenesis (Martin, 1999).

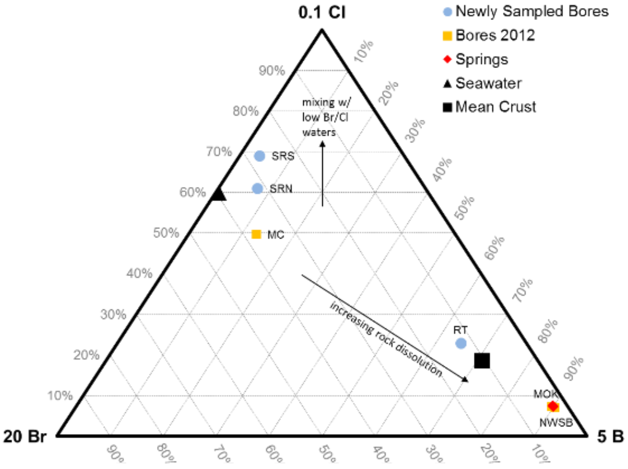

Figure 9: Cl-Br-B ternary diagram for Te Aroha region between 1993 and 2017.

4.2 B-F Cross Plot

This cross plot compares B/Li and F/Li concentration ratios of fluids while referencing them against two end members (Andesite and heated meteoric water from Table 2). These ratios are impacted by the degree of mixing of meteoric waters with mineral waters from different sources. Variations in the ratios are also affected by uptake of fluorine (F) in fluorite and the discharge or integration of lithium (Li) and boron (B) from chlorite and quartz (Reyes et al., 2010). Additionally, the F/Li ratio increases as the proportion of the dissolved rock component increases.

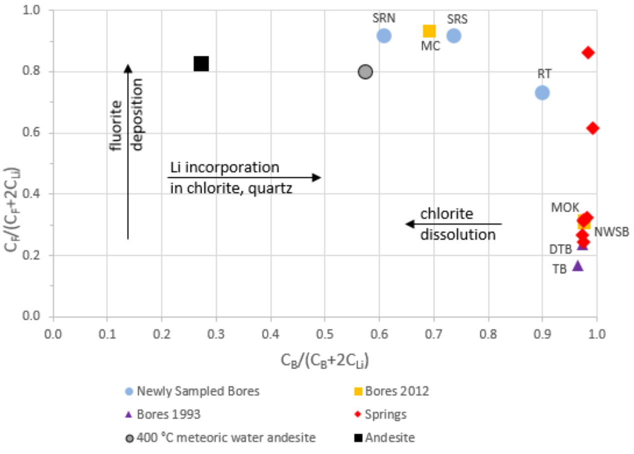

Figure 10: Cross plot of cB/(cB+2cLi) and cF/(cF+2cLi) for Te Aroha region between 1993 and 2017.

5. RESULTS AND DISCUSSION

The concentrations of chloride, sulphate and bicarbonate are plotted in Figure 5 to classify the Te Aroha waters. Since it is known that Te Aroha is a low enthalpy/temperature system, this diagram is not very relevant but was included as it is standard practice to use the Cl-SO_4-HCO_3 ternary diagram when assessing geothermal fluids and doing so provides a benchmark to reference. Waters from two of the three Newly Sampled Bores and all of waters from the other data sets plotted near the bicarbonate corner. Therefore, the majority of the bores indicate bicarbonate fluids characteristic of the outflow zone of a geothermal system with high HCO_3 relative to SO_4 and Cl. The SRS bore had a higher SO_4 concentration plotting much closer to steam heated waters than the other bores. Considering all other fluids plot near the bicarbonate apex and there are no steam heated surface manifestations (mud pools, fumaroles, etc.), this higher SO_4 concentration is viewed as an anomaly. However, more sampling from this bore and nearby bores could be conducted to make further determinations about the subsurface conditions.

The Na-K-Mg diagram (Figure 6) shows that the majority of the waters sampled prior to this study are partially equilibrated while a few springs plot on the immature waters. All of the waters from the Newly Sampled Bores plot in the immature waters section which is indicative of fluids that are mixed with ground waters. Dilution from the high levels of rainfall prior to sampling resulted in the fluids plotting in the immature section. Though this means the waters from the Newly Sampled Bores are unsuitable for solute geothermometry, all of the data points are plotting in the same range of temperatures of the ternary plot. This indicates the Te Aroha geothermal system has a maximum reservoir temperature of approximately 140° C and has not varied a notable amount since 1993.

The vast majority of fluids from the springs and bores sampled in 2012 and 1993 in the Te Aroha Domain plot near the boron corner of the Cl-Li-B ternary diagram (Figure 7). This indicates these fluids belong to young hydrothermal systems. However, fluids from outside the domain (including those from 2 of the 3 Newly Sampled Bores) plot near the chloride apex suggesting that these fluids originate from older hydrothermal systems. Interestingly, the fluid from the Race Track (RT) bore has a much lower Cl/B ratio than the two other fluids in the Newly Sampled Bores data set. This indicates that the Race Track (RT) bore, the closest of the three sampled for this study to the Te Aroha Domain, is on a transitional boundary of the Te Aroha geothermal system. The low concentrations of lithium suggest that lithium has either been diluted or incorporated into alteration minerals from the slow rate at which water travelled to the surface or from the water having traveled far from the source.

All of the fluids from the data sets plot near the bicarbonate corner of the Cl-B-HCO_3 diagram (Figure 8). This shows that all the bores have strong communication with fresh, shallow groundwater indicating good permeability. This also points to a lack of communication with basement or deeper formation fluids. Thus, the Cl-B-HCO_3 ternary diagram provides evidence that the source of the fluids in the Te Aroha region has been consistent since 1993.

The Cl-Br-B ternary diagram plots only the fluids from the Newly Sampled Bores and Bores 2012 data sets as the analysis from 1993 did not include bromine sampling (Figure 9). This diagram shows that the Stanley Road South (SRS) and Stanley Road North (SRN) bores have a compositional signature similar to seawater but with a slightly higher Cl/Br ratio. This indicates diagenesis and the mixing of heated sea and meteoric waters. With the bores being at an elevation less than twenty meters above mean sea level, the seawater influence is likely a remnant from when the Firth of Thames extended as far as Te Aroha. The fluids from the Motor Camp (MC) bore also plot near the Seawater end member but indicate a higher component of rock dissolution. The fluids from the Race Track (RT) bore indicate even greater rock dissolution by plotting near the Mean Crust endmember. Finally, the fluids from the Mokena Bore (MOK) and New Wilson Street Bore (NWSB) have a higher boron concentration than the Mean Crust end member, plotting near the boron apex. This is indicative of fluids from young geothermal systems. The boron-fluorine cross plot (Figure

10) relates B/Li and F/Li ratios to two end members: Andesite rock and heated meteoric water that has interacted with andesite at depth. From this plot, it is clear that the fluids from two of the Newly Sampled Bores have similar B/Li and F/Li ratios as the heated meteoric water andesite end member. This is logical as the stratigraphy in Te Aroha region is comprised of layers of highly altered andesite. The fluid of the Race Track (RT) bore has a similar B/Li ratio (>0.9) as the majority of the fluids from the Bores 2012 and Bores 1993 data sets. All of the fluid compositions are indicative of those resulting from high temperature fluid-rock interaction at depth. Additionally, the F/Li and B/Li ratios in all of the fluids from the Newly Sampled Bores are indicative of high degrees of fluorite deposition and lithium incorporation in chlorite and quartz. This plot further supports that the compositions of the fluids in the Te Aroha region have been consistent since 1993.

6. CONCLUSION

The Te Aroha geothermal system is a low enthalpy reservoir with maximum deep temperatures of 140° C, bicarbonate rich fluids and good permeability providing strong communication with fresh, shallow groundwater. This is supported by the geochemical analysis of fluids in the region conducted over the past twenty four years. Though production of electricity could be achieved through the installation of a binary plant, this reservoir is best suited for direct use applications such as those currently utilized in the Te Aroha Domain. A complex of faults, including the active Kerepehi fault west of Mount Te Aroha within the Hauraki Depression, provide the strong vertical permeability. The geochemical data shows that the fluids within the Te Aroha region exhibit a seawater signature with varying degrees of rock dissolution across the reservoir. The fluids within the Te Aroha Domain display negligible changes from 1993 to 2012 and belong to young hydrothermal systems while those beyond the Domain analyzed for this study are indicative of older systems comprised of andesite. This transition from fluids typical of younger to fluids typical of older hydrothermal systems indicates that the bores sampled for this study are on the margins of the Te Aroha geothermal reservoir.

7. RECOMMENDATIONS

Analysis of fluids from springs and bores in the Te Aroha Domain and additional water bores in the Te Aroha region should be conducted annually to provide conclusive results on the chemistry of the fluids and to determine the hydrology of the geothermal system. Due to the potential impacts of meteoric water diluting fluid samples, the samples should be collected in the drier, summer months. Indeed, the three bores sampled for this study should be sampled for analysis again to determine the influence that meteoric water may have had on the laboratory results.

With maximum temperatures of 140° C based on the Na-K-Mg triangular diagram, the Te Aroha reservoir is not commercially suitable for electricity production. However, deeper bores could be drilled to extract high temperature, less diluted fluids for direct use applications. Any extraction must be accompanied with a thorough monitoring program and contingency plans for 100% reinjection of fluids if pressure reductions in the reservoir which would cause the geothermal system to deplete are observed.

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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, 167, 136-147.

Davidge, S. C. (1982). A geophysical study of the south Hauraki lowlands (Doctoral dissertation, University of Auckland).

Jenkinson, D. G. (1994). Studies of thermal waters and thermal wells in the Hauraki Depression (Doctoral dissertation, University of Auckland).

Martin, J. B. (1999). Nonconservative behavior of Br−/Cl− ratios during alteration of volcaniclastic sediments. Geochimica et Cosmochimica Acta, 63(3), 383-391.

Michels, D. E., Jenkinson, D., Hochstein M. P. (1993). Discharge of thermal fluids at Te Aroha. Proceedings of the 15th New Zealand Geothermal Workshop 1993, 21-27.

Mnjokava, T. T. (2007). Interpretation of Exploration Geochemical Data for Geothermal Fluids from the Geothermal Field of the Rungwe Volcanic Area, SW-Tanzania. UNU-GTP Reykjavík, Iceland, Reports, (14), 303-332.

Moodie, K., Zarrouck, S.J., Luketina, K. (2016). The Te Aroha Low Enthalpy Geothermal System, New Zealand: Review and Analysis. (Unpublished thesis) University of Auckland, Auckland, New Zealand.

Murithi, L. M. (2012). The chemistry of waters of Te Aroha geothermal system. Waikato Regional Council.

Persaud, M., Villamor, P., Berryman, K. R., Ries, W., Cousins, J., Litchfield, N., & Alloway, B. V. (2016). The Kerepehi Fault, Hauraki Rift, North Island, New Zealand: active fault characterisation and hazard. New

Zealand Journal of Geology and Geophysics, 59(1), 117-135.

Powell, T., & Cumming, W. (2010, February). Spreadsheets for geothermal water and gas geochemistry. In PROCEEDINGS, Thirty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California (p. 10).

Reyes, A. G., Christenson, B. W., & Faure, K. (2010). Sources of solutes and heat in low-enthalpy mineral waters and their relation to tectonic setting, New Zealand. Journal of Volcanology and Geothermal Research, 192(3), 117-141.

Yalniz, M. U. (1997). Preliminary interference measurements at Te Aroha using capillary tubing. (Geothermal Institute Report 97-30). University of Auckland, Auckland, New Zealand.Reyes, A. G., Christenson, B. W., & Faure, K. (2010). Sources of solutes and heat in low-enthalpy mineral waters and their relation to tectonic setting, New Zealand. Journal of Volcanology and Geothermal Research, 192(3), 117-141.