The Te Aroha Low Enthalpy Geothermal System, New Zealand: Review and Analysis

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Keywords: *geothermal, low-enthalpy system, geyser, carbon dioxide, Te Aroha, aragonite, New Zealand.*

ABSTRACT

All available data related to the Te Aroha low enthalpy geothermal system were collated and analysed. The geothermal system produces low temperature bicarbonate and mineral-rich fluid, historically used directly for drinking and bathing, although drinking the water is now discouraged. To extract higher quantities of fluid from the system to satisfy the demand, bores have been drilled within the domain. As of 2014, there are three geysering (self-discharging) bores, within the Domain, and geysering is driven by the release of carbon dioxide gas from solution.

The Te Aroha Domain is a historic area with collected data dating back to 1889. The data can be used to determine how the system has been affected by exploitation. All the relevant studies conducted on the Te Aroha domain have been analysed to gain a further understanding of the geothermal system.

This work gives an insight into the geological setting of the geothermal resource and models and interprets the system using the available wellbore pressure and temperature data.

1. INTRODUCTION

The Te Aroha thermal area is a localized system that originates from low temperature bicarbonate springs, located along the western edge of Mount Te Aroha, on the eastern side of the North Island of New Zealand. The long history of human use of the springs is summarised in Moodie (2014).

Mount Te Aroha is part of the Kaimai Mountain Range, which trends in a southeasterly direction and extends south from the Coromandel Range. The eight-acre domain, where the springs are located, is at the edge of the Te Aroha town, between Wilson and Whitaker Street. The permeability, which permits geothermal fluids to access the surface, is created by the Hauraki fault and subsequent fractures produced by this fault zone. Te Aroha geothermal fluids have significant levels of dissolved mineral content (most importantly bicarbonate) and have, consequently, been used to treat a variety of ailments. A preliminary overview of Te Aroha's scientific records is covered in an extensive bulletin published by Henderson (1913). As popularity for the hot springs at Te Aroha increased, there was a demand to extract larger quantities of geothermal fluid than were naturally produced by the springs. Resultantly, to fulfill the demand for additional fluid, two geothermal bores were constructed that would act as conduits for the thermal fluids to flow to the surface. Following the construction of the bores Henderson (1938) was able to report on subsurface temperatures, chemistry and geology, within the domain. The drilled bores were successful in producing significant quantities of geothermal fluid. Therefore, in following years, as there continued to be an increase in the demand for mineral-rich geothermal fluid, studies were conducted by Healy (1956) and Woodward-Clyde (1993) to further understand and model the system to determine the viability of extracting supplementary fluid from the source. Additionally, Jenkinson (1994) presented a detailed analysis of all historic geochemical data, as part of his work on thermal waters of the Hauraki Depression.

In addition to reports focusing on the extractability of the thermal fluids, other scientific reports and analyses have been conducted on the Te Aroha Geothermal Domain, in order to understand the subsurface connectivity and develop a hydrological model for the system. In 1993, Mwangi logged down hole temperature and pressure measurements of the wellbores. Yalniz (1997) took reservoir pressure measurements using the capillary tubing (gas bubbling) technique to investigate hydraulic connectivity of the field with interference testing. Leaver (1999) analyzed pressure data from 2 wells within the domain using Fourier and Wavelet Techniques to determine whether they were in hydraulic communication with one another.

Furthermore, the geysering behavior of the wells was of interest, as drilled bores within the domain, regularly and consistently ejected water at the surface. The geysering behavior of the bores was unanticipated, as fluid temperatures at Te Aroha were below boiling point for depth, indicating that the geysering was not due to water flashing to steam, as is ordinarily the case. Subsequently, this became one of the main focuses for further scientific research. Michels (1993) reported on chemistry of selected waters within the domain and used these values to estimate the amount of CO_2 present in the system. Nurkamal (1999) took detailed measurements of the Wilson Street Bore throughout the geysering process to develop a model for geysering. Lu (2004) further added to this study and was able to accurately predict the geysering process of Wilson Street Bore using a mathematical model.

As can be seen, from 1889 to present, a significant amount of data has been collected at the Te Aroha Domain and published in several theses, scientific papers, and professional reports; however, this data has not yet been collated for analysis. Thus, the present paper is a review paper that combines all pertinent data available related to the geology, domain history, geothermal system, geysers and wellbores, spring history and geochemistry within the Te Aroha geothermal system. The data are then examined to gain an understanding of the Te Aroha system, how it has been affected by development and how it has evolved over time.

2.0 GEOLOGICAL BACKGROUND

2.1 Regional Geology

The Te Aroha area is located toward the southeastern extent of the Hauraki Rift Valley Depression, an active rift zone that formed as a result of the collision of the Indian and Pacific plates. The Hauraki depression is approximately 25 km wide and 220 km long with a maximum thickness of 3 km (Hochstein and Nixon, 1979), as shown below on Figure 1. Infilling the Hauraki Depression is a mixture of Tertiary and Quaternary sediments. The Hauraki depression is bound by two mountain ranges that are controlled by steeply dipping normal faults. To the west, there is the coal-bearing Hapuakohe Range controlled by the Firth of Thames Fault. To the east, there are the Coromandel (northern) and Kaimai (southern) mountain ranges, which are composed of volcanics, and are controlled by the Hauraki Fault (Hochstein and Nixon, 1979). There is a third fault, the Kerepehi fault, which cuts directly through the centre of the depression (Hochstein and Nixon, 1979). The geothermal system at Te Aroha occurs because of the permeability created along the Hauraki Fault.

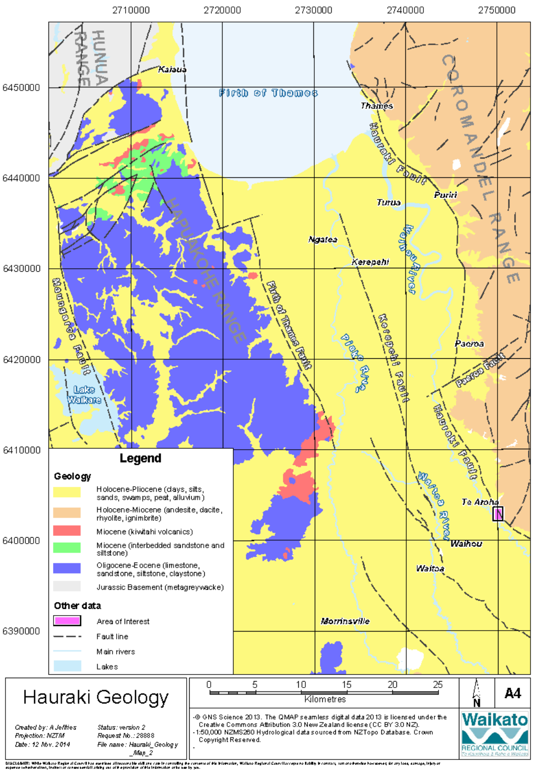

Figure 1: Geological map of Hauraki Rift Valley Depression and location of Te Aroha Domain (Waikato Regional Council, 2014).

2.2 Local Geology

The Te Aroha domain is situated on the western flank of Mount Te Aroha, which is part of the Kaimai Mountain Range and at 952 m is the highest peak of both the Coromandel and Kaimai ranges (Jenkinson, 1994). The mountain is composed of Beesons Island Volcanics, unconformably overlain by Whaitawheta Dacites (descriptions in Table 1). More specifically, the domain is underlain by highly altered andesitic debris deposits and rhyolitic material overlying moderately hard, highly altered andesite (propyllite). The andesite is highly fractured, and in-filled with quartz and calcite veins and pyrite (Jenkinson, 1994). The entire area is underlain by metagreywacke.

Rock Formation	Age	Description
Hinuera sediments	Quaternary - Tertiary	Undifferentiated alluvium - primarily rhyolite and ignimbrite sands, gravel, clay silt and peat.
Minden Rhyolite	Pliocene	Rhyolitic pumicious tuffs, and sphereulitic rhyolite in eroded domes, intruded by dykes.
Waitawheta Dacites	Miocene-Pliocene	Hornblende dacites and ignimbrites, from volcanic eruptions resulting in hot gas and rock pyroclastic flows.
Beesons Island Volcanics	Miocene (4.7 Ma)	Mixture of hornblende (older) and pyroxene andesites breccias and lava flows.
Metagrey-wacke and argillite	Triassic-Jurassic	Basement rock type underlying entire region.

Table 1: Geological stratigraphy of Te Aroha domain modified from Sharma (1982).

To the west of Mount Te Aroha is a gentle talus slope that extends toward the domain, where it meets alluvial fan deposits of the Waihou River. These fan deposits can be seen in Figure 2. Consequently, the sediment deposits underlying the domain consist of a mixture of talus from the fault scarp and sand and silt alluvial deposits, mixed with gravel from the gullies (Henderson, 1938). These surface deposits contribute to the topography of the area (Jenkinson, 1994). Since springs are located close to the fault scarp, it is likely that the topsoil cover is relatively thin (Henderson, 1938). Further west, past the fan deposits are the Hauraki Plains (Healy, 1956).

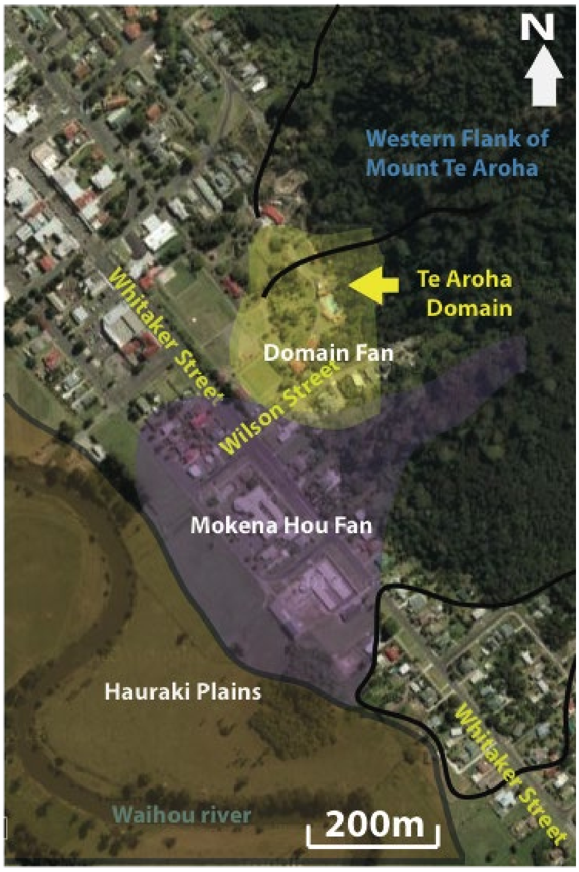

Figure 2: Surface deposits of Te Aroha, with alluvial fans, adapted from Jenkinson 1994

2.3 Faults

All previous studies on the area have been consistent in stating that the springs in the domain are associated with faults along the western edge of the Kaimai Range, which is bounded by a fault complex (Healy, 1956). Faulting is validated by small dacite breccia hills seen against Te Aroha Mountain (Henderson, 1913). The fault zones contain multiple shear zones and irregular fissures (Henderson, 1938). Thus, there are multiple fault planes along the edge of the base of Mount Te Aroha, all related to the Hauraki fault. However, there are two principal directions of faulting. These are 170° trending faults that are trans-current faults, and 140° trending faults that are parallel to the direction of principal horizontal stress (Henderson, 1938). The Te Aroha springs are thought to occur at the intersection between the 170° and 140° trending faults, and these faults act as the pathway for geothermal fluid to access the surface (Henderson, 1938). The dip of the fault planes is to the southwest beneath the domain (Healy, 1956).

3.0 GEOTHERMAL SYSTEM

Te Aroha is a low temperature, low-enthalpy geothermal resource, located over a bicarbonate outflow zone (Jenkinson, 1994). Historically, the fluid within the wells has been understood to be a mixture of deep sodium bicarbonate water and cool surface meteoric water (Henderson, 1938). The source of the fluid is unknown, potentially originating from one of either the Coromandel or Kaimai ranges (Michels, 1993).

Springs are located along a fault scarp defined by the face of Mount Te Aroha (Henderson, 1913). Within the domain, there are warm springs in the north and cold springs in the south, which use faults as a passage to the surface (Henderson, 1913). Cold springs originate from surface fluids and warm springs have a deeper origin. Consequently, cold springs are more radioactive, as surface rocks are more radioactive (Henderson, 1913) and warm springs, which had longer contact with deep rocks, are more likely to be mineralized (Henderson, 1938).

Additionally, there are bores in the area, most of which have, at one point, been geysering wells (Henderson, 1938). High levels of CO2, degassing from within the wellbores are the cause for geysering at Te Aroha. (Healy, 1956; Henderson, 1938).

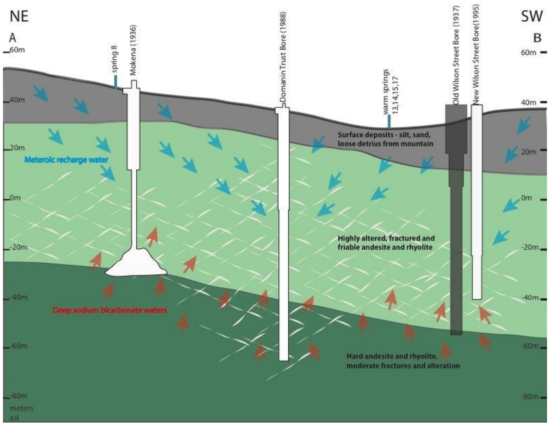

Figure 3: Cross section of Te Aroha Domain.

3.1 Borehole Geology

There are 4 bores that have been drilled in the Te Aroha domain; these bores provide insight into the local geology. The main rock types underlying the domain are altered rhyolites and andesites, overlain with various clays and sandy sediments (Henderson, 1938).

Rhyolites are highly fractured and often combined with silt, clay or sand. Andesites are heavily altered with quartz and calcite veining (Henderson, 1983). Figure 3 is a map view showing a geological cross-section of the domain across the Hauraki fault zone, where the geysering wellbores are located.

3.2 Geysering Mechanism

The geysering of Te Aroha wells is driven by supersaturated CO_2 gas dissolved in the geothermal fluid and is facilitated by the narrow passageways created by the wellbores. Temperatures measured were below boiling point for depth However, there was a high concentration of bicarbonate measured in solution and a high percentage of CO_2 measured in gas released by the bores. Thus, it was suspected early on, that CO_2 was the driving mechanism for the geysers.

The eruption of a CO_2 driven geyser functions similarly to a hot water geyser except that CO_2 drives the geysering instead of steam (Glennon, 2004). Normal geysers erupt when an increase in temperature causes water to boil and turn to steam, whereas CO_2 driven geysers erupt when there is a pressure decrease in a supersaturated liquid that causes CO_2 gas to come out of solution (Lu, 2004). In the case of the Te Aroha geysers, the pressure decrease that leads to the CO_2 being released is a decrease in hydrostatic pressure that occurs as fluid rises within the wellbore (Lu, 2004).

The geysering process at Te Aroha begins when water level is low, and therefore pressure due to hydrostatic head is also low, and water is able to enter the wellbore from the feed zones. Deep water is rich in CO_2, however initially the CO_2 is dissolved in solution, due to water pressure being greater than gas pressure at depth (Nurkamal, 1999). As the wellbore fills up, fluid rich in dissolved CO_2 rises in the water column and pressure decreases to a point at which CO_2 bubbles come out of solution. The bubbles migrate upward due to buoyancy and increase in volume at the same time, as buoyancy is proportional to volume (Lu, 2006), then bubbles begin to coalesce, forming larger bubbles called Taylor bubbles (Nurkamal, 1999). Bubbles continue to grow and the flow regime near the top of the well changes to slug flow. The momentum of the slugs, as they move toward the wellhead, displaces water and initiates geysering (Lu, 2006). The flow of CO_2 into the well is slow, and during the geysering cycle the amount of CO_2 released is much greater than the amount flowing into the well (Lu, 2004). Eventually, the amount of gas is depleted to a point, at which it is no longer sufficient to initiate geysering. After geysering, water level declines and the process repeats.

3.3 Age

In July 2012, radiocarbon age dating was performed on Mokena well groundwater (GNS 2013). Two values for groundwater age were estimated (Table 2) based on measured C^{14} values and using two different dilution factors.

q (dilution factor)	Corrected age (years)	± (years)
0.91	14000	1800
0.89	13800	2100

Table 2: Radiocarbon age of groundwater in Mokena Well.

Radiocarbon dating involves measuring the concentration of dissolved inorganic carbon. The age of the Mokena well ground water is estimated to be between 13800 and 14000 years. Since there are high levels of CO_2 in the water originating from the springs this affects the carbon concentration in the groundwater and, therefore, the calculated age should be treated with caution (GNS, 2013).

Groundwater age is important when determining the recharge time for a hydrothermal system. Young ground water will recharge relatively quickly, whereas old ground water will recharge at a slower rate (Bethke, 2008). Mokena groundwater is relatively old indicating a slow recharge rate.

3.4 Hydraulic Connectivity

Various different testing methods on hydraulic connectivity between wells have been conducted and have not yielded consistent results. Further analysis into the connectivity of the wellbores is recommended.

4.0 TE AROHA GEYSERS AND WELLBORES

4.1 MOKENA WELL

Mokena Well (Figure 4) is the oldest producing geothermal bore, in New Zealand (Michels, 1993). The wellbore was designed near a cluster of springs thought to rise above a permeable fault zone, to penetrate this zone and provide supplementary water to the mineral baths. The fluid from Mokena Well has similar chemistry to the warm springs in the area, indicating that the fluid came from the same source (Henderson, 1938). The amount of CO_2 present within the Mokena wellbore is within the range of 1.5-5.0 g/kg of fluid ± 0.5 g/kg (Michels, 1993). The Mokena wellbore is known as Mokena Geyser as it naturally erupts due to an inflow of CO_2 rich fluid from a deep surge zone (Michels, 1993).

The temperature profile for Mokena Wellbore (Figure 4) is relatively stable from 30-40 m which is indicative of conductive heat transfer from surrounding rock formation, meaning it is highly permeable (Woodward-Clyde, 1993). At 61 m there is thought to be a fracture where hot water enters the wellbore. The large increase in temperature profile below 61 m means the andesite is impermeable.

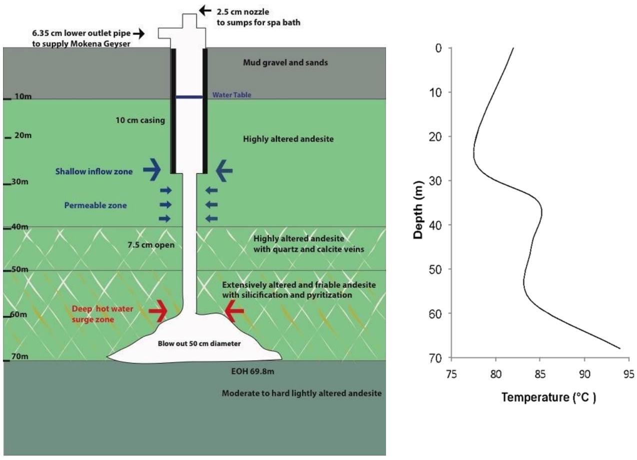

Figure 4: Downhole temperature profile of Mokena Well from April 1993 data averaged from Jenkinson, (1994)

4.2 Domain Trust Bore

The DTB (Figure 5) was drilled by the Domain Trust Board. Its purpose was to extract more mineral-rich fluid from the source. The hole was designed to tap into surface alluvium, which was thought to contain warm fluid that travelled up through fractures from hot andesitic rocks at depth (Woodward-Clyde, 1993).

The temperature profile of the DTB (Figure 5) has a steep temperature gradient from 30 m to the bottom of the hole, indicative of either upflow within the well or a highly permeable formation (Woodward-Clyde, 1993).

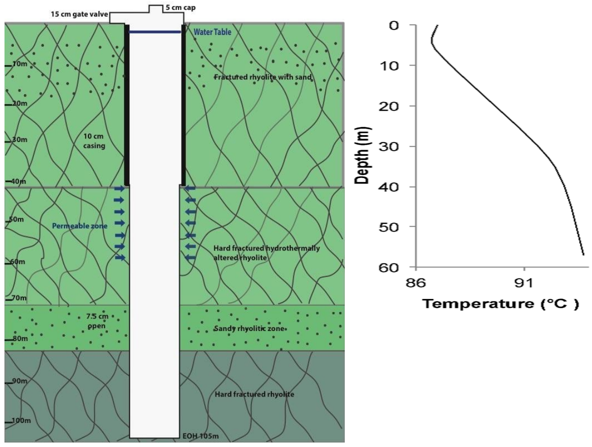

Figure 5: Downhole temperature profile of DTB from April 1993 data averaged from Jenkinson, 1994.

4.3 Wilson Street Bore (Old/New)

The original (Old) Wilson Street bore was drilled, along with Mokena wellbore, to supplement the existing supply of water to baths and mineral pools (Henderson, 1938). The New WSB was drilled to replace the old one that had caved in. It is currently closed, unless used for testing, in order to avoid scaling build up within the well (Lu, 2006) However, Matamata-Piako District Council (MPDC) plans to take from the bore to provide for anticipated increased usage through visitors brought to the area by the Hauraki Rail Trail (which has opened in recent years as a trail cycling destination) and in response to a request by local Maori. WSB has large temperature gradient nearer the surface and has a fluid production that is relatively constant indicating good permeability in the andesite. As can be seen on Figure 6, from approximately 68 m to the bottom of the hole the temperature gradient is steeper; this is likely due to warm water inflow at the bottom of the well, and an uncased wellbore at that depth.

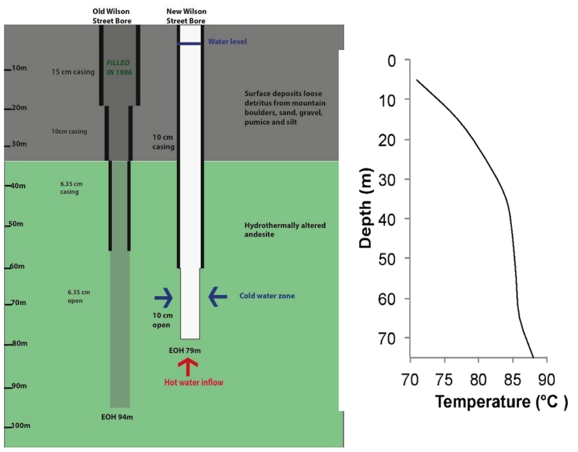

Figure 6: Wilson Street Bore (Old and New) geology and downhole profile of New WSB modified from Nurkamal, 1999.

4.4 Other Significant Bores

Test Bore: located just off Whittaker Street in the Te Aroha domain with stable temperature for depth curves indicating that surrounding rock material is highly impermeable (Woodward-Clyde, 1993). Also, the high temperature gradient of 0.66 °C/m is indicative of a thermal source located beneath (Jenkinson, 1994).

Mangaiti Drill hole: located 10 km north of the domain (Sharma, 1982) with a depth of 294 m, composed of silicified dacite overlain by pyroxene andesite; temperatures indicate that geothermal source is less than 150 °C (Sharma, 1982).

Baxter Bore: located on Whittaker Street, across from the Waikato Regional Council office (Woodward-Clyde, 1993), cold water bore (18 °C) depleted in sodium and enriched in calcium, therefore thought to be from a near-surface source composed of hydrothermally altered andesite or slope debris deposits with moderate permeability (Woodward-Clyde, 1993).

5.0 SPRING HISTORY

Table 3 has a summary of observations of the Te Aroha springs. Observations may include temperature, use, chemical composition and size. Cells marked with an X signify that the spring is no longer visible at the surface. There has been a steady decline in the number of springs over the years, with the largest decline being after the 1936/1937 installation of the Mokena and Wilson Street bores.

Name	Sample ID	Location	1913 (Henderson)	1938 (Henderson)	1956 (Healy)	1993 (Jenkinson)	2012 (Murithi)
1	X	Te Aroha Domain, Off Boundary Street	CO2 & H2S	bath	bath	X	X
2	72_2226	Te Aroha Domain Wilson Street	bath, warm	bath	bath	bath	bath
3	X	Te Aroha Domain, Whitaker Street	X	X	X	X	X
4	X	Te Aroha Domain, Off Boundary Street	bath, warm	bath	bath, colder	small	X
5	X	Te Aroha Domain Wilson Street	X	X	X	X	X
6	72_6561	Te Aroha Domain off Whitaker Street	bath, warm	bath	X	small	X
7	X	Te Aroha Domain, Whitaker Street	bath, warm	unmentioned	warm	X - faint noise	X
8	72_2251	Te Aroha Domain off Boundary Street	bath, warm	drink, cold	X	drink, warm	drink
9	X	Te Aroha Domain, Off Boundary Street	unused, small, warm	unmentioned	X	X	X
10	X	Te Aroha Domain, Off Boundary Street	unused, small, warm	unmentioned	cold	X	X
11	X	Te Aroha Domain, Off Boundary Street	unused, small, warm	unmentioned	X	X	X
12	72_6560	Te Aroha Domain off Boundary Street	unused, small, warm	unmentioned	X	X	X
13	72_2116	Te Aroha Domain Wilson Street	bath, large, warm	bath, large	warm	warm	X
14	72_2214	Te Aroha Domain Wilson Street	bath, large, warm	bath, large	not seen	warm	Foot pool
15	72_2225	Te Aroha Domain Wilson Street	drink, bath, warm	cold, bath	warm	warm	warm spring
16	X	Te Aroha Domain, Whitaker Street	HCl & SO4,cold, small	unmentioned	warm	X - faint noise	X
17	72_2249	Te Aroha Domain Wilson Street	dilluted, cold	unmentioned	cold	cold	cold pond
18	72_6559	Te Aroha Domain off Boundary Street	small, tunnel, warm	unmentioned	warm	X - inaccessible	X
19	X	Te Aroha Domain off Boundary Street	large, tunnel	cold, tunnel	warm	X - inaccessible	X
20	72_2247	Te Aroha Domain Wilson Street	cold	cold, drink	cold	cold	drink, iron
21	72_2248	Te Aroha Domain Wilson Street	cold, drink	cold, drink	cold	cold	drink, magnesia
22	72_2250	Te Aroha Domain off Boundary Street	cold, drink	cold, drink	cold	X - dry	X
		Total Springs:	20	20	15	10	7

Table 3: Summary of springs in Te Aroha Domain

5.1 Spring Temperature

As a general trend, spring temperatures have decreased in the domain.

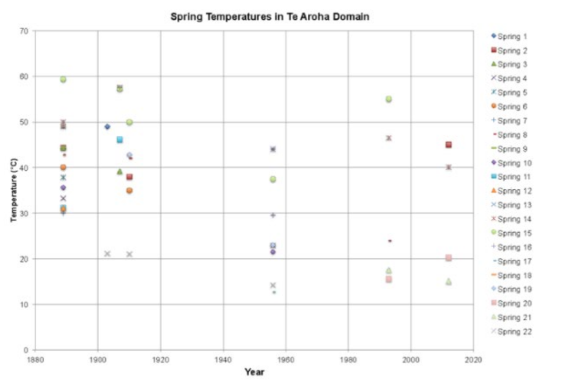

Figure 7: Surface temperatures of springs measured since 1889

Although data have not been consistently collected over the past years, it can be noted that there was a recognisable decrease in spring temperatures by 1956, after the installation of the Mokena and Wilson Street bores in 1936/1937 (Figure 7).

6.0 GEOCHEMICAL ANALYSIS

6.1 Geochemical monitoring history

Geochemical sampling data dates back to 1889, and early analysis classified Te Aroha fluids as bicarbonate, originating from a mixture of meteoric surface water and deep thermal waters (Henderson, 1938).

Chemistry data for the springs and bores was collected and reanalysed in 1956. Geochemical composition of the springs was quite similar, indicating a single source and deviations were attributed to variations from the source (Healy, 1956). The deep source was thought to be potentially magmatic in origin, because of the high boron levels (Healy, 1956). There was no correlation between spring temperature and chemical composition as temperature was either altered by the atmosphere or controlled by the steam and gas bubbles in the fluid (Healy, 1956).

In 1993, further geochemical analysis was undertaken, and it was found that bores, which had direct access to the source, had higher bicarbonate values than springs, which were diluted by surface waters (Michels, 1993). Mokena, DTB and the Test Bore all had similar composition, suggesting the same source (Woodward-Clyde 1993). Additionally, the concentration of chloride entering Mokena well is indicative of undiluted source fluids (Mwangi, 1993). Various estimates of reservoir temperature were made with K-Mg geothermometer temperatures of 110 °C (Mwangi, 1993) and SiO_2 temperatures of 115 °C - 140 °C (Michels 1993; Woodward-Clyde, 1993). In 2008, Reyes observed that the ratio of HCO_3/Cl decreased from SW to NE and attributed this to seawater influx. It was suggested that the Hauraki fault acted as a conduit pathway for these marine waters (Reyes, 2008).

6.2 Geochemistry Ternary Diagrams

Data included in the analysis is related to data sets collected from 1889 to 2012. Sampling methods and elements assayed have changed over time and this may affect data reliability.

Na- K-Mg

The Na-K-Mg Tri-linear diagram combines the Sodium-Potassium and the Potassium-Magnesium geothermometer equations (Powell, 2010). It classifies waters into immature, partially equilibrated, and fully equilibrated and gives an indication of the equilibration temperature. Five data sets for Te Aroha were available since 1889 to compare equilibration temperatures and equilibration states of fluids, (Figure 8). Data are consistently plotting in the same range of temperatures in the partially equilibrated section of the ternary plot indicating Te Aroha geothermal system has not varied an appreciable amount since 1889. Waters that are plotting in the immature section of the ternary diagram are cold springs (20, 21, Baxter) and bores (Motor camp bore at the Holiday Park) that are mixed with ground waters.

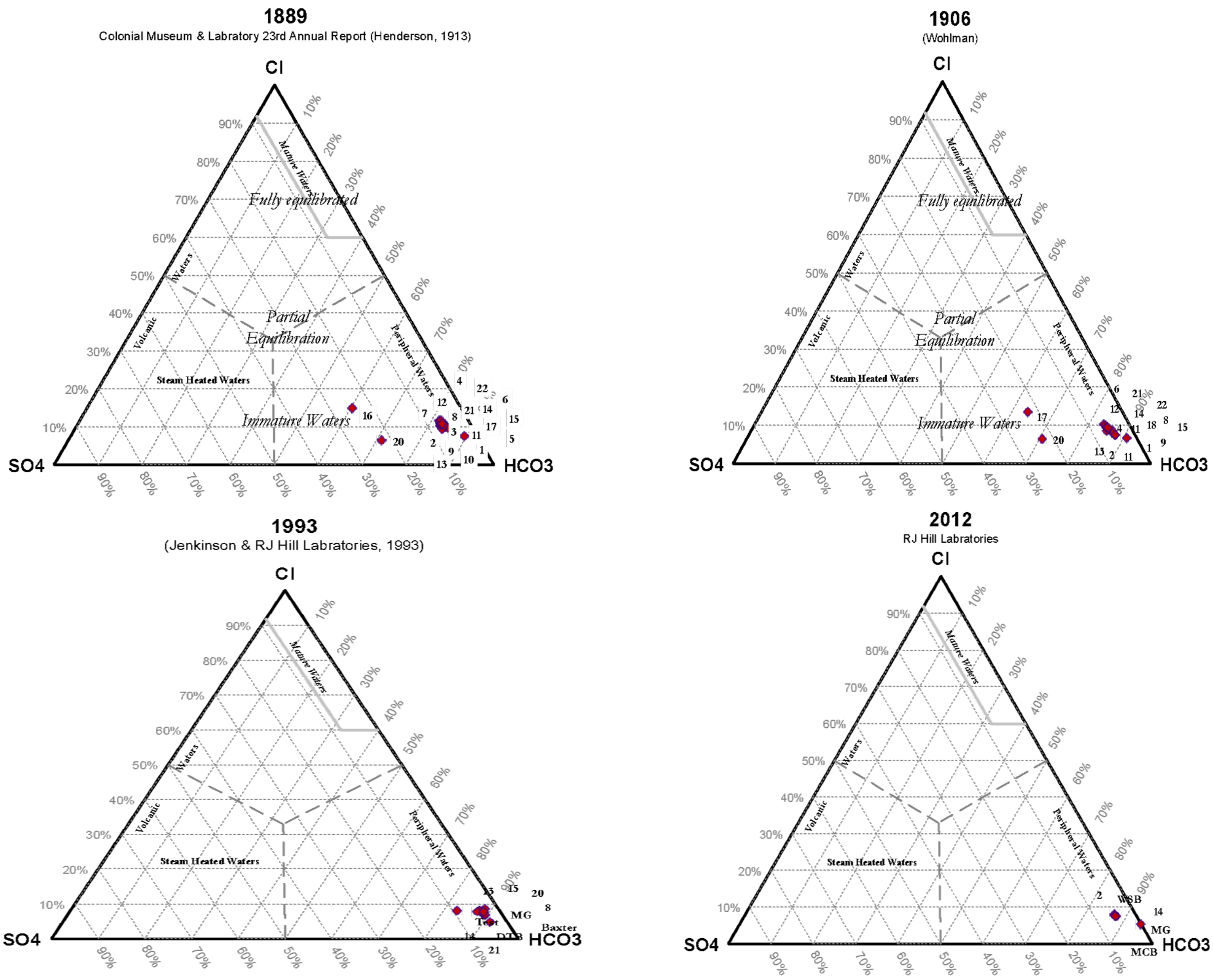

Figure 8: Na-K-Mg ternary diagram for Te Aroha Geothermal Domain between 1889 and 2012

Cl-SO₄-HCO₃

The Cl-Li-B ternary diagram gives an indication of the origin of the geothermal fluid. The concentration of boron in the fluid is related to the age of the geothermal system. Boron is quite volatile in nature and is released from fluid as it heats up. Therefore, fluids with high concentrations of boron are relatively young (Huenges, 2010). Chloride is a conservative element and concentrations will be relatively stable. Therefore, waters with high Cl/B ratios are indicative of older hydrothermal systems.

Lithium is a rare alkali metal, meaning it is a conservative element and will remain unaltered as conditions such as temperature and depth change. However, the relative concentration of lithium will decrease as it migrates farther from the source, both laterally and vertically, and becomes diluted by groundwater and/or becomes incorporated into secondary alteration minerals (O'Brien, 2010). Using the relative concentration of these three elements it is possible to determine the source of and the rate at which the fluid migrated from the source.

There are three main types of fluids associated with geothermal systems. The first type is deep reservoir water, which contains high concentrations of chloride (Cl). These waters are commonly associated with geothermal upflow zones. The second type of fluid is surface steam-heated water, which is highly concentrated in sulfate (SO_4). These high sulfate concentrations are due to subsurface minerals leaching into the solution. The third type of fluid is bicarbonate fluid, which has relatively low levels of chloride and is highly concentrated with the bicarbonate anion (HCO_3).

The Cl-SO_4-HCO_3 ternary diagrams (Figure 9) consistently classify all waters within the Te Aroha domain as bicarbonate fluids characteristic of the shallow outflow zone of a geothermal system. This indicates that the source of the springs and well bores in the area has remained constant since 1889.

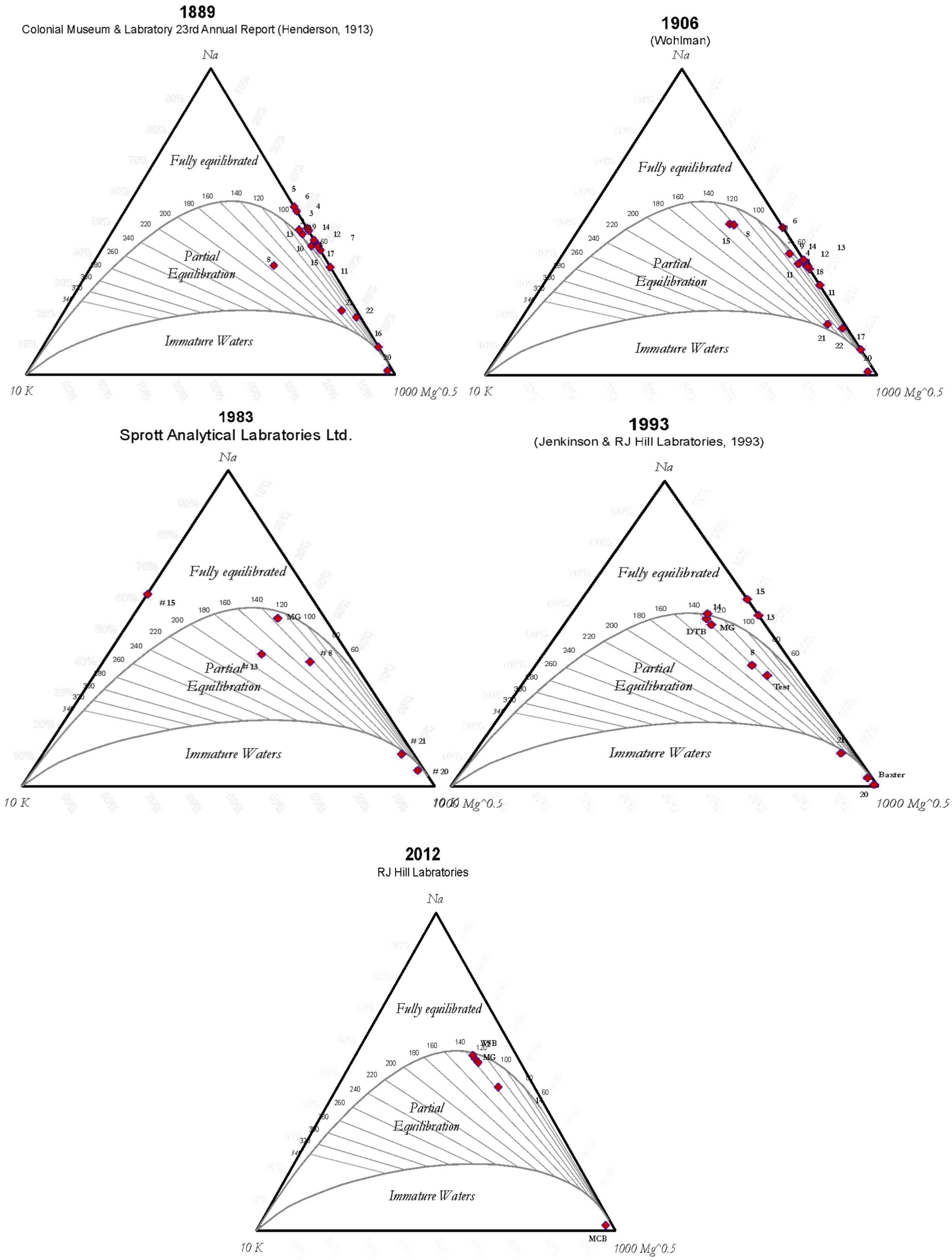

Figure 9: Cl-SO4-HCO3 ternary diagrams for Te Aroha Geothermal Domain between 1889 and 2012

Cl-Li-B

Only more recent data sets (from 1993 and 2012) include boron and lithium sampling. Therefore, the Cl-Li-B ternary diagram cannot be produced for years preceding 1993. Data from springs and bores in Te Aroha consistently plot near the boron corner of the triangle (Figure 10), indicating that the waters of Te Aroha belong to young hydrothermal systems.

Low concentrations of lithium indicate that either water has travelled far from the source or the rate at which water travelled to the surface was slow, the explanation for this being that lithium has either been diluted or incorporated into secondary alteration minerals. Waters plotting at the top corner toward the high chloride-concentrated end of the triangle (Motor camp bore and Baxter spring) are located outside of the domain, implying that these belong to older hydrothermal systems.

Thus, the Cl-Li-B ternary diagram is further evidence for the source of the fluids at Te Aroha having remained unchanged and having been consistent for, at least, the past 20 years.

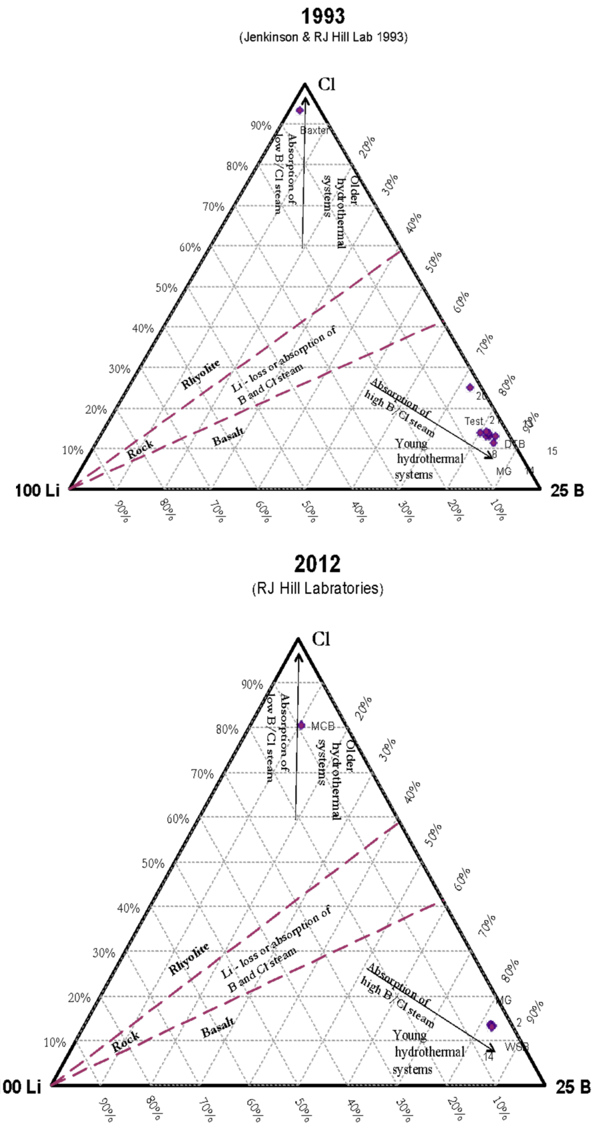

Figure 10: Cl-Li-B ternary diagrams for Te Aroha Geothermal Domain.

6.3 Geothermometers

Geothermometers use fluid chemistry as an indicator of subsurface temperature and rely on the assumption that fluid chemistry is constant from depth to the surface. There are a variety of different geothermometers, and each is valid for specific temperature ranges and for specific types of thermal waters. In this case, the silica polymorph α-cristobalite geothermometer was selected because calculated temperatures most closely resembled downhole temperatures (Jenkinson, 1994). The α-cristobalite geothermometer uses silica concentration to calculate temperatures, thus, cold springs that are diluted with surface waters would not accurately reflect subsurface temperatures.

When comparing temperatures generated with the α-Christobalite geothermometer (Figure 11) it is important to consider that not all springs were measured consistently for all of the data sets. Since 1906, most of the data points for spring and bore subsurface temperatures fall within the range of 80 – 100 °C. However, as a general trend, spring temperatures are mildly decreasing over time, with the exception being in the most recently collected data.

There are two data points from 1906 that are much higher than the rest of the points, at 125 °C and 127 °C. One of these outlying points belongs to cold spring # 21, therefore the data may not be valid as the fluid has likely been mixed with surface waters. The other point appears to be correct but could be caused by some unknown effects.

6.4 Gas Geochemistry

The gas chemistry composition for all springs and wellbores in the Te Aroha area has a very high percentage of carbon dioxide, ranging from 92 to 98.8 mole% dry gas (Table 4).

Site	CO_2	CH_4	N_2	O_2
Mokena	94	1.5	4.1	
Mokena	98.8	0.002	0.9	0.3
Spring B	96	1.63	2.37	
Spring H	95.2	1.66	3.13	
Spring K	94.2	2.06	3.22	
Te Aroha	92	0.0003	7.1	0.92

Table 4: Gas composition data from Te Aroha. Quantities are in mole% of dry gas.

Analysis of the composition indicates thermal origin, due to methane contents of fluid, high carbon isotope equilibrium temperatures and oxygen-18 shifted water (Lyon and Giggenbach, 1992). Chemical composition of gases indicates that the water is of andesitic origin and the relatively high levels of oxygen-18 enrichment are thought to be caused by calcite dissolution in the greywacke basement (Reyes, 2008).

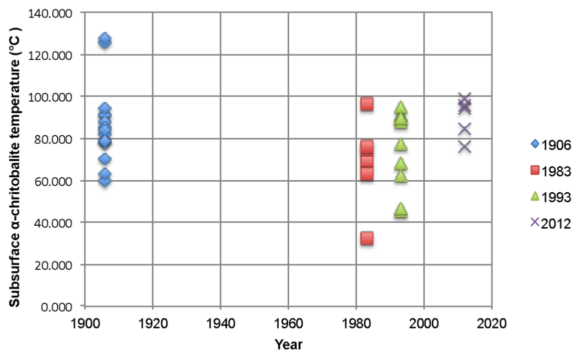

Figure 11: Subsurface α-cristobalite calculated temperatures for the Te Aroha Geothermal Domain.

7.0 CONCLUSION

The Te Aroha geothermal system is a low-temperature bicarbonate outflow zone. Geochemical data collected across three centuries consistently support this statement. The mechanism for discharge of the geothermal fluids is high levels of carbon dioxide from deep geothermal sources, which expand causing water to rise up to the surface. The main source of permeability, which allows fluid to access the surface, is the complex system of faults located along the western margin of Mount Te Aroha.

Geochemical data show that the origin of the fluid in the springs and bores of Te Aroha has been unaltered since 1889. Waters can be classed as bicarbonate waters, belonging to young hydrothermal systems. Additionally, they are in partial equilibrium, with subsurface temperatures, currently, ranging from 75 °C to 98 °C.

The geochemical composition of fluids has remained consistent since 1889. However, it does seem that the resource is finite in size. There is a direct relationship between the installation of a new bore on the springs in the surrounding area drying up or ceasing to discharge (disappearing). Nevertheless, it may be possible to extract larger volumes of fluid from the system without risking depletion of the source. Furthermore, if the decision is made to extract supplementary fluid from Te Aroha, springs and bores should be carefully monitored to identify interference and prevent further decline.

ACKNOWLEDGEMENTS

Thank you to the Department of Engineering Science at the University of Auckland for supporting and funding the publishing of this paper. Thank you to the Waikato Regional Council for their contributions to this paper including access to data and production of maps.

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