Waikato Regional Council Technical Report 2013/07

The chemistry of waters of Te Aroha geothermal system

www.waikatoregion.govt.nz
ISSN 2230-4355 (Print)
ISSN 2230-4363 (Online)

Waikato
REGIONAL COUNCIL
Te Kaunihera ā Rohe o Waikato

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October 2012

Document #: 2292573

Peer reviewed by
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Approved for release by:
Ed Brown Date February 2013

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THE CHEMISTRY OF WATERS OF TE AROHA GEOTHERMAL SYSTEM

BY

LAWRENCE M. MURITHI

OCTOBER, 2012

ABSTRACT

Te Aroha geothermal system has been used for more than 100 years for several uses, including bathing, swimming and balneology. Previously there were more than 20 springs but this number has been halved in the intervening years.

The chemical surveys and analyses of the springs and determining the trends of the springs can be used to determine their potential application as well as their sustainability.

This project seeks to assess the chemistry of Te Aroha geothermal resource to determine the sustainability for continued production as well as assess the trends of the geothermal fluids.

ACKNOWLEDGEMENTS

This report is an adaptation of a project prepared in part-fulfilment of the requirements for the University of Auckland Post-graduate Certificate in Geothermal Technology programme. The report is based on data obtained in the field with the assistance of Waikato Regional Council, and existing data obtained from Waikato Regional Council, University of Auckland, and other sources.

I wish to most sincerely thank the following people:

Dr. Sadiq Zarrouk, the course coordinator and my supervisor, for sharing his geothermal knowledge and experience with us and his help in carrying out this project without which I could not have managed;

Katherine Luketina, a geothermal scientist at Waikato Regional Council for her tremendous advice and support in collecting chemical data at Te Aroha as well as provision of documents on past reports;

John Hughey of Waikato Regional Council, who supervised the field work in collecting the chemical samples.

Institute of Geological and Nuclear Science (GNS), who provided geological maps and bore data through Katherine.

Geothermal Development Company (GDC) for releasing me from my duties to undertake this course.

TABLE OF CONTENTS

INTRODUCTION

Te Aroha Domain is one of New Zealand's small low-enthalpy geothermal systems and has been utilized since the 19th century for balneology, therapeutics and other recreational activities. Chemical analysis has since been carried out to understand the nature and origin of the geothermal waters as well as determine their suitability for such activities. Several chemical analysis methods have been developed since geothermal development began.

In this study, use of geothermometers and ternary diagrams will be used in analysing the chemistry data from the Te Aroha hot springs (domain). Hot springs and geysers are surface manifestations of hydrothermal activities and are expressions of the sub-surface activity of heated water, steam and gases that flow to the surface. Geothermal resources contain thermal energy at depth in the earth's crust, which is mostly extracted by convection from the fluids resident at depths of less than 3 km (Kruger and Otte, 1973).

Continuous monitoring of such fluids used for recreational purposes is therefore very crucial to ensure that they remain safe for such purposes as well as check for any chemistry changes with time. The sustainability of the system to ensure continued production for centuries is also very important. These therefore formed the reasons for studying the domain discharges.

History of the system

Te Aroha geothermal system is one of 28 small geothermal systems in the Waikato region in New Zealand (Figure 1). It covers 8.0937 ha (20 acres). The thermal water domain has been utilised for balneology and therapeutics since the 19th century. Surface features have been mapped since 1880s, and monitoring of spring temperatures began some time after that (Healy, 1956).

Figure 1. Map of Geothermal systems in the Central North Island (Waikato Regional Council)

The Domain is classified as a ‘recreation reserve’ under the Reserves Act 1977 and as a ‘Historic Area’ under section 49 of the Historic Places Act 1993 (Piako County Council management plan, 1980).

The Te Aroha area/block was originally owned by the Marutuahu people and used for hunting. Due to the saltiness of the water from some of the springs, they believed the water came from the sea through a tunnel through the mountain. There was intertribal warfare with the Ngati Haua people between 1830 and1840, who disputed the ownership claim. The Maori land court gave the certificate of title to Ngati Haua tribe in 1869 but other tribes objected. A rehearing was done in 1871 and the title was reverted to Marutuahu. The land was, however, sold to the crown in 1879.

The first bath was made in the 1880s after discovery of gold in Waiorongomai valley in 1881. Tui mine was one of the major mines in the area, and attracted a huge number of miners. Gold mining resulted in development of the town and opening of transport sector including construction of a railway line linking Auckland. This increased the number of tourists, both local and international, thus accelerating the development of the area (Ian Rockel, 1986).

In 1881, the 20-acre hot spring domain was gifted to Te Aroha town by the Maori chief Makena Hou and was gazetted in 1882 under The Public Domains Act 1881, which allowed the Maori people to use it freely for bathing. Several baths constructed directly above the hot springs were in use by this time while other hot springs were used for medicinal drinking water. In 1882, the domain was vested under the Te Aroha hot spring domain board whose members were elected by the local people. Establishment of the borough council in 1898 increased the board members since the Mayor and councillors were absorbed into the board directly (Piako County Council management plan, 1980).

As the township grew and the hot spring domain became widely known, there was need for major improvements to raise the domain's standards but this was not possible due to lack of funds. In 1903, the department of Tourists and health Resorts assumed control of the domain. The Department, however, handed control of the Domain to a joint Piako and Te Aroha Borough Council administrative body in 1978 due to high financial requirements for maintenance of the domain (Piako County Council management plan, 1980).

To take advantage of the pleasant taste of the Te Aroha waters, in 1886 Te Aroha Soda And Mineral Water Company commenced bottling and sales, and two years later they exhibited the waters at Melbourne centennial exhibition. Earlier the Te Aroha residents had petitioned the Minister of Lands, John Balance, for a medical practitioner who would supervise and advise on the use of the waters, especially for bathing of invalids. This had resulted from the death of one person who they believed had used an excessively hot bath. The government helped them and they employed Dr Alfred Wright who later made several publications including a guide for invalids and visitors (Ian Rockel, 1986).

Te Aroha hot springs domain has provided a variety of recreational activities to the public and sporting clubs since it began. Among them are:

- **Sporting clubs –** Men's bowling club, ladies bowling club, croquet club, skating club and domain tennis club are some of the clubs in the domain each with its own membership.

- **Museum society –** located in the Cadman building (Figure 2**).**

- **Amenities –** hot pools, mineral fountains, picnic areas and barbecues, Mokena geyser, lily pond, sundial, aviary and gardens.

When the County councils were drafting a management plan for the geothermal field, they came up with goals that would help them in running the domain (Piako County Council management plan, 1980). The goals included:

- To manage the domain in perpetuity as a recreational reserve for the physical welfare and enjoyment of the public.
- To develop facilities for cultural, recreational and sporting activities in harmony and integrated with historical features of the domain.
- To conserve the qualities of the domain that contribute to pleasantness, harmony and cohesion of natural environment.
- To preserve any historic, scenic and scientific features in the domain.

Figure 2. Satellite imagery of Te Aroha Domain from Google earth.

Objectives of the report

The Te Aroha geothermal system had had more than 100 years of monitoring history but the information has never been collated in one place. This project thus aims to map the features, buildings and bores in the domain as well as analyse the chemistry data available and interpret the results to monitor the sustainability of the system.

PREVIOUS WORKS

Michels *et al*, 1993 did an analysis on the discharge of thermal fluids at Te Aroha on the geysering wells driven by CO_2 discharge with focus on Mokena and Domain Trust bore in 1993. Wilson street bore had been closed.

Discharge rates of Mokena bore were measured in November 1936 and June 1937 (Henderson, 1938), September 1956 (Healy, 1956) and April 1993 and they noted that the eruptive period and volume discharged in each discharge increased with time. This they attributed to aragonite deposition since reaming resulted in a decrease in the cycle period with an increase in the total volume discharged. They also observed temperatures at various depths during the cycles and noted that each cycle had different temperature values making it difficult to generate a temperature-depth profile. They, however, noted that a large decrease in temperature occurs at about 28m but remains almost constant up to about 60 m from where temperature increase starts. They determined that the amount of CO_2 required to lift a liquid column of water from 60 m depth is 2.5 g CO_2 per Kg of liquid.

Wilson street bore discharge behaviour is described by Henderson, 1938. He notes that geysering action began at 35 m during drilling but periodic discharges began at 59m depth. The long term flow rate was small 0.45 m^3/hr while the cycle period was 39 minutes with a discharge period of about 10 minutes. In 1956 the cycle period was noted to have changed to 22 minutes.

Domain Trust Bore (DTB) caved in at 57 m and was sealed. It was re-opened in April 1993 and discharged periodically with a long-term discharge being about 0.45 m^3/hr and a cycle period of between 15 and 21 minutes. Temperature observations during the cycles were noted to have similar characteristics to Mokena bore. There was minor scaling observed at the well head.

Herbert, 1921 in his hot springs of New Zealand report indicates that Te Aroha was a gold mining town in the early 19^{th} century but has since changed to a tourist attraction. The area then had over 20 springs, which were scattered over the foot of the mountain due to limitation in the outflow.

He classified the mineral waters into:

- Alkaline waters - He pointed out that these waters have temperatures of about 55 ^{o}C are best for therapeutic use. He indicated that Te Aroha springs fall under alkaline waters with very high concentrations of sodium-bicarbonates and free carbonic acid gas but little concentrations of other constituents. He also explained the pharmacological action on each of the constituents in the waters.

- Magnesium waters – these are cold waters.

- Chalybeate waters – are cold with iron salt but less free carbonic acid. These waters are extremely palatable.

Yalniz (1997) used two bores to monitor pressure of the field in his preliminary interference measurements at Te Aroha using capillary tubing (gas bubbling technique) with nitrogen. He conducted three measurements of new Wilson street bore at different depths, duration and recording intervals. The times of eruption of Mokena bore were recorded during the time of carrying out the measurements. This he did for a few weeks. He then used autocorrelation function to carry out his analysis and thereafter show the cycling behavior of the wells. He determined that pressure measurement technique was a good way of analyzing small scale interferences due to the sensitivity of the instruments. He also notes that weather conditions may affect the results thus precaution should be taken. Some of the cycling data he came up with are shown on Table 1.

Time (sec)	Pressure (bar a)
0	3.822515
10	3.822515
20	3.822515
30	3.822184
40	3.821852
50	3.822184
60	3.822184
70	3.822184
80	3.821852
90	3.821852
100	3.821521
110	3.821190
120	3.821190
130	3.821190
140	3.821190
150	3.821190
160	3.821521
170	3.821521
180	3.821521
190	3.821852
200	3.821852
210	3.821852
220	3.821852
230	3.821852
240	3.821521
250	3.821852
260	3.821521
270	3.821190
280	3.821190
290	3.821190
300	3.822184
310	3.822184
320	3.821852
330	3.821852
340	3.821190
350	3.821852
360	3.821852
370	3.821190
380	3.821190
390	3.821190
400	3.821521
410	3.821521
420	3.821190
430	3.821521
440	3.821521
450	3.821521
460	3.821852

Time (sec)	Pressure (bar a)
470	3.822184
480	3.822184
490	3.821852
500	3.821852
510	3.822184
520	3.822184
530	3.822515
540	3.822846
550	3.822846
560	3.822846
570	3.822515
580	3.822515
590	3.822846
600	3.822846
610	3.823178
620	3.823178
630	3.823509
640	3.823509
650	3.823840
660	3.823840
670	3.823509
680	3.823840
690	3.823840
700	3.824503
710	3.824503
720	3.825166
730	3.825166
740	3.825497
750	3.825497
760	3.825497
770	3.825497
780	3.825497
790	3.825166
800	
810	3.825497
820	3.824834
830	3.824834
840	3.824834
850	3.824834
860	3.824834
870	3.825166
880	3.824834
890	3.824834
900	3.825166
910	3.825166
920	3.825166
930	3.825497
940	3.825828

Time (sec)	Pressure (bar a)
950	3.825497
960	3.825497
970	3.825166
980	3.825497
990	3.825828
1000	3.825828
1010	3.825497
1020	3.825828
1030	3.826159
1040	3.825828
1050	3.825828
1060	3.825828
1070	3.825828
1080	3.825828
1090	3.825828
1100	3.826159
1110	3.825828
1120	3.825828
1130	3.825497
1140	3.825497
1150	3.825497
1160	3.825166
1170	
1180	
1190	3.824834
1200	3.824834
1210	3.824834
1220	3.824834
1230	3.824834
1240	3.824834
1250	3.824834
1260	3.824503
1270	
1280	3.824172
1290	3.824172
1300	3.823840
1310	3.823840
1320	3.823840
1330	3.823509
1340	3.823178
1350	
1360	
1370	3.823178
1380	3.823178
1390	3.822846
1400	3.823178
1410	3.823178
1420	3.823178

Table 1. Part of Mokena geyser cycling data (Yalniz, 1997)

Leaver *et al.* (1999) used Geokon vibrating wire pressure transducers that had surface readout to a data logger or computer to analyse pressure data by fourier, autocorrelation and wavelet analysis techniques. Fourier analysis for Mokena demonstrated pressure cycling at a frequency of about 410 cycles per 200 hours or a cycling period of about 29 minutes while other features had frequencies of 910 cycles or period of 13 minutes and 1150 cycles or period of 10 minutes.

They concluded that that the combination of conventional Fourier analysis with autocorrelation and wavelet analysis provided a greater clarity in detecting characteristics of pressure fluctuations. Figure 3 shows the cycling results he obtained.

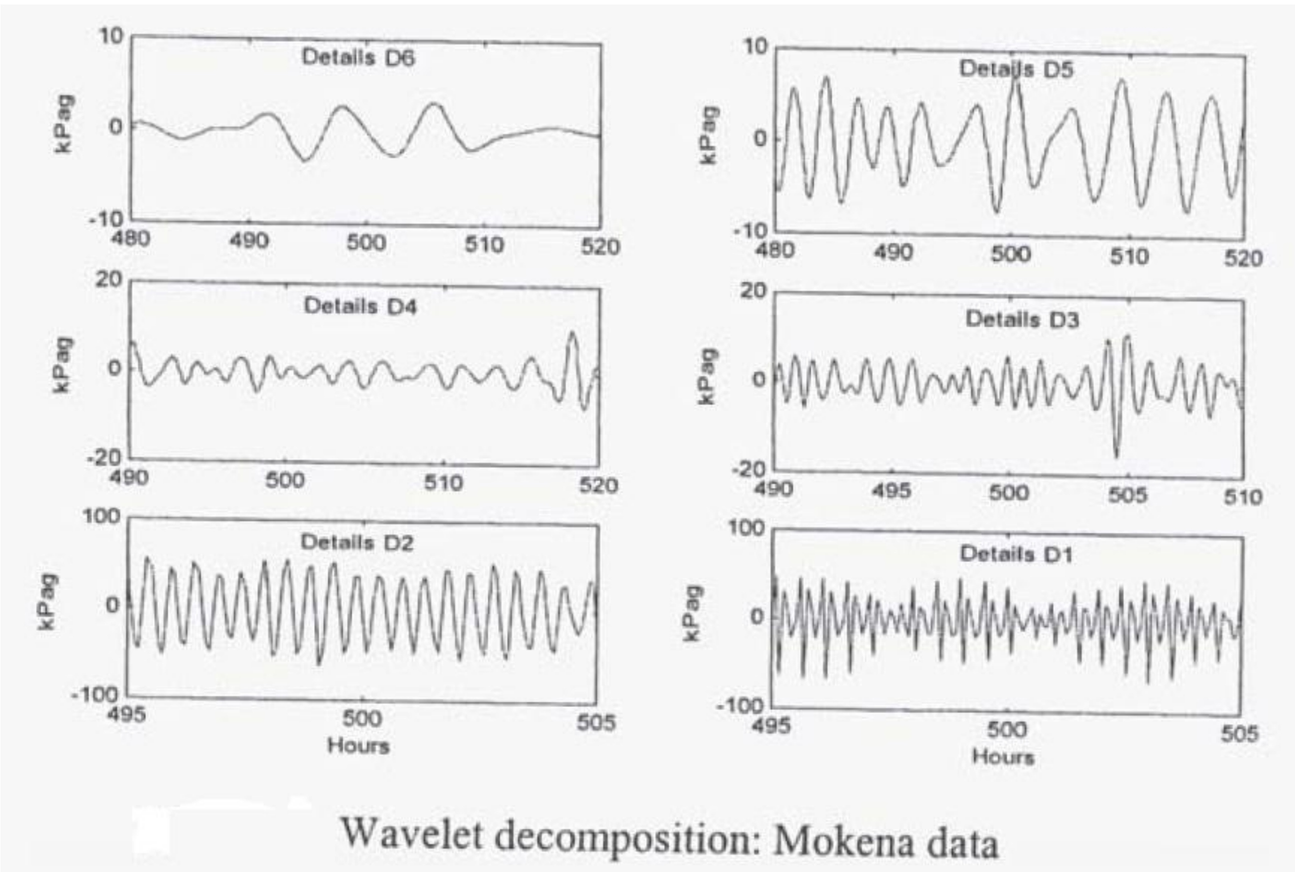

Figure 3. Cycling data of Mokena geyser (Leaver J, Watson A and Ding J, 1999)

THE TE AROHA GEOTHERMAL SYSTEM

Location

Te Aroha is a town in the Waikato region of New Zealand about 19km south of Paeroa and sitting at the foot of 952-metre Mount Te Aroha (Figure 4). The township lies between the base of Mount Te Aroha and the Waihou river, and has an area of 11.6km^2 and a population of 3,768 (2006 census). The Te Aroha geothermal springs are located at the edge of Te Aroha township to the eastern side of Whitaker Street between Wilson and Boundary Streets (Figure 6). The study area was chosen to cover around the domain where the springs and other surface features are located.

Figure 4. Entrance to the hot spring domain

The Resource

Te Aroha geothermal prospect is a small and low temperature geothermal system found in the Hauraki rift zone. It has been used for balneology and therapeutics since the 19th century. Heated groundwater, hydrothermal fluids and gas from cooling magma rise through rock fissures and fractures to the surface. Past investigations indicate that the source of the hot fluids could be about 150 metres (Henderson, 1938).

The fluids have high CO_2 content (96-98 mole %) from the magma source, causing the water to bubble at the surface. As the geothermal fluids rise, they react with minerals in the rocks resulting in a slightly alkaline solution. Springs that rise directly to the surface have slightly higher temperatures and bubble at the surface. However, most of the springs are not as warm or bubbly, and contain a range of other minerals dissolved from the volcanic rock (Michels *et al*, 1993).

Since the domain has a small extent of the surface manifestations with little discharge rates and low productivity of the wells, it is believed that the reservoir beneath is of small extent although no extensive research has been carried out.

Several wells have been drilled in the area (Figure 6) to provide thermal waters that are then collected for recreational purposes. Most of the wells became cold and were closed while others have broken down and been neglected. In the current survey others could not be located because they were cemented and covered with top soil. Originally there were more than 20 springs in the domain but this number has significantly reduced in the recent past.

Among existing springs are:

- Wilson Street bore (64_512)

  The well was drilled in 1937 and geysering started at a depth of 35m thus 34 m deep casing set. The bore was deepened to 95 m but caved in at 59 m (Henderson, 1938). It was later closed and another bore drilled next to it in 1995 but has remained closed although it was been used for experiments by the Geothermal Institute Diploma students up to 2002. It discharges with a period of approximately 15 minutes at and an average rate of 0.1kg/s long term equivalent, at temperatures up to 75 °C (Leaver J, Watson A and Ding J, 1999).

- Mokena Geyser (72_2227)

Figure 5. Mokena geyser

It is the oldest well and was drilled in 1936 to a depth of 105m, cased with 4'' to 28 m and 3'' from 28-67 m. It is fully open and discharges like a geyser with a period of approximately 30 minutes. The well has an average discharge rate of about 0.7 kg/s and maximum temperatures of 83 °C. Due to aragonite deposition, well reaming is done every 6 months. It is the main attractive geyser in the domain (Leaver *et al*., 1999).

- Test Bore (72_2252)

It was drilled in 1956 between Whitaker Street and the croquet club and encountered temperatures of 62 °C at 65 m depth but was non-productive so was sealed off. (Michels, 1993).

- Domain Trust Bore (64_276)

The well was drilled in 1986 and also discharges water periodically. It had temperatures of up to 88 °C and flow rate of about 0.1kg/s (Michels, 1993).

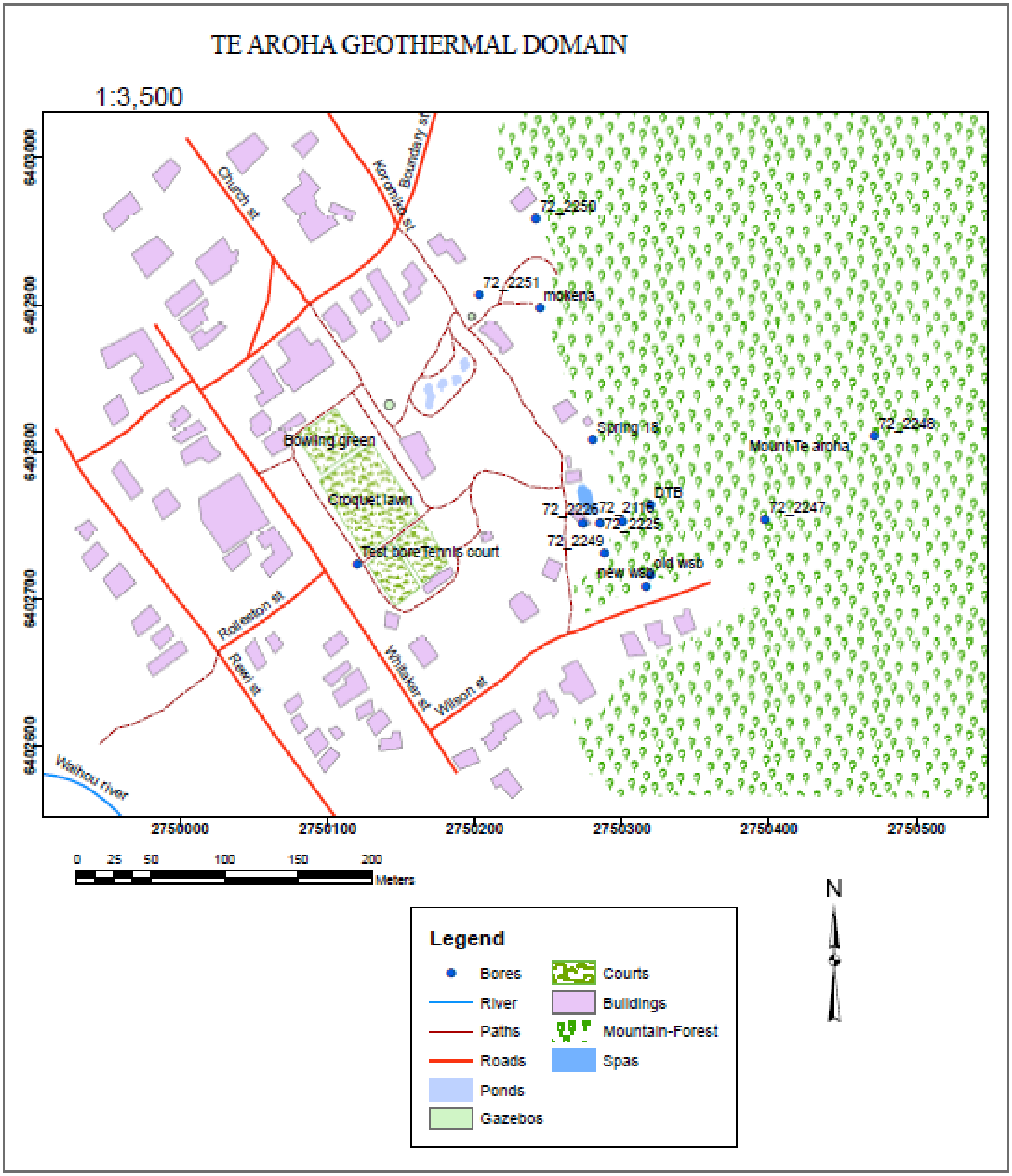

Figure 6. Map of the Te Aroha geothermal domain showing bore locations

Geology

The Te Aroha Domain is found on a fractured fault zone at the foot of the western escarpment of the Kaimai Ranges. The Range consists of ancient andesitic volcanic rocks formed between 25 million and 2 million years ago and alluvial sediments. The rocks were uplifted and formed a continuous mountain range that is about 70 km in length. The Te Aroha bedrock is therefore formed by the altered andesites. The boundary between the mountain ranges and the valley of the Waihou River is defined by a fractured fault line and steep escarpment. Mount Te Aroha, however, stands out as the landmark feature since it is bounded by faults and forms an outcrop on the western margin of the Kaimai Range (Henderson, 1938).

The domain is majorly of conglomerate rock type but Mount Te Aroha consists of altered andesite (Figure 7). The conglomerates are of clastic sediments while the andesites are intermediate extrusives (Geological data from Institute of Geological & Nuclear Sciences).

The Aroha sandy sediments are formed from andesite and ash, and thus have a weak crumbly structure and are therefore prone to slip and erosion. The Tuhi sandy loams (alluvium) are found at the foot of Mount Te Aroha and are friable and fine textured.

Stratigraphic logs (Appendix A) of four wells provided by the Waikato Regional Council, however, indicate a difference in the substructure of the domain with Domain Trust bore (64_276) indicating rhyolite as the primary rock from the surface with silt, sand and clays as secondary rocks below 35 m. Since the stratigraphic log of bore 64_398 is up to 36 m, it is inferred from the previous reports that the basement rock is andesite. The geological cross-section of the domain is shown in Figure 8.

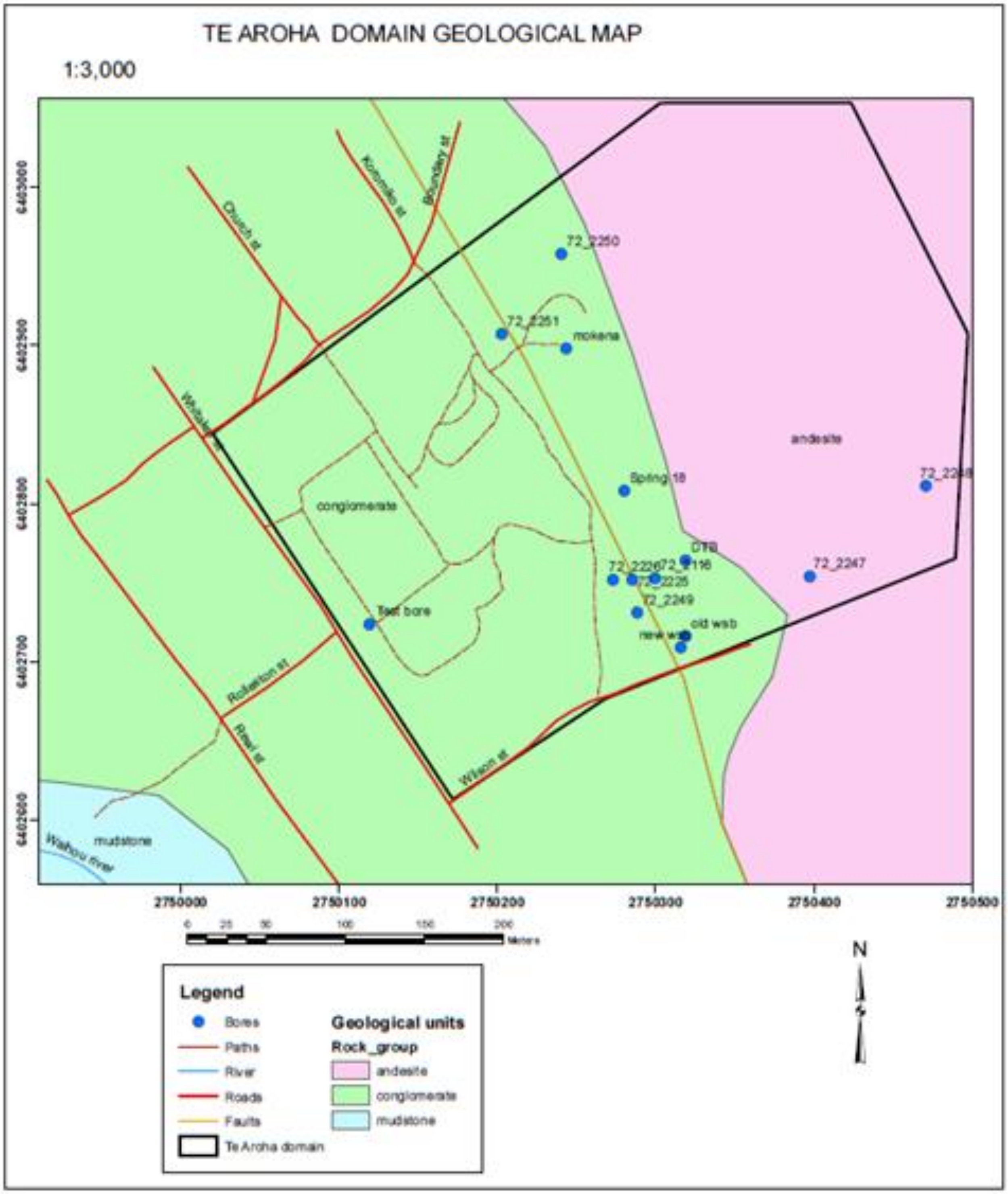

Figure 7. Geological map of Te Aroha geothermal system (Geological units from GNS)

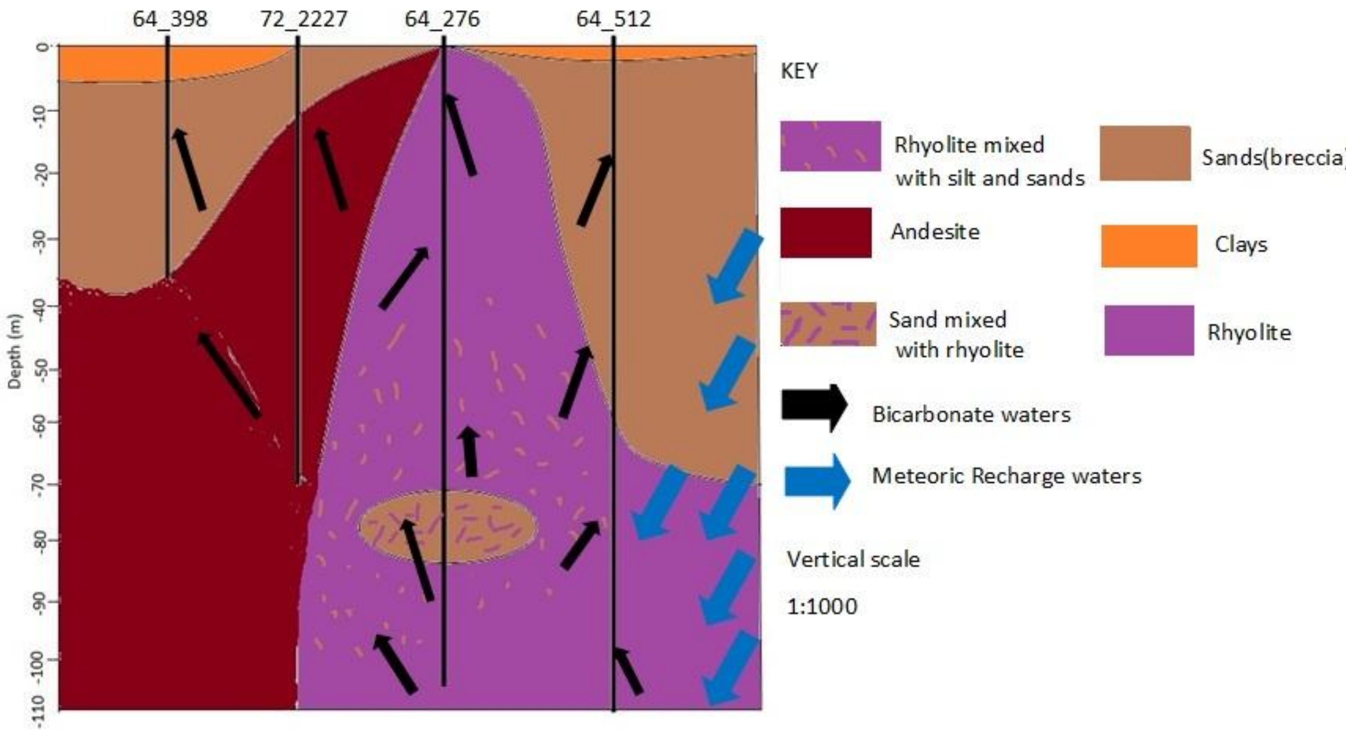

Figure 8. Hydrogeology of Te Aroha Domain (data from Waikato Regional Council)

Chemistry

Most of the waters in the Te Aroha system are believed to be of meteoric origin, penetrating to some depth and being heated before flowing to the surface through fissures and fractures of the Hauraki fault (Healy, 1956). The steep hydraulic gradient that leads from east to west is most likely used by the heated waters as they flow to the surface.

Herbert (1921) lists three types of waters at the domain; hot sodium bicarbonate, cold magnesium and cold chalybeate. These were indicated for curing gastro-intestinal, heptobiliary and rheumatic diseases.

All the samples taken from the bore waters indicate that the waters are rich in sodium and bicarbonates except the cold springs, which have relatively smaller quantities. This can be seen from Table 1 (Michels, 1993 and Waikato Regional Council, 2012).

Geothermal fluids with high bicarbonates and low chlorides mostly occur in volcanic areas and the spring waters will have a near-neutral pH.

On 19th October 2012 as part of the current survey, samples were collected from all boreholes that could be found and sampled (Appendix B). They were sent to R.J. Hill laboratories for analysis. The results from the laboratory were then used for analysis of the geothermal system (Table 2). Silica results had not been received by the time of completion of this report thus silica geothermometry couldn't be applied on the samples.

			Michels, 1993						All values in mg/kg (ppm)					
Sample Name	**Sample Label**	**Temp C**	**pH**	**Li**	**Na**	**K**	**Ca**	**Mg**	**SiO2**	**B**	**Cl**	**F**	**SO4**	**HCO3**
DTB	10	67	7.9	2.1	3159	74	5.6	3.5	108	158	631	1.29	348	7700
DTB	11*	67	7.9		3200	66	11.2	4	133	159	550		390	7700
MOKENA	2*	85	7.3		3200	66	6.9	3.9	135	162	550		390	7500
MOKENA	1	85	7.2	2.13	3385	70	8.2	3.6	116	156	574	1.72	312	7500
SP-15	7	55	7.3	0.48	2911	69	6.8	3.4	106	145	611	1.53	335	6700
SP-13	5	46	7	1.84	2825	67	13.6	5	102	145	609	1.18	330	6600
SP-14	6	46.5	6.3	1.99	3071	73	11.2	4	107	155	524	1.51	279	6600
SP-8	4	24	5.8	1.38	2176	53	31	7.8	84	99	433	1.01	273	4900
SP-21	9	17.5		0.26	663	20	141	27.5	63.4	28	111	0.25	81	2100
SP-20	8	15.5		0.03	110	3.4	24.5	13.1	44	3	31	0.38	35	320
			Waikato Council, July 2012											
Mokena	1	92	7.8	1.96	2900	63	12.2	3.9	117	138	600	1.76	360	7220
Mokena	2	94	78	1.9	2900	59	9.3	3.5	120	160	580	1.7	39	6900
			Waikato Council, October 2012											
72_2227(mokena)	Mokena	90	8.5	1.97	3100	70	6.0	3.8		154	640	1.81	410	6940
72_2214(Foot pool)	Pool 14	40	7.5	1.52	2400	53	9.8	5.7		117	490	1.41	320	5500
72_2951 (MotorCamp)	Camp	23	7.5	0.0128	45	5	10.5	7		0.057	11.1	0.37	0.5	197
72_2226 (Bath)	Bath	45	7.5	1.96	3200	70	9.0	3.6		157	630	1.77	390	7290
New Wilson St (64_512)	Wilson	53	7.4	1.95	3100	69	20.0	4.3		148	580	1.74	3800	6700

Table 2. Chemistry bore data from Michels (1993) and Waikato Regional Council
2* and 11* were analyzed by RJ Hill Laboratories while others by University of Auckland

The composition of the constituents from all the bores is similar, indicating that they tap the same source. This is, however, not true for SP-20, SP-21and the motor camp bore, which are cold ground water. This is explained by the high magnesium and low chloride levels and low temperatures from the two bores. The moderate chloride and magnesium levels and moderate temperature of Sp-8 suggests that it is likely to have been diluted by near-surface cold ground water.

Henderson (1938) and Healy (1956) suggested that the driving mechanism for the well discharges was not flashing of steam but a periodic build-up of CO_2 since the bottom temperatures in the geysering wells were below boiling point.

Samples taken and analysed in April 1993 indicated that the waters could be originating from the Kaimai ranges. Lyon and Giggenbach (1992) interpreted the ^{18}O shifts and low (<150 °C) cation temperatures (Na/K Giggenbach) as partial re-equilibration along flow paths, and thus concluded that the springs of Te Aroha Domain could be an outflow.

Temperature with depth profiling was conducted and it was determined that the temperature profiles of the wells were different. The profiles of two of the wells are shown in Figure 9.

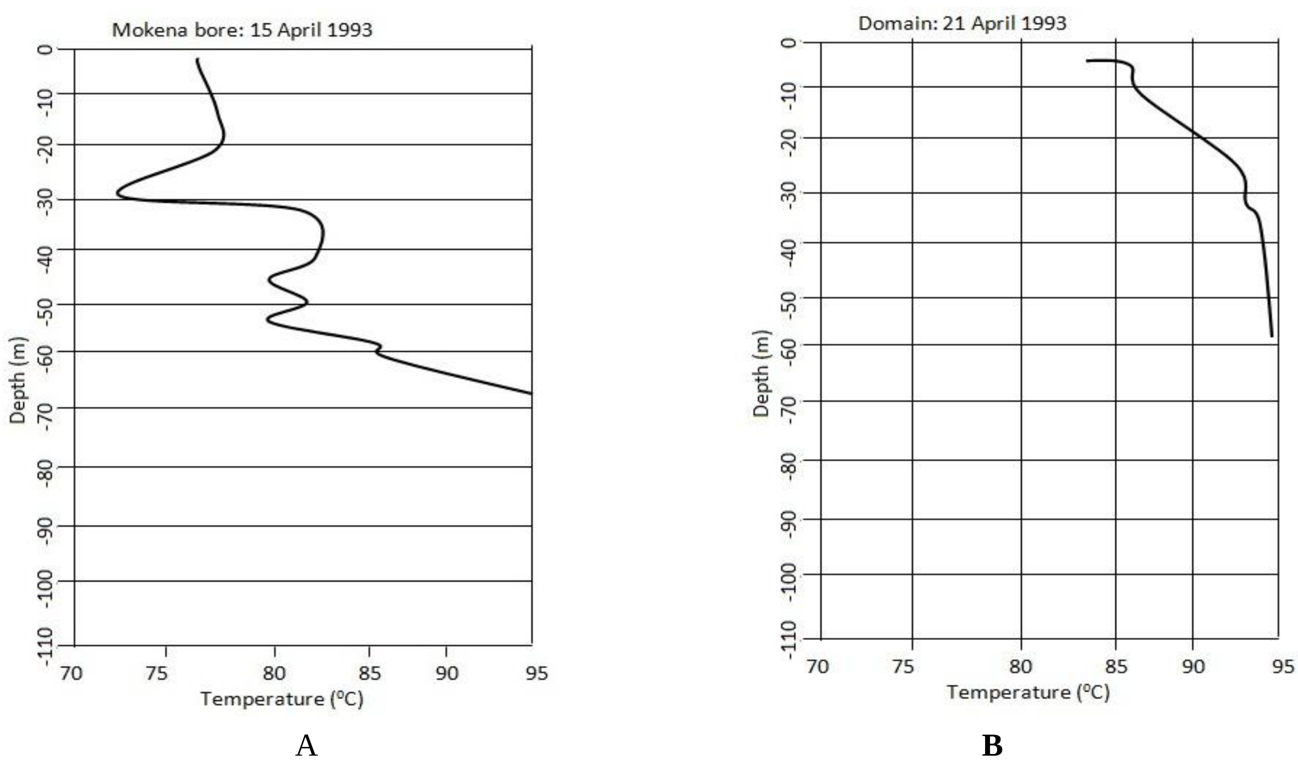

Figure 9. Temperature-depth profiles of Mokena and Domain Trust bores (Michels, 1993).

Graph A on Figure 9 shows the temperature profile of Mokena geyser. The geyser is cased to 30 m while the rest of the borehole is open hole. From the graph, there is a sudden temperature drop at 32 m and this can be attributed to the cold water inflow. Another cold water inflow in the geyser is noticed at about 50 m but a constant temperature gradient below 50 m is maintained.

The temperature profile of the Domain Trust bore is shown in graph B. This well was cased at 40 m, thus shielding the inflow of the cold water at 30 m. A slight temperature drop can, however, be noticed at 30 m as the water flows to the surface. This can be attributed to the cooling of the casing by cold ground water. There is, however, a very gentle temperature gradient below 30 m, which indicates that the zone could be highly permeable.

METHODOLOGY

Geothermometers

Geothermometers are used to estimate subsurface temperatures in geothermal systems by analyzing the concentrations of constituents from the subsurface. They are all based on the assumption that (Utami Chemistry lecture notes, 2012):

- Temperature-dependent reaction and fluid-mineral equilibrium occur in the geothermal reservoir.
- There is adequate supply of solid phases for the fluid to be adequately saturated with the constituents used for geothermometry.
- No mixing of hot and cold water occurs as water flows to the surface.

Some of the processes that may affect geothermometers include:

- Lack of equilibration with a particular mineral
- Different rates of equilibration reaction between minerals and water
- Boiling and condensation during upflow.

Geothermometers have been classified into three groups:

- Liquid geothermometers – Includes silica and cation geothermometers.

Silica geothermometers include quartz, chalcedony (Fournier, 1981)

Cation geothermometers include Na/K (Fournier, 1981 and Giggenbach, 1988) and Na-K-Ca (Fournier and Truesdell, 1973).

- Gas geothermometers – Includes Fischer-Tropsch and Hydrogen/Argon (H/Ar) geothermometers. The Fischer-Tropsch gives high temperatures estimates while H/Ar is limited by air entrapment, second-stage boiling, magmatic vapours and drilling using aerated water.

- Isotope geothermometers – Uses isotopes e.g $^{16}O/^{18}O$

Silica (quartz) geothermometers

These are based on the solubility of quartz, which is dependent on pressure, temperature and salinity. However, at temperatures below 300 °C, and at large depths, variations in pressure at hydrostatic conditions have little effect on the solubility of quartz and amorphous silica (Fournier and Potter, 1982; Fournier and Rowe, 1966). These geothermometers are best suited for well waters with subsurface temperature range of 100-250 °C (Fournier, 1981).

Some factors should be considered when using quartz geothermometers (Fournier and Potter, 1982):

- The temperature range in which the equations are valid;
- Possible polymerization or precipitation of silica before sample collection;
- Possible polymerization of silica after sample collection;
- Control of aqueous silica by solids other than quartz;
- The effect of pH on quartz solubility;
- Possible dilutions of hot water with cold water before the thermal waters reach the surface.

Fournier (1981) indicated a quartz geothermometer with a maximum steam loss and no steam loss at 100 °C as a function of silica concentration (SiO_2) in mg/kg:

Quartz-maximum steam loss

$$T = (1522/(5.75\text{-}\log(\mathrm{SiO_2}))) - 273.15 \ldots\ldots\ldots..1$$

Quartz- no steam loss

$$T = (1309/(5.19\text{-}\log(\mathrm{SiO_2}))) - 273.15 \ldots\ldots\ldots.2$$

Where T - temperature in ^{o}C

Cation geothermometers

These are based on ion exchange reactions with a temperature – dependent equilibrium constant.

Na/K geothermometers work best at temperatures greater than 180 ^{o}C.

Fournier in 1981 presented a function of Na-K geothermometer as:

$$T = (1217/(\log(Na/K) + 1.483)) - 273.15 \ldots\ldots\ldots..3$$

The Na-K geothermometer function presented by Giggenbach in1988 is expressed as:

$$T = (1390/(\log(Na/K) + 1.75)) - 273.15 \ldots\ldots\ldots...4$$

Fournier and Truesdell (1973) developed the equation for the Na-K-Ca geothermometer that can be used to both low-temperature and high-temperature geothermal reservoirs and is expressed by:

$$T = (1647/(\log(Na/K) + \beta(\log((\sqrt{Ca})/Na) + 2.06) + 2.47)) - 273.15 \ldots\ldots\ldots..5$$

Where T – temperature in ^{o}C

$\beta = 4/3$ when calculated temperature is >100 °C;

$\beta = 1/3$ when calculated temperature is < 100 °C.

The Na-K-Ca geothermometer may give erroneous calculated temperatures due to boiling and mixing with cold water and gives high estimates when applied to waters rich in magnesium. Boiling results in loss of CO_2, which causes $CaCO_3$ to deposit.

Classification of thermal waters

Cl-SO_4-HCO_3 ternary diagram

This diagram classifies geothermal waters using the major anion concentrations (Chlorides, Sulphates and bicarbonates) (Giggenbach, 1988) and also helps distinguish the waters as mature, peripheral and volcanic and steam-heated waters. 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, bicarbonates contents increasing with time and distance travelled underground (Giggenbach, 1988).

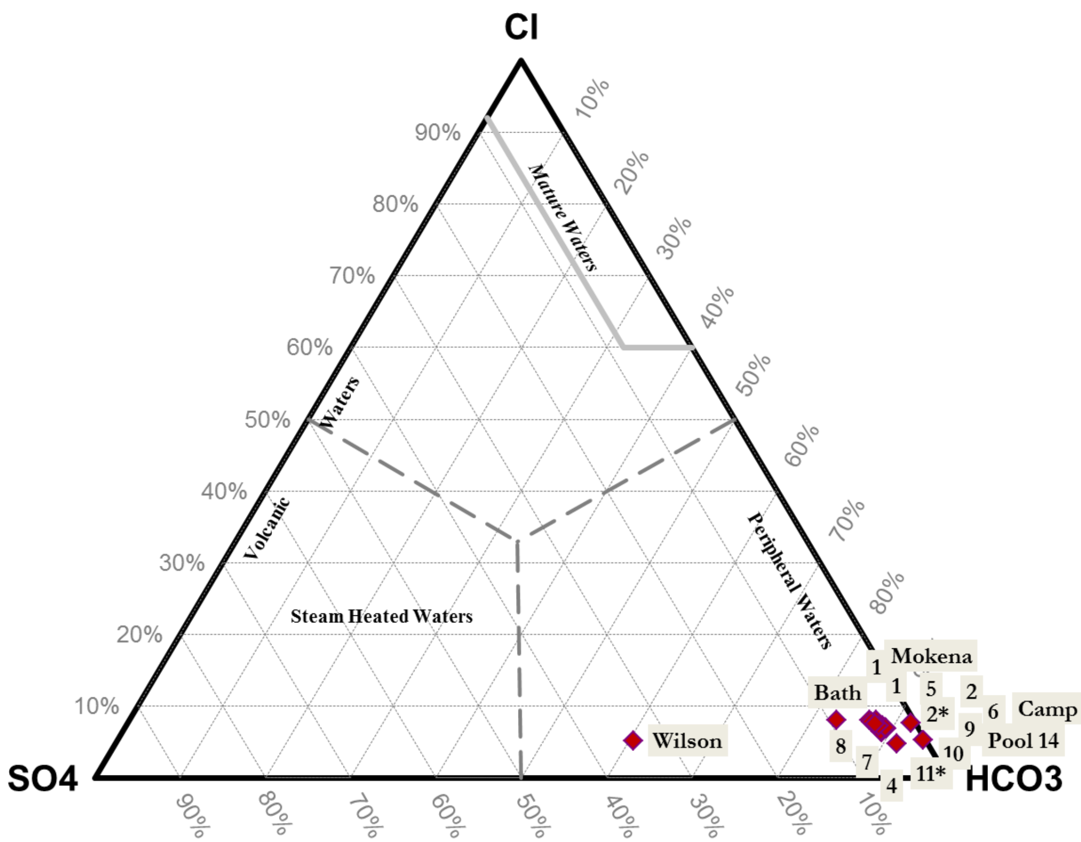

Figure 10. Cl-SO_4-HCO_3 ternary diagram (Giggenbach and Goguel, 1989).

Na-K-Mg triangular diagram

This triangular diagram classifies waters 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 that plots on the full equilibrium in the diagram indicate attainment of water-rock equilibrium. Plotting on the partial equilibrium indicates either a mineral that has dissolved but has not attained equilibrium, or geothermal water that has reached equilibrium with dilute unequilibrated cold water. Immature water indicates initial dissolution of minerals before equilibrium reaction begins. Data points that plot 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 that 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 geoindicator (Powell T and Cumming W, 2010).

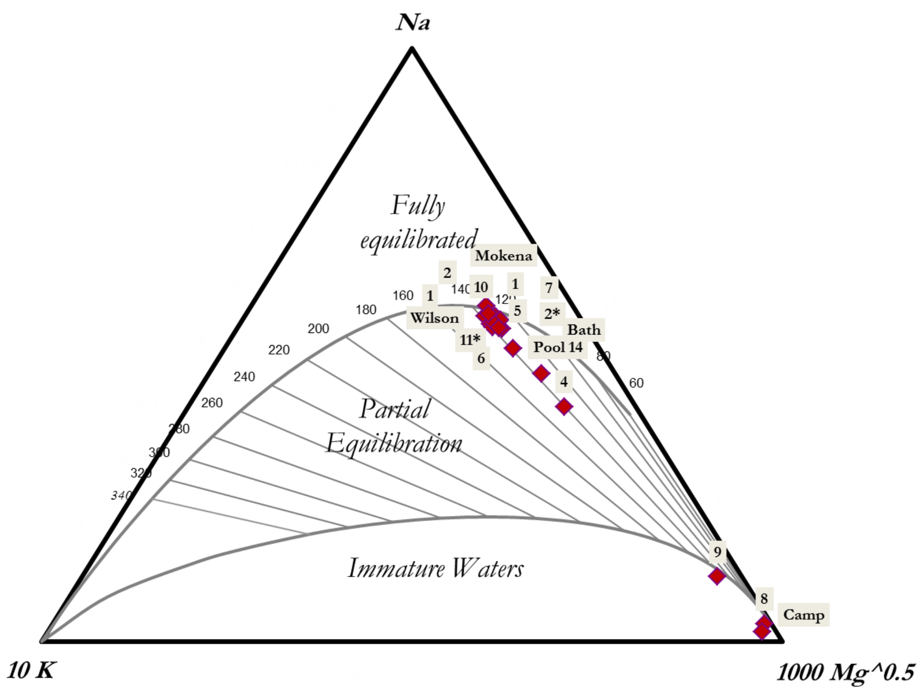

Figure 11. Na-K-Mg ternary diagram (Giggenbach, 1991a)

Cl-Li-B ternary diagram

Lithium is the alkali metal least affected by secondary processes. It is therefore used as a tracer for the initial deep rock dissolution process and to evaluate the possible origin of two important conservative constituents of geothermal water. The boron content of thermal fluids reflects the degree of maturity of a geothermal system. It is expelled during the early stages of heating up due to its volatility. Fluids from older hydrothermal systems therefore have less boron content but higher content for younger hydrothermal systems. At high temperatures, chloride occurs as hydrochloric acid (HCl) and boron as boric acid (H_3BO_3), and both are volatile and able to be mobilized by high temperature steam. At lower temperatures, the acidity of HCl rapidly increases and it is changed by the rock to the less volatile NaCl but B remains in its volatile form and is carried to the surface in the vapour phase. The Cl/B ratio is used to indicate a common reservoir source for the waters. Caution should, however, be taken in applying this interpretation because waters from the same reservoir can show differences in Cl/B ratio due to changes in lithology at depth in a field (e.g. the introduction of a sedimentary horizon), or by the absorption of B into clays during lateral flow.

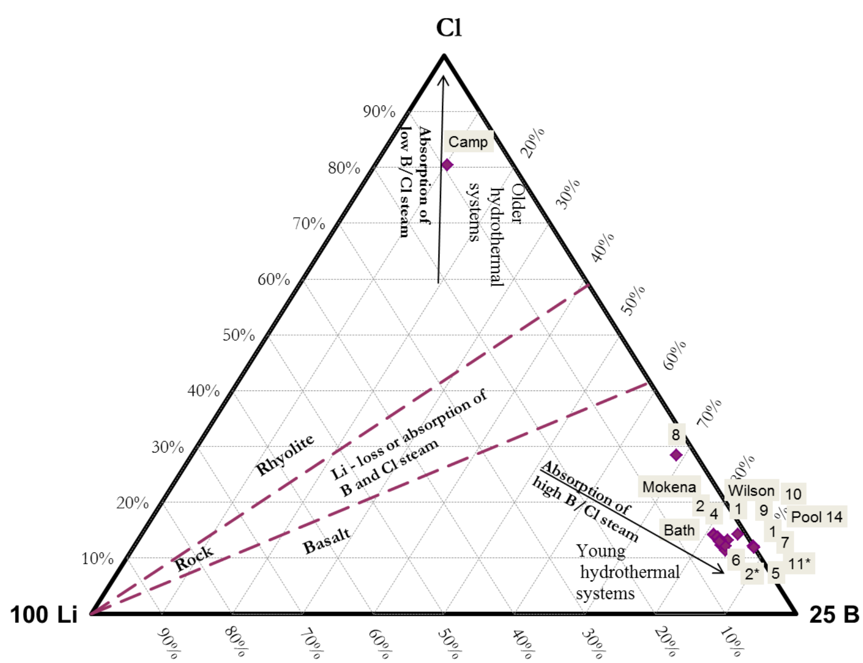

Figure 12. Cl-Li-B ternary diagram (Giggenbach, 1991a)

RESULTS AND DISCUSSION

In order to classify the Te Aroha waters, the concentrations of Cl-SO_4 and HCO_3 of the bore waters were plotted in Figure 10. All the bore waters plotted on the bicarbonate corner indicating they have high HCO_3 relative to SO_4 and Cl. Wilson Street bore, however, had high SO_4 concentrations, thus, though plotting on peripheral waters, was near the steam heated waters. This suggests that the waters could be peripheral waters or have a high proportion of cold groundwater.

From the Na-K-Mg triangular diagram shown in Figure 11, it is notable that the waters from most of the wells are partially equilibrated except the motor camp bore and wells 9 and 8, which plotted on the immature waters. Some of the waters are on the margin of partial equilibration and full equilibration. This indicates a direct and quick path to the surface with little dilution or contamination. Waters from Sp-8 and foot pool 14 shows high level of dilution from ground water or partial equilibration. The waters from the motor camp and SP-20 and SP-21 have low temperatures, high magnesium and low chloride levels; an indication that these waters are cold ground waters.

Figure 12 shows a plot of boron-lithium-chloride. Mass ratios of concentrations like Cl:B and Na:Li indicate homogenous fluid source at depth. All the thermal water samples indicate a high B concentration relative to Li and Cl. This means that they are from a relatively young hydrothermal system, with absorption of high B/Cl magmatic vapour into the system. The motor camp bore, however, plotted on the chloride corner because the waters had very low levels of boron and moderate chloride levels indicating absorption of low ratios of B/Cl.

Using the geothermometry methods, subsurface temperatures from the data in Table 2were calculated using equations 1-5 above and the results are shown in Table 3 below.

Geothermometers										
Temperatures in degrees C										
Sample Name	Amorphous Silica	Chalcedony cond	Quartz cond	Quartz adiabatic	Na-K-Ca	Na-K-Ca Mg corr	Na/K Fournier	Na/K Truesdell	Na/K (Giggenb ach)	K/Mg (Giggenb ach)
DTB	21	115	142	136	167	72	118	71	138	137
DTB	32	129	154	147	155	59	111	63	131	131
MOKENA	33	130	155	147	159	52	111	63	131	131
MOKENA	25	120	146	140	158	68	111	63	132	135
SP-15	20	114	141	135	164	71	118	72	139	135
SP-13	18	112	138	134	158	42	118	72	139	128
SP-14	20	115	141	136	161	68	119	72	139	134
SP-8	8	100	128	125	148	11	120	73	140	114
SP-21	-4	84	114	112	129	-29	132	87	152	72
SP-20	-19	66	96	97	61	-157	133	88	153	42
Mokena	25	120	146	140	155	60	114	66	134	130
Mokena	26	122	148	141	154	59	110	63	131	130
72_2227(mokena)					164	59	116	69	136	134
72_2214(Foot pool)					154	-6	115	67	135	119
72_2951 (MotorCamp)					81	-177	226	199	241	56
72_2226 (Bath)					159	70	114	67	134	135
New Wilson St (64_512)					153	71	115	68	135	131

Table 3. Estimates of reservoir temperatures from geothermometers using equations 1-5.

For all the bores analysed, temperatures were less than 100 °C. Both of the quartz (no steam loss and maximum steam loss) geothermometers are suitable for temperatures between 100-250 °C while the Na-K cation geothermometer is best for temperatures above 180 °C. The Na-K and quartz geothermometers therefore cannot be used in this case. Na-K-Ca is, however, recommended for such temperatures.

The geothermometry methods cannot be used with confidence on the motor camp bore, SP-20 and SP-21 because they are ground waters as seen from the Na-K-Mg ternary diagram.

From the Na-K-Ca geothermometry method adopted, the reservoir temperature can be estimated to be between 150-170 °C as shown in Table 4 below.

Geothermometers	
Temperatures in degrees C	
Sample Name	Na-K-Ca
DTB	167
DTB	155
MOKENA	159
MOKENA	158
SP-15	164
SP-13	158
SP-14	161
SP-8	148
SP-21	129
SP-20	61
Mokena	155
Mokena	154
72_2227(Mokena)	164
72_2214(Foot pool)	154
72_2951 (MotorCamp)	81
72_2226 (Bath)	159
New Wilson St (64_512)	153

Table 4. Reservoir temperatures determined from Na-K-Ca geothermometry

CONCLUSION

The water chemistry from the majority of the wells except those exhibiting cold ground water characteristics shows that they share the same source. This is an indication of the high vertical permeability or presence of a geological structure e.g fissures or faults that the fluids follow as they flow to the surface (Figure 7). This can also be noted by the fact that most of the waters are close to full equilibration (Figure 11). It can, therefore, be inferred that the waters could have reached the surface quickly following the fault without any ground water dilution.

The geothermal waters of Te Aroha Domain are sodium-bicarbonate waters with surface temperatures ranging between 50 and 90 ^oC. Minimal or no changes can be detected in the chemical composition of the discharging fluids from Mokena geyser between 1993 and 2012.

All the waters plotted close to boron on the Cl-Li-B ternary diagram suggesting they are from a young hydrothermal system. The motor camp bore, however, plotted at the chloride, indicating it could be from an older hydrothermal system or very low absorption of B/Cl

RECOMMENDATIONS

Chemistry analyses of other discharging bores should also be carried out at least twice a year to come up with a reliable conclusion on the chemistry trends of the fluids.

Samples of cold groundwater from the area should be analysed for a detailed study on the fluid flow characteristics to enhance modeling of the geothermal system.

Since the Na-K-Ca geothermometry estimated subsurface temperatures of between 150 and 170 ^oC, deeper bores could be drilled to tap the high temperature zone as well as reduce the dilution form ground waters.

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APPENDIX A

Bore ID : 64-276 (Domain Trust Bore)

Stratigraphic Log

Depth (m)	Primary Lithology	Secondary Lithology	Description
0 - 2	Rhyolite	Clay	broken (fractured) white
2 - 4.74	Rhyolite		broken (fractured) blue
4.74 - 19.74	Rhyolite		broken (fractured) sandy
19.74 - 28.9	Rhyolite		blue silt sandy broken (fractured)
28.9 - 33.48	Rhyolite		blue broken (fractured)
33.48 - 39	Rhyolite	Silt	broken (fractured) blue white
39 - 41.1	Rhyolite	Silt	very hard broken (fractured) blue white
41.1 - 51.77	Rhyolite	Silt	very hard broken (fractured) blue white
51.77 - 70	Rhyolite	Silt	hard broken (fractured) blue white
70 - 72.2	Rhyolite	Clay	pink
72.2 - 83.76	Sands	Rhyolite	green
83.76 - 90.33	Rhyolite	Clay	interbedded hard soft broken (fractured)
90.33 - 95			hard
95 - 105			very broken (fractured)

Bore ID : 64-398 (48 Whitaker st)

Stratigraphic Log

Depth (m)	Primary Lithology	Secondary Lithology	Description
0 - 4	Clay		
4 - 6	Clay		blue
6 - 7.5	Sands		
7.5 - 18	Sands		clean
18 - 23	Sands		green yellow
23 - 36	Sands		fine

Bore ID : 64-512 (Old Wilson st bore)

Stratigraphic Log

Depth (m)	Primary Lithology	Secondary Lithology	Description
0 - 2	Clay		
2 - 25	Sands	Pumice	
25 - 48	Sands	Sedimentary Breccia-Conglomerates	very fine
48 - 60	Sands		very fine
60 - 110	Rhyolite		firm

Bore ID : 72-2227 (Mokena bore)

Stratigraphic Log

Depth (m)	Primary Lithology	Secondary Lithology	Description
0 - 11	Mud	Sands	Mud gravels & sands
11 - 40	Andesite		Highly altered andesite
40 - 49	Andesite		Highly fractured andesite with quartz & calcite veins
49 - 69.5	Andesite		Extensively altered & friable andesite with large mats of water eruptively discharged
69.5 - 69.8	Andesite		Moderately to hard highly altered andesite

Appendix B: <u>Geothermal Water Quality Site Description Sheet</u>

Site Number:	72_2227	Landownership:	Matamata-Piako DC
Feature Name:	Mokena Geyser	Road:	Off Boundary Street
Geothermal Field:	Te Aroha	Number:	
Feature Type:	Artificial Geyser	Contact:	
Map Reference:	E2750244 N6402898	Phone:	
GPS location:		Source Document:	

<u>Description</u>

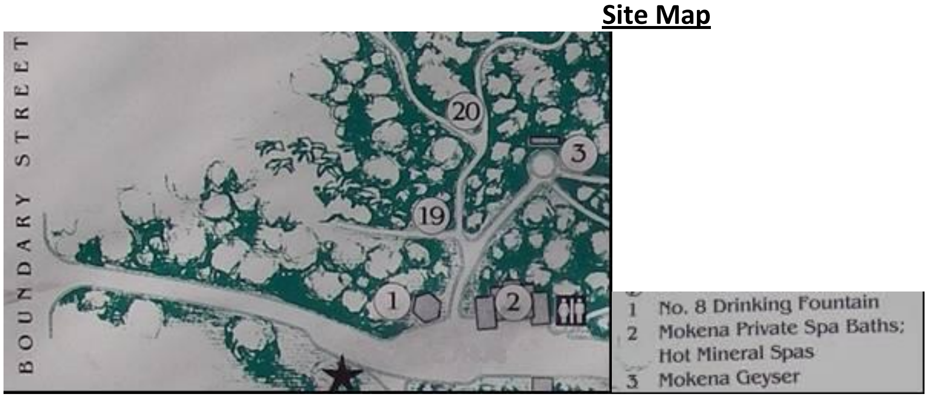
Access to Geyser is via the walking track that runs uphill beside the Mokena Private Spa Baths.

Geyser is operational between 12 and 2pm each day, though It is worth checking in Mokena Private Spa Bath's office whether geyser is switched on or off.

<u>Comments/Precautions</u>

Water was very hot ~90^{o}C with Conductivity of 11.57 millisiemens/m
Sample can be done with a sampling stick from behind the safety rail, or get key from office and open chamber beside geyser, or enter gulley behind Mokena private spa bath and sample from outlet.

<u>Site Map</u>



Site Number:	72_2251	Landownership:	Matamata-Piako DC
Feature Name:	Drinking spring no 8	Road:	Off Boundary Street
Geothermal Field:	Te Aroha	Number:	
Feature Type:	Mineralised cold water	Contact:	
Map Reference:	E2750203 N6402907	Phone:	
GPS location:		Source Document:	

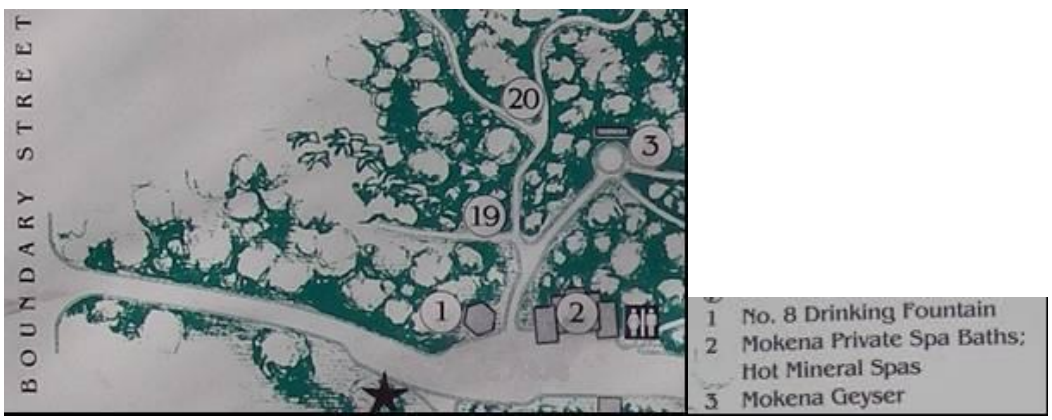
Description

Accessed via Boundary Street, Te Aroha. See attached map.
Spring is no longer fed into the drinking fountain in the octagonal gazebo labelled 1 on map. Sample from alkathene pipe coming out of low bank immediately behind gazebo.

Comments/Precautions

Water is cold and slightly alkaline with strong mineral taste.
It is a spring.

Site Map



Site Number:	72_2214	Landownership:	Matamata-Piako DC
Feature Name:	Foot pool spring 14	Road:	Off Boundary Street
Geothermal Field:	Te Aroha	Number:	
Feature Type:	Geothermal bore	Contact:	
Map Reference:	E2750290 N6402753	Phone:	
GPS location:		Source Document:	

Description

Go to swimming pool shown in photo. Behind it is an octagonal gazebo. Wellhead is in a recess under a plate on the ground behind the gazebo. Actual foot bath is further down the hill.

Comments/Precautions

Water was ~40°C with Conductivity of 8.84 millisiemens/m
The Water is not sampled from the well itself.

Site Map

Site Number:	**72_2226**	**Landownership:**	Matamata-Piako DC
Feature Name:	**bath-house no. 2 spring**	**Road:**	Off Boundary Street
Geothermal Field:	**Te Aroha**	**Number:**	
Feature Type:	**Geothermal Spring**	**Contact:**	
Map Reference:	E2750273 N6402752	**Phone:**	
GPS location:		**Source Document:**	

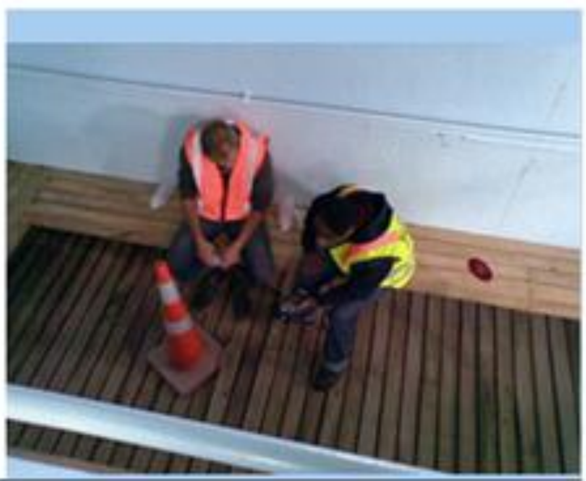
Description

Bath house is adjacent to outdoor swimming pool. It is not in use and is locked. Raise a board in the floor of the pool to access the water, which bubbles up from the ground in the base of the pool.

Comments/Precautions

Water was ~45°C with Conductivity of 11.31 millisiemens/m
No gas hazard in the pool.

Site Map



Site Number:	**64_512**	**Landownership:**	Matamata-Piako DC
Feature Name:	**New Wilson St bore**	**Road:**	Off Boundary Street

Geothermal Field:	Te Aroha	Number:	
Feature Type:	Artesian bore	Contact:	
Map Reference:	E2750316 N6402709	Phone:	
GPS location:		Source Document:	

Description/sample method

5 m from old Wilson St bore (Bore 20).
Opposite square grey house, 3rd house from top of road
Sampled from outlet in gulley immediately behind bore

Comments/Precautions

When allowed to discharge vertically, goes 2 -3 m up. Water was ~53 ^{o}C but when allowed to flow freely for an extended time (hours) gets up to 74 deg. Flow = 1000 L /45 min
Conductivity 11.36 millisiemens/m

Site Map

Site Number:	**72_2951**	**Landownership:**	Matamata-Piako DC
Feature Name:	**Motor camp bore**	**Road:**	217 Stanley Rd South
Geothermal Field:	**Te Aroha**	**Number:**	
Feature Type:	**Warm bore**	**Contact:**	
Map Reference:	E2750571 N 6400285	**Phone:**	
GPS location:		**Source Document:**	

Description

From Te Aroha main road, turn first right onto Stanley Rd South. Past the racecourse and Silver Fern Farms, the motor camp has big flags and is on the left.
Bore is in paddock at back of farm.

Comments/Precautions

Water was 23 ^{o}C.
Sample from outlet to spa.

Site Map

Site Number:	**72.2225**	**Landownership:**	**Matamata-Piako DC**
Feature Name:	**Spring 15**	**Road:**	**Off Boundary Street**
Geothermal Field:	**Te Aroha**	**Number:**	
Feature Type:	**Geothermal bore**	**Contact:**	
Map Reference:	E2750273 N6402758	**Phone:**	
GPS location:		**Source Document:**	

Description

Go to swimming pool shown in photo. Behind it is an octagonal gazebo with a hand pump. 10 m from spring 14.

Comments/Precautions

Pump is broken you can't sample the bore.

Site Map

Site Number:	72_2116	Landownership:	Matamata-Piako DC
Feature Name:	Spring 13	Road:	Off Boundary Street
Geothermal Field:	Te Aroha	Number:	
Feature Type:	Geothermal Spring	Contact:	
Map Reference:	E2750300 N6402753	Phone:	
GPS location:		Source Document:	

Description

Go to swimming pool. Behind it is an octagonal gazebo. Spring 13 is behind it under a metal plate. 2 m left of spring 14.

Comments/Precautions

No longer in use

Site Map

Site Number:	**64_512**	**Landownership:**	**Matamata-Piako DC**
Feature Name:	**Old Wilson St bore**	**Road:**	**Wilson St**
Geothermal Field:	**Te Aroha**	**Number:**	
Feature Type:	**hot water bore**	**Contact:**	
Map Reference:	E2750319 N6402716	**Source Document:**	
GPS location:			

<u>Description</u>

5 m from new Wilson St bore
Opposite square grey house, 3rd house from top of road.

<u>Comments/Precautions</u>

Not been opened for many years

<u>Site Map</u>

Site Number:	72_2247	Landownership:	Matamata-Piako DC
Feature Name:	Wilson St Bore No 21	Road:	Wilson St
Geothermal Field:	Te Aroha	Number:	
Feature Type:	Cold water bore	Contact:	
Map Reference:	E2750397 N6402754	Phone:	
GPS location:		Source Document:	

Description

From Wilson St new bore take bush track uphill about 50 m. There are 2 hand pumps for bore 21 at different locations. Neither works. This is opposite the last house on Wilson St.

Comments/Precautions

Water was 15 deg and Conductivity 961 Microsiemens/m
Can't sample.

Site Map

Site Number:	72_2248	Landownership:	Matamata-Piako DC
Feature Name:	Spring with iron water	Road:	Wilson St
Geothermal Field:	Te Aroha	Number:	
Feature Type:	Cold water spring	Contact:	
Map Reference:	E2750471 N6402811	Phone:	
GPS location:		Source Document:	

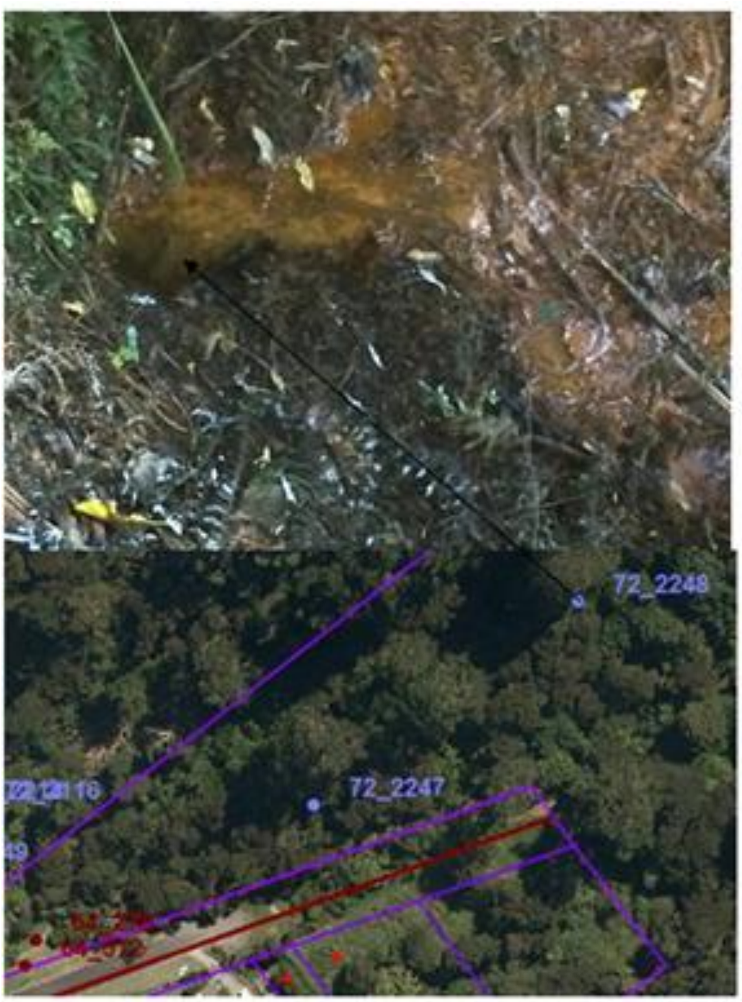
Description

From bore 21 take bush track uphill. Turn left at junction and continue along for about 5 min. Spring is at bottom of 1.5 m cutting. Discharges about 100 ml/s.

Comments/Precautions

Water was 20.3 deg with conductivity of 387 Microsiemens/m
Can't sample.

Site Map



Site Number:	**72_2252**	**Landownership:**	**Matamata-Piako DC**
Feature Name:	**Bore**	**Road:**	**Whitaker St**
Geothermal Field:	**Te Aroha**	**Number:**	
Feature Type:	**Domain bore**	**Contact:**	
Map Reference:	E2750110 N6402725	**Phone:**	
GPS location:		**Source Document:**	

Description

On verge, just inside shrub border, by boundary between whitaker st and bowling greens. Covered by a green cylinder.

Comments/Precautions

Couldn't sample.

Site Map

Site Number:	**no number**	**Landownership:**	**Matamata-Piako DC**
Feature Name:	**Spring 18**	**Road:**	**Off Boundary Street**
Geothermal Field:	**Te Aroha**	**Number:**	
Feature Type:	**Geothermal Spring**	**Contact:**	
Map Reference:	**E2750280 N6402808**	**Phone:**	
GPS location:		**Source Document:**	

Description

Spring water used to come out from a tunnel. Tunnel has now collapsed. Only a pipe coming out from the hill now. Can't sample.

Comments

Site Map

Site Number:	**no number**	**Landownership:**	**Matamata-Piako DC**
Feature Name:	**Spring 12**	**Road:**	**Off Boundary Street**
Geothermal Field:	**Te Aroha**	**Number:**	
Feature Type:	**Geothermal Spring**	**Contact:**	
Map Reference:		**Phone:**	
GPS location:		**Source Document:**	

Description

Area is now flat benched campervan sites.

Comments/Precautions

No sign of spring.

Site Map

Site Number:		**Landownership:**	**Matamata-Piako DC**
Feature Name:	**Bath house 6**	**Road:**	**Off Boundary Street**
Geothermal Field:	**Te Aroha**	**Number:**	
Feature Type:	**Geothermal Spring**	**Contact:**	
Map Reference:		**Phone:**	
GPS location:		**Source Document:**	

Description/sample method

According to Peter Jonkers, Pools staff member, it has been demolished.

Comments/Precautions

No sign of spring.

Site Map