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The Waikite Thermal Valley, New Zealand

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ABSTRACT

The Waikite thermal valley is located in the centre of the Taupo Volcanic Zone (TVZ) of New Zealand about 25 km to the south-east of Rotorua city. Many natural thermal springs At Waikite discharge near-boiling water along the local NE-SW Paeroa Fault in what appears as a fault-dominated high-temperature two-phase geothermal system. Current hypotheses suggests that Waikite thermal futures are an extended outflow of the nearby Waiotapu geothermal system. However, more recent assessment indicates that Waikite is an isolated liquid dominated hot water (<220 °C) system or simply another smaller upflow from Waiotapu. In both settings the Paeroa Fault simply provides access to the outflowing geothermal fluids to reach the surface at near-boiling temperature. The natural thermal springs have a unique mineral deposition of lilypad-shaped formations that extend over the water surface. They consist of mainly calcite crystals, and are not found elsewhere in the high-temperature systems of the TVZ.

The Waikite thermal valley is known for its thermal bathing facility. Hot mineral water is channeled from one of the near-boiling discharging natural springs under gravity into a long man-made terrace to cool by evaporation. Additionally, fine temperature control is provided through controlled spraying some of the mineral water into the air using a small pump. At the end of the terrace, the mineral water flows into six hot pools and baths. It is also used in a heat exchanger for heating fresh water for the showers, bathrooms and kitchen. The used thermal water is discharged into the hot Otamakokore Stream, which it would naturally flow to. This eventually flows into the Waiotapu Stream, which is also naturally geothermally-influenced, and then to the Waikato River.

1. INTRODUCTION

The tectonic setting of New Zealand has produced approximately 129 geothermal fields (Mongillo and Clelland, 1984), some of which are used in a variety of ways including electricity production, direct heat use for primary production and industrial processes, recreational facilities and some are set aside for ecological and geodiversity protection.

On the North Island of New Zealand, the Taupo Volcanic Zone (TVZ) hosts dominantly young rhyolitic heat sources caused by the near-surface intrusion of magma. All but one of the nation's 21 recognised high-temperature geothermal systems are found here. At 5 km depth, heated fluids can reach 350 °C in some places. An overview of the TVZ is presented in Figure 1.

All the geothermal systems present in the TVZ have been classified by the two local government bodies responsible for their environmental management, the Waikato and Bay of Plenty Regional Councils, into usage categories. These categories depend on the size of the system, any existing uses, and the number of surface geothermal features vulnerable to large-scale extractive use. The categories can be described as Development Systems, Limited Development Systems, Research Systems, Protected Systems and Small Systems.

The Waikite geothermal field is part of the Waikite-Waiotapu-Waimangu geothermal system, which is classified as a Protected Geothermal System, and lies within the Waikato Region. (Waikato Regional Council, 2011). A natural thermal bathing complex, Waikite Valley Thermal pools, was established in 1972 with the help of local volunteers and fundraising. The bathing complex has a permit for minor uptake and discharge of geothermal fluid and groundwater. The facility benefits the local community through employment, provision of recreational facilities, and the input of tourist dollars to the local economy. The business also includes a café and campground. The Waikite Valley Thermal pools are located 25 km south of Rotorua, a major tourist town of New Zealand.

The geothermal fluid is taken from springs and used in the thermal pools, then discharged into the hot Otamakokore stream, which it would naturally flow to. This eventually flows into the Waiotapu Stream, which is also geothermally-influenced, and then to the Waikato River.

The geochemistry of the springs' discharge has been analyzed to investigate what the source of these fluids might be and to which geothermal system the Waikite Valley belongs to. The resistivity boundaries of the surrounding area in the TVZ have been assessed extensively in previous research and are shown in Figure 2. This provides insight into the geophysics of the area and could be used to gain more understanding of the possible linkages of the geothermal fields in the area. A summary of these aspects will be presented and, subsequently, a description of the natural features and fundamental elements of the Waikite Valley thermal pools will be provided in the following assessment. An overview of the surface geology and distribution of hot springs around the Waikite area is given in Figures 2 and 3.

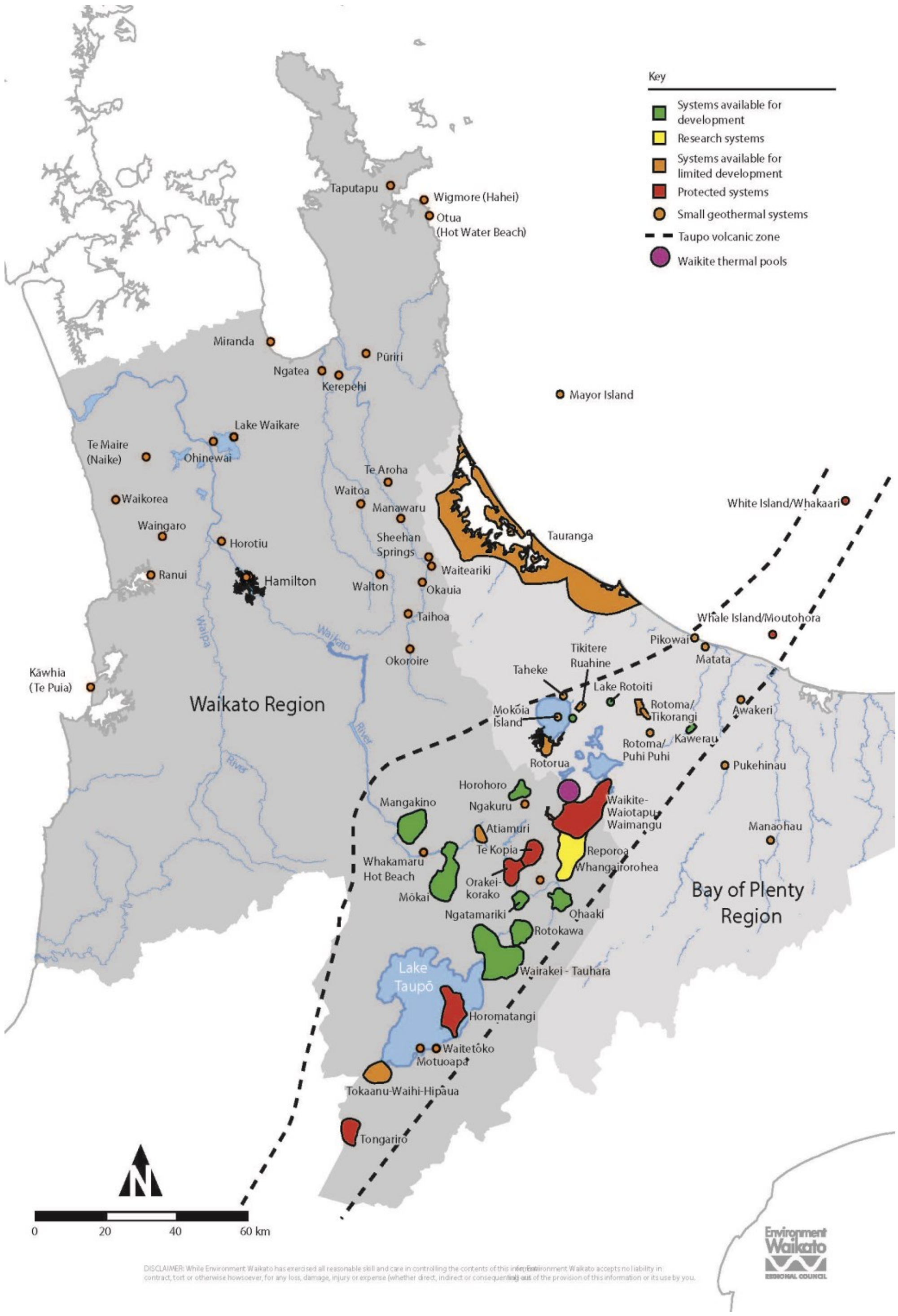

Figure 1. The distribution of geothermal systems within the TVZ, with study area marked in pink © Waikato Regional Council

2. GEOLOGY

The TVZ contains 29 geothermal areas, of which 19 geothermal fields have a natural heat output exceeding 20 MW of thermal energy (MWth) (Bibby, 1995). It is about 300 km long and 60 km wide (Figure 1), located above the westward dipping subduction of the Pacific plate under the Australian plate, forming a rifting arc basin (Wilson et al., 1995). The basement consists of sedimentary rocks, on which volcanic deposition has occurred. The geology consists mainly of rhyolitic rocks, followed in order of abundance by dacite and andesite.

A depression between the areas of Taupo and Rotorua formed by hydrothermal eruptions exposes a heat source beneath the Tarawera volcano (Wood, 1994). The Waikite geothermal system lies within this depression, between the Paeroa and Te Weta Faults. Surface expression includes many springs that discharge near-boiling water from upflows along the Paeroa Fault (Figure 3). This fault is a major contributor to the formation of the geothermal system. There are many adjacent southwest trending faults. Figure 3 shows the distribution of geothermal locations along the Paeroa fault. Outflow from the Waiotapu area terminates near the Te Weta Fault.

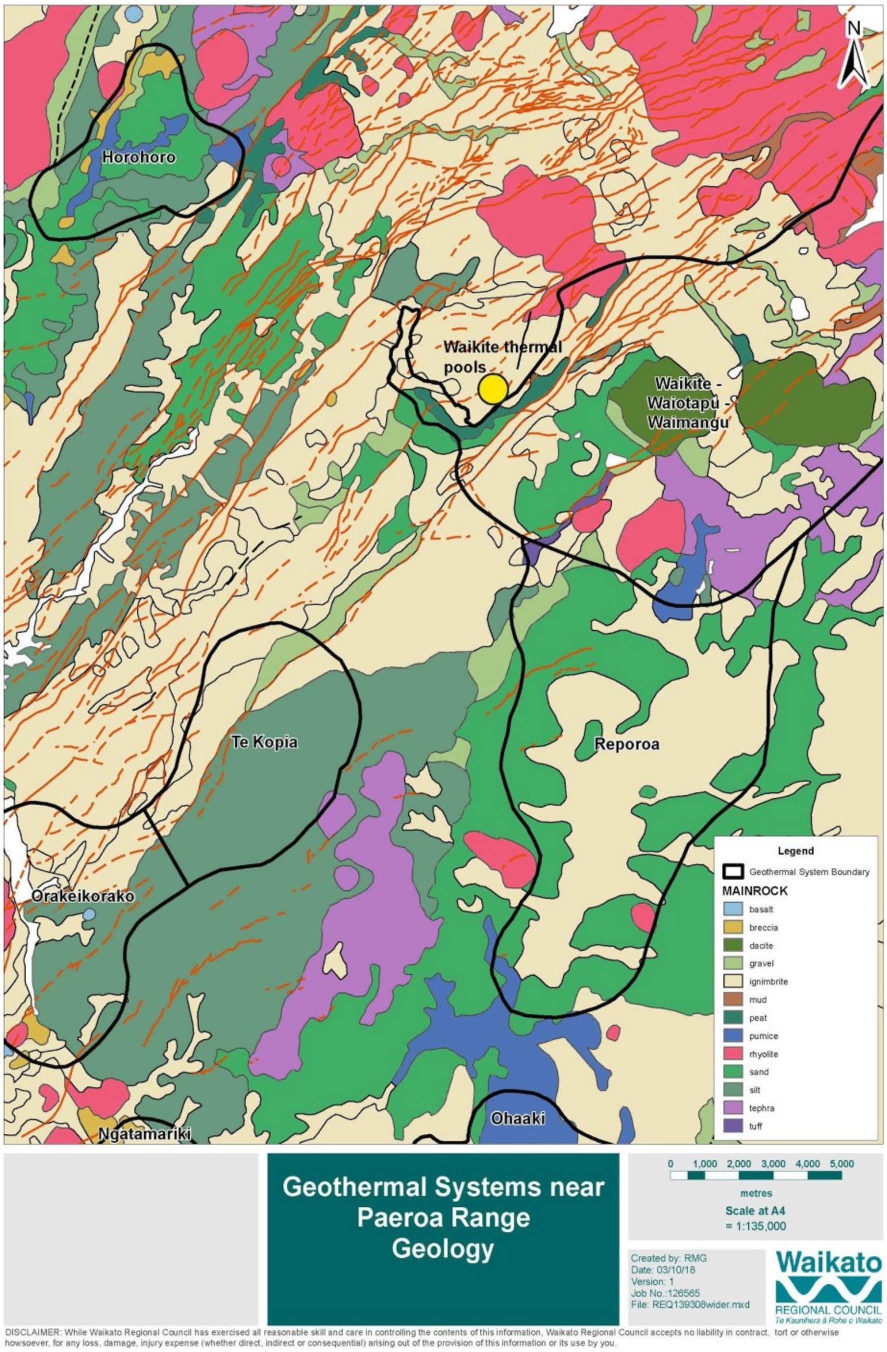

Figure 2. The surface geology of the geothermal systems surrounding the Waikite geothermal area. (© Waikato Regional Council)

Once the water reaches the surface at Waikite, there are three paths it could have followed towards the major river systems (Bibby et al., 1995). The geothermal fluids discharged at the springs flow into the Whirinaki arm of Lake Ohakuri. This lake is a hydroelectric lake in the Waikato River. There is also a second drainage divide which has the potential to transport the water to the north of the Tarawera River, which leads to Lake Tarawera or southwards towards the Waiotapu stream and eventually Waikato River. There are two calderas in the area around the Waikite springs, Horohoro and Reporoa (Figure 2), and it is suggested these contain the heat source and provide pathways for geothermal fluids to transport this heat along faults that trace the rim of the caldera. The Waiotapu and Waikite geothermal fields lie between these calderas, in which the largest heat output takes place.

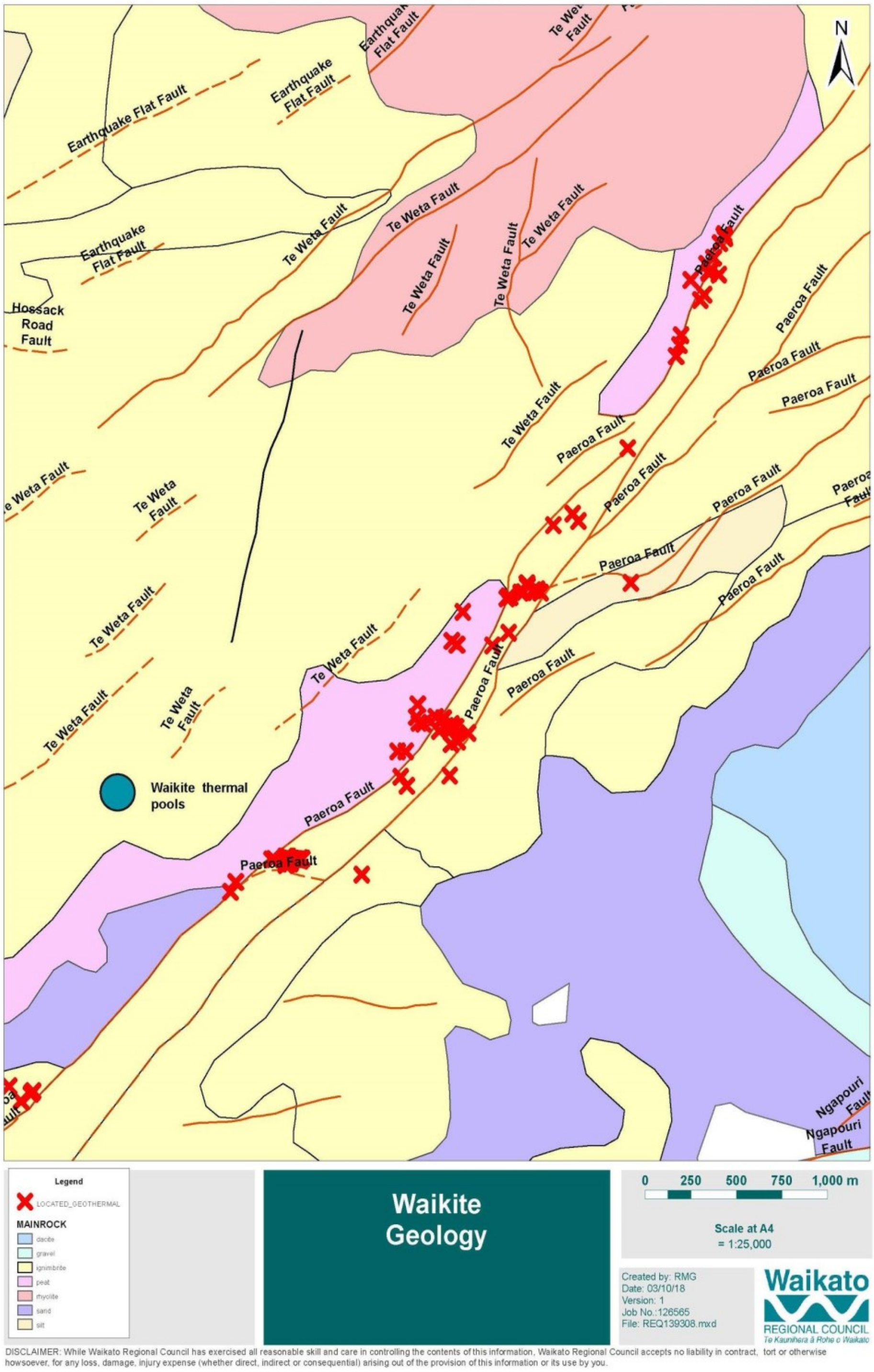

Figure 3. The distribution of geothermal surface activities along the Paeroa Fault. © Waikato Regional Council

3. GEOCHEMISTRY

Geothermal geochemistry aids in locating productive geothermal zones and assessing water quality. Comparison of concentration ratios gives information on the distribution of subsurface flows. Isotopic analysis provides information on minerals solubility and phase equilibria, which can be used to assess temperatures beneath the surface in geothermal fields (Ellis, 1977).

Overall, the soluble element ratios (Cl, Li, Br, As) differ little when comparing these to surface springs and deep wells, whilst the ratios of rock-forming elements, such as Si, Ca, Mg and K, do change significantly. This can be explained by the reaction of these elements, present in the hot fluids, with the host rocks (Ellis, 1970). Giggenbach (1988) derived a Cl-HCO_3-SO_4 ternary diagrams to define certain ratios of determining elements in geothermal fluids. This provides insight into the type and origin of geothermal fluid. As can be seen in Figure 4, the geothermal fluid present in the Te Manaroa spring, Waikite, is considered to be of peripheral origin. These are bicarbonate waters, which often occur at shallow depths, a distance away from the original source of the geothermal fluid. Te Manaroa is the largest-producing spring at Waikite, and is reputed to be produce the greatest flow rate of all geothermal springs in New Zealand. The samples taken at Te Kopia, the geothermal system ~10 km SW along the Paeroa fault (Figure 2), and observation of its geothermal surface features, suggest Te Kopia is fed by steam-heated water. The spring chemistry for the Waiotapu geothermal system (5 km SW from Waikite) plotted in Figure 4 derive from the main (Champagne) pool. From the location on the ternary diagram, it can be concluded that the Waiotapu waters coincide with mature waters, which supports the suggestion that this water is from the upflow.

The Na-K-Mg trilinear plot of geothermal fluids (Figure 5) can be used as a geothermometer. A geothermometer is a tool which can be used to assess the temperature or temperature range at which a certain geologic event or process has taken place. There are a variety of geothermometers that can be used for geothermal systems. The relative concentrations of the three constituents, Na, K and Mg are fixed at a certain temperature in a thermodynamically stable environment, which can be visualized in a trilinear plot (Giggenbach, 1986). The degree to which the fluid and host rock are in equilibrium with each other can be assessed by plotting the relative concentrations of Na-K and K-Mg. The rate at which these equilibria are found can indicate the deep geothermal system temperatures. As can be seen in Figure 5, the Na-K-Mg trilinear plot of Te Manaroa spring, gives evidence for a high, near-boiling, temperature, while the upflow of geothermal fluid at Waiotapu coincides with higher temperatures. The samples taken at Te Kopia are plotted in the immature water area (not representative of the deep system temperatures), which is expected as they are steam heated.

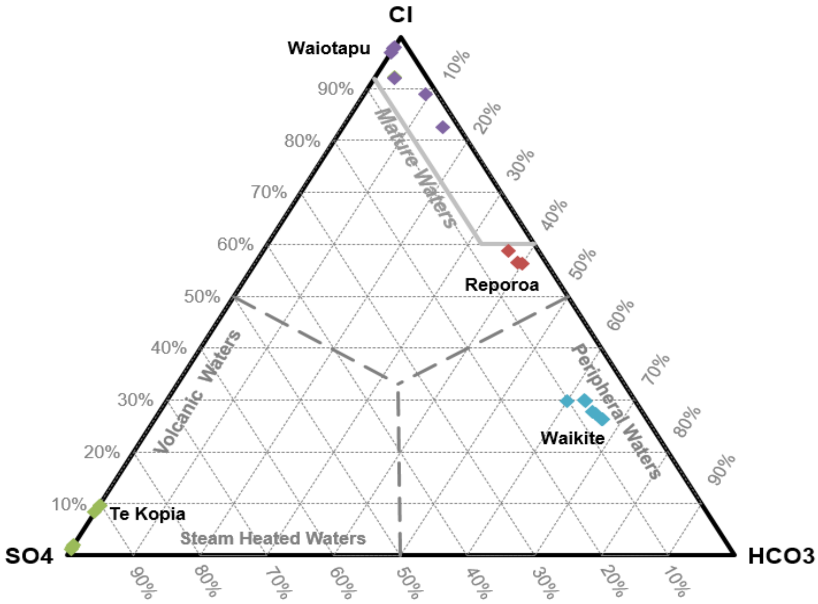

Figure 4. Cl-HCO$_3$-SO$_4$ ternary diagram of the Te Manaroa spring, Waikite.

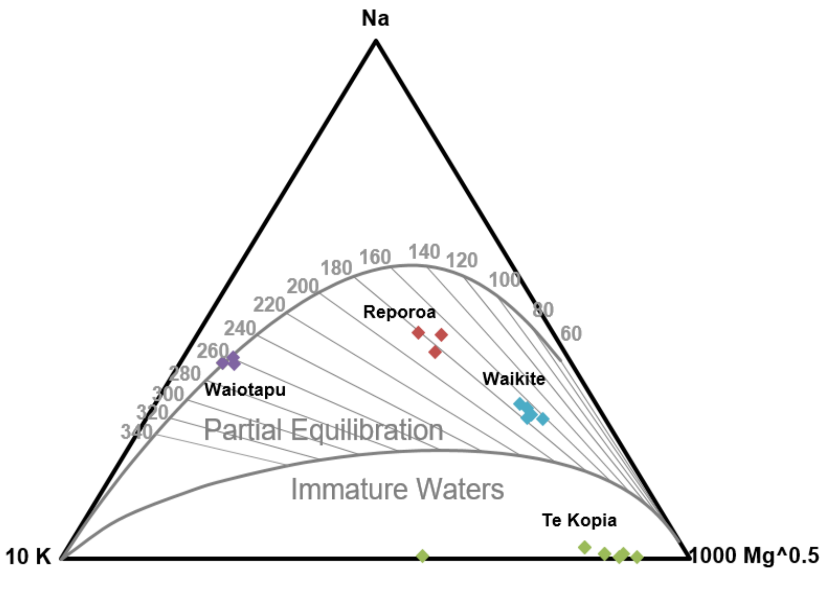

Figure 5. Na-K-Mg trilinear plot of the Te Manaroa spring, Waikite.

The analysis of chloride fluxes assumes conservation chloride ions of geothermal fluids, as the chloride flux flowing at depth within the upflow area must coincide with the summation of the chloride fluxes of rivers which are used for draining the geothermal fluids (Bibby, 1995). Chloride waters indicate direct upflow in low-relief geothermal areas, which is associated with silica deposition in the form of silica sinter. The Waikite system has, mineral depositions of mainly are travertine (calcite) rather than silica sinter (Kaya, et al., 2014). This is in favor of the suggestion that Waikite is an outflow of the upflow at Waiotapu where silica sinter is present, as is also the case further up the Waikite valley.

Both Te Kopia and Waikite have substantial silica sinter deposits in places that are up to two meters deep and occupy hectares, although much of this ancient sinter is now covered by soil and vegetation. At Te Kopia there is now almost no silica deposition occurring, and at Waikite, silica deposition occurs one kilometer further up (NE) the Waikite Valley from the bathing complex at the Scalding Spring, HT Geyser and one or two other springs. The chloride concentration in these springs is about one fifth of that of Champagne Pool at Waiotapu (Stewart 1994) and the bicarbonate concentration is quite high, indicating dilution. The outflow from Te Kopia and Waikite is clearly much less than in the ancient past. It is also possible that there is some over printing of up-flow at Wiakite on some outflow sinter deposition from Waiotapu. At Te Kopia the topography suggests that the geothermal fluid discharge was once so great as to cause a chloride-rich stream 100 meters wide and 2 meters deep cascading down the Paeroa fault scarp and into the valley. According to White *et al.* (2018), "Such a transition, from high-chloride to low chloride chemistry, demonstrates field evolution as indicated by spring outflow that shifts over time from geothermal-reservoir-dominated to cold-groundwater-dominated."

Stewart (1994) conducted geochemical analysis on water samples of all known springs in the Waikite area, which showed a linear correlation between chloride and bicarbonate concentrations. The depletion of Rb in the Waikite water samples suggested an increased uptake of the water in clays at Waiotapu due to the fact the Cl/B and Cl/As ratios of the Waiotapu and Waikite water samples coincided. There was also similarity with the chemical features of water samples taken from Te Kopia and Orakeikorako. Similar low mineralisation and Cl/HCO_3 ratios were thought to derive from similar geological and topographic settings rather than from the areas being connected (Stewart, 1994). Furthermore, the tritium concentrations indicated no connection between Waikite and Te Kopia. If this were to be the case, little dilution had been needed and no tritium should be expected.

Isotope studies on the Waikite and Waiotapu springs indicate that the Waikite springs are an outflow of the Waiotapu parent system based on analyzing stable isotopes, oxygen-18, Deuterium, and chloride concentrations of the groundwater present at both areas. The authors of that study conclude that the Waikite springs developed from a concealed outflow from the Waiotapu field in the north-west direction (Kaya et al., 2014).

4. GEOPHYSICS

Studying the geophysics of geothermal areas can give information on several important processes, such as hydrothermal alteration. Such studies include heat flow, resistivity, magnetisation, natural radioactivity, rock density and seismicity. Resistivity surveys are common and measure the ability of the earth to pass an applied electrical current. Resistivity surveys are a proxy for clay content and the extent to which alteration associated with geothermal activity has occurred. They can provide insight into the composition and solubility of the fluids present in the geothermal system. In a study by Bibby et al. (1994), Schlumberger arrays were used to examine a large part of the geothermal area within the TVZ, across an area of 650 km^2. An area of over 100 km^2 in the TVZ was found to have an electrical resistivity of less than 30 Ω m. Within this larger area, three smaller regions of an electrical resistivity less than 10 Ω m were found, which represent Waimangu, Waiotapu and Reporoa areas (Bibby et al., 1994). The Waikite field is separated from these by the high-elevation Paeroa fault range (Figure 6). It is suggested that Waimangu, Waiotapu and Reporoa form a lineament. It was found that the location of these fields did not necessarily coincide with the volcanism in the area.

The resistivity structures of the Waikite area provide evidence for the linkage of the Waiotapu and Waikite geothermal areas by addressing a deep, low resistivity structure under the high elevation ground. It is also an indicator of hot water hydrothermal alteration. However, this linkage was not always assumed, as previous models have shown incoherent resistivity structures of the two areas, bringing two separate systems to light (Kaya et al., 2014). Despite the assumptions that Waikite and Waiotapu are connected outflows from the same deep geothermal plume and that Waikite is a part of the Waiotapu geothermal system, Waikite is in fact located within another drainage system (Bibby et al, 1995).

As can be seen from the resistivity maps in Figure 6 below, it can be inferred that the Waikite geothermal field is possibly an outflow structure. If this area were an upflow structure, this would have been defined by electrical resistivity boundaries, which are not present around the Waikite area in the 500 m depth and 1000 m nominal spacing maps. The upflow zone is indicated to be near the Waiotapu area rather than the Waikite area. Therefore, the lack of a resistivity signature at the Waikite area is in favor of the suggestion that this is an outflow zone rather than an upflow area.

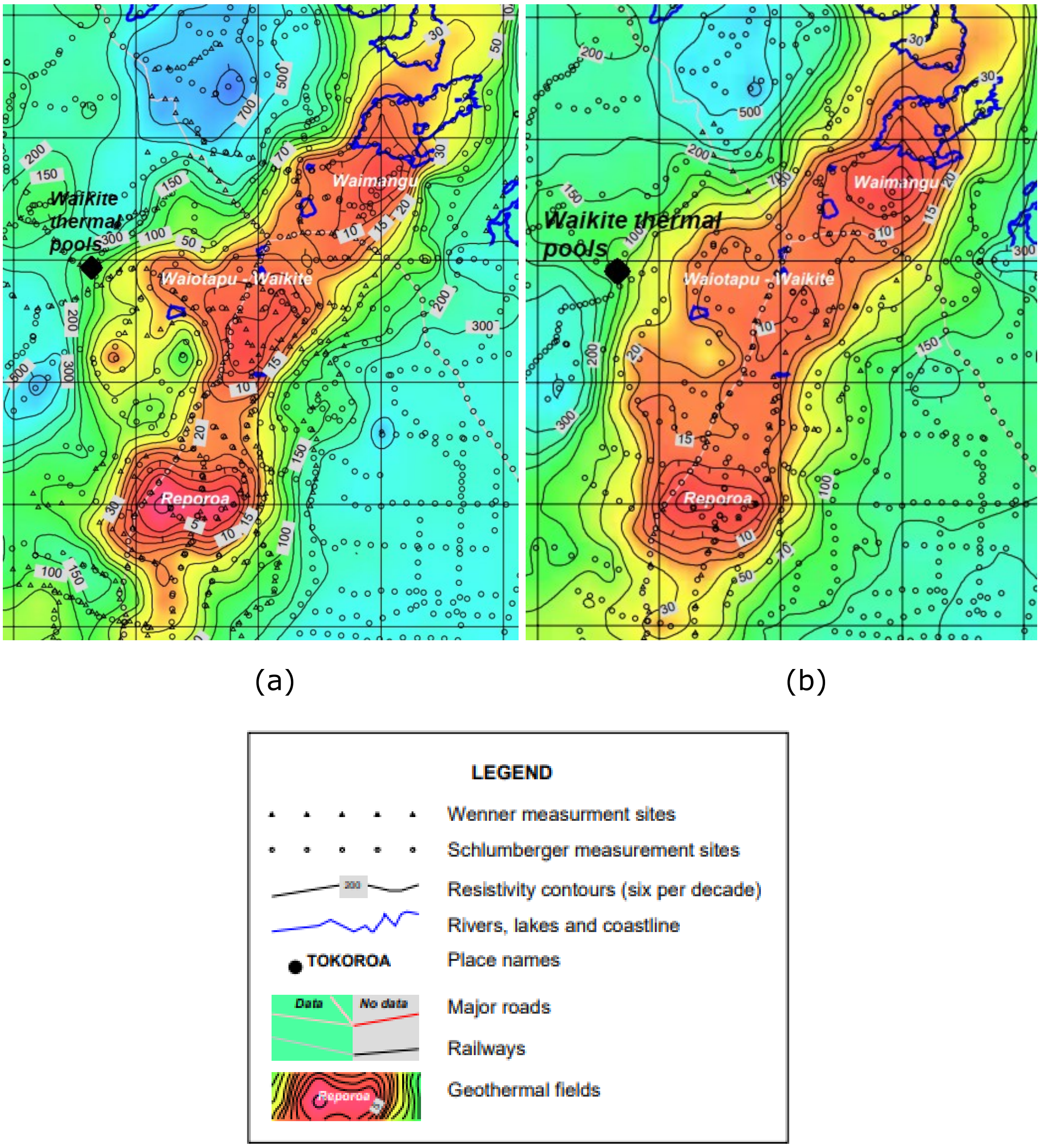

Figure 6. The resistivity map of the Taupo Volcanic Zone, New Zealand; (a) nominal array 500 m and (b) 1000 m spacing (Stagpoole & Bibby, 1998a).

5. NATURAL FEATURES

The Te Manaroa spring, located upstream of the thermal pools, discharges water at a measured temperature of 99.6 °C, providing a heat discharge of 3 MWth. This is the largest single source of geothermal water in the whole of New Zealand. It flows into the Otamakokore stream, that originates from cold and hot springs further up the Waikite Valley.

The Waikite thermal pools are fed by two smaller springs. Multiple sources of geothermal fluids come together in an open feed, in which the water is cooled to the preferred temperature. The geothermal fluid is collected in a channel, before being led into the man-made cooling system. Due to these high temperatures, significant cooling is required before the water is safe enough to be used for bathing in the thermal pools. It is then discharged to the Otamakokore stream after use.

The Waikite thermal area is a fluid-heated system, in contrast to the nearby vapour-dominated system Te Kopia geothermal system, also located along the Paeroa Fault. The presence of bicarbonate fluids, as well as the occurrence of travertine deposits rather than silica sinter, which is associated with chloride fluids, supports the Waikite system being a fluid-heated system. The travertine present at Waikite is deposited by these bicarbonate fluids as degassing of the CO_2 present in the water occurs. The solubility of carbonate decreases with an increase in pH. Such an increase in pH can occur when this degassing occurs, causing the precipitation of carbonate. Additionally, to these travertine deposits, lilypad formations were visible upstream, near the Te Manaroa spring. These lilypads consisted of unusual platy calcite crystals (Figure 7). The observed calcite and travertine depositions are formed by the conversion of dissolved CO_2 to HCO_3 in bicarbonate water.

Careful examination of the geology and geothermal fluid chemistry indicates that while the fluid at Waikite thermal futures is not different isotopically from the surrounding geothermal systems (Waiotapu, Reporoa and Te Kopia), it might be sourced from an isolated low temperature hot water (< 220 °C) geothermal system according the classification given by Zarrouk and McLean (2019), or is sourcing fluids that are marginal to a deep Waiotapu upflow (private communications with Dr. Andrew Rae, GNS). Therefore, it may not be an extended (shallow) outflow of the Waiotapu geothermal field, where the Paeroa and Ngapouri Faults provide access to the outflowing geothermal fluids to reach the surface at near-boiling temperature.

From a reservoir engineering point of view, the distance between Waikite and Waiotapu (~5 km) or even from Te Kopia to Waikite (~10 km) are relatively too long for a shallow outflow to discharge high flow rates at boiling temperatures. At the same time the distinct deposition of lilypad-shaped formations consisting mainly of calcite crystals that are not found elsewhere in the TVZ (apart from the Calcite Spring at Ngatamariki, which naturally stopped flowing in the early 2000s), is another indicator that the Waikite fluid source has originated from a separate > 1000 m deep low temperature system where calcite solubility in the reservoir rock is higher than that of higher temperature two-phase geothermal systems (see Zarrouk and McLean, 2019).

Figure 7 Lily pad formations on both sides of the Te Manaroa spring.

6. DIRECT USE

The Waikite springs provide direct-use geothermal energy utilized for recreation and tourism, providing employment for the local community. No wells have been drilled in the area due to the high temperature natural discharge of the thermal springs, of which the largest is the Te Manaroa spring.

In total, there are 10 thermal pools, comprising six larger hot thermal pools and four private pools. As mentioned before, the water discharge must be significantly cooled (< 44 °C) before being safe enough for recreational uses, as the water in the pools is unaltered geothermal fluid, which cannot be reused. To achieve this, an air shower and open terrace system, with a larger cascading channel have been constructed. A schematic overview of the fluid supply system is given in Figure 8. Firstly, the captured spring water is sprayed through an air shower (Figure 9), allowing for natural cooling by the air. This open air shower can be regulated as suits; therefore, it is not required to be switched ON all the time. A shield at the back of the air shower acts as a barrier and protection against the wind drift (Figure 9).

Subsequent to this air shower, there are man-made terraces which allow the water feed to cool by evaporation and by mixing with freshwater in order to obtain the desired temperature (Figure 10). These terraces are gravity fed, as the only pump used in the system, which pumps the water upwards for spraying, is located at the air shower.

At the beginning of the first terrace, which is the largest, the water discharged through the pipe was measured to be 94 °C. Only a meter away the temperature dropped to 87 °C, resulting from the high temperature difference between the air and the water. Before the water is discharged to the smaller terraces further on, the temperature dropped to 53 °C, about four meters away from the feed by the pipe.

Before the water is used for the thermal pools, it is brought along a sequence of smaller terraces for further cooling; see Figure 10. The water feed is constantly maintained and fed directly into the pools after the cooling system. A portion of the water is used for heating a secondary fluid through a once through shell and tube heat exchanger (Figure 8), which is used to heat the hot water demand of the facilities at the thermal pools, such as showers and kitchen.

After the geothermal fluid goes through the man-made cooling system, it is circulated through the thermal pools, used for bathing and recreation. Safety regulations do not allow public bathing pool temperatures above 44 °C. Rotorua District Council is responsible for the safety of these pools. During opening times, every half hour the temperature of the pools is measured. The target temperatures of the pools lie between 30 and 41 °C, varying per pool. Once the temperatures exceed the desired temperature of the pool, the geothermal fluid feed is reduced or terminated. If this does not cause a high enough temperature drop, the pools are fed with cold water. Subsequently, when the temperatures drop below the sought amount, more geothermal fluid is added to the pools. Every day, the larger six pools are drained after closing hours, cleaned and filled again with fresh geothermal fluid overnight.

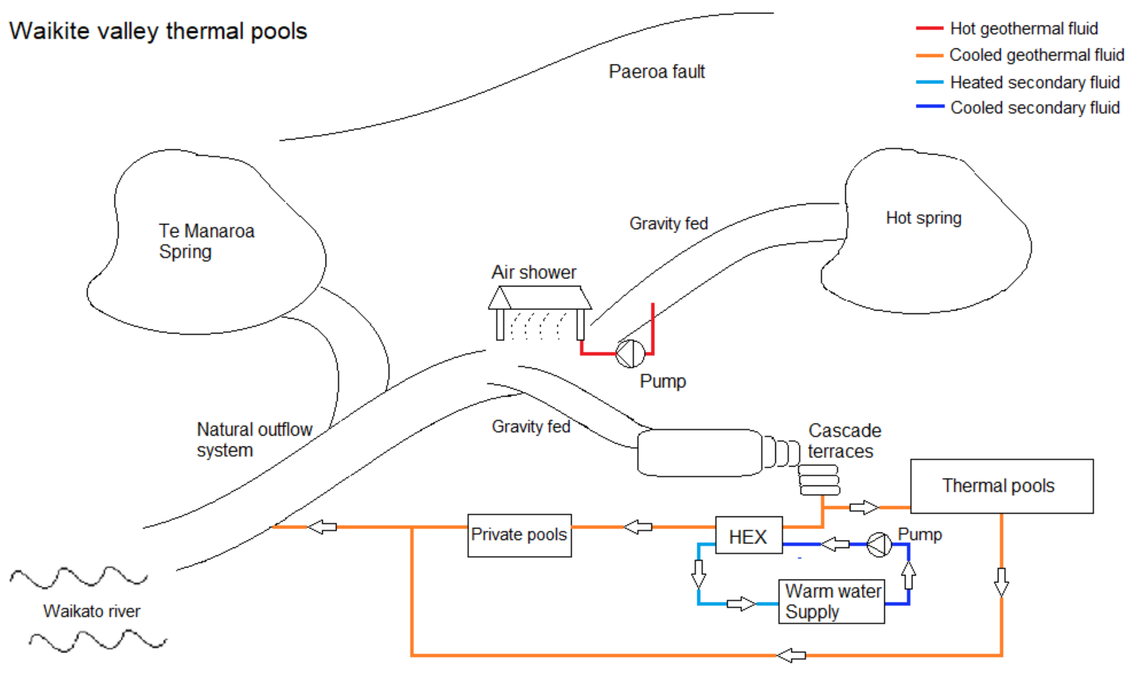

Figure 8. Schematic overview of the man-made cooling system at the Waikite Valley thermal pools.

Figure 9. The open air shower cooling system at the Waikite Valley thermal pools.

Once the geothermal fluid is used, it is discharged back, not influencing the natural hydrology of the area. Only a minor portion of the water, which is fed into the system by the discharge of the hot springs, is not circulated back into the system. Therefore, depletion of the hot spring is out of the question. After the water is used in the pools, it is discharged back into the Otamakokore stream, which subsequently flows into the Waikato River. The resource consent for uptake and discharge of geothermal fluid is up to 3000 m^3/day. The water which is not required in the pools of the bathing area is diverted directly back into the Otamakokore stream. The only way the water which is used in the thermal pools is affected is by the addition of bacteria and body fats, alongside the lowering of temperature. The former is monitored by sampling the water downstream for faecal coliform counts.

Figure 10. The sequence of smaller (man-made) cascade terraces designed for cooling before the thermal pools.

The successfulness of the Waikite thermal pools stresses the understanding of the local community of dealing with geothermal resources, which provides a pathway for the development of other geothermal resources which then would stimulate the economic growth. However, attention to the location dependency of such systems is needed, as these are determined by the resources in the near neighborhood. The Waikite thermal springs could only be developed in this area due to the high-temperature hot springs, despite the location not being very conveniently reachable.

7. DISCUSSION

While it has been widely agreed that Waikite is an outflow of the Waiotapu geothermal system, recent studies suggest that it is likely to be a small lower temperature hot water (< 220 °C) isolated up flow.

The resistivity map of the surrounding area showed no reason to believe the fluids discharged at the Te Manaroa springs at the Waikite spring derive from a deep upflow from the source.

The Cl-HCO_3-SO_4 ternary plot of the fluid discharged at the Te Manaroa spring provides insight into the evidence of the discharged waters being from bicarbonate origin, which is in favor of the presence of travertine at the springs as opposed to silica sinter, which coincides with chloride water.

The Na-K-Mg trilinear plot shows the ratio of constituents being in line with the measured near-boiling temperature of the discharged water.

Furthermore, the direct use of geothermal resources present at the Waikite Valley Thermal Baths is a successful, low-maintenance, simple system, built with the knowledge of the local community in the area. The minor uptake of geothermal fluid and natural discharge back into the system provide no interference with the local environment. This way, the pools are fed with natural geothermal fluids and the geothermal springs can still discharge the fluid naturally towards the local streams and river.

8. CONCLUSIONS

Although the Waikite geothermal field is generally considered to be an outflow of the upflow present at the Waiotapu field in the area, there is some evidence that it is fed by a separate upflow from a deep source. The Paeroa Fault is an important indicator for the flow of the fluid in this area, which includes the Te Manaroa spring, the largest single source of geothermal water in New Zealand. The thermal pool system built at the Waikite area feeds from another spring with minor interference with the environment. Establishing these thermal pools has been beneficial for the local economy and the use of low-cost materials is unique and results in low maintenance and risk.

REFERENCES

Bibby, H. M., Bennie, S. L., Stagpoole, V. M., and Caldwell, T. G. Resistivity structure of the Waimangu, Waiotapu, Waikite and Reporoa geothermal areas, New Zealand. *Geothermics*, *23*(5-6), 1994, 445-471.

Bibby, H. M., Caldwell, T. G., Davey, F. J., and Webb, T. H. Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation. *Journal of Volcanology and Geothermal Research*, ***68*****(1-3)** (1995), 29-58.

Bibby, H. M., Glover, R. B., and Whiteford, P. C. *The heat output of the Waimangu, Waiotapu-Waikite and Reporoa geothermal systems (NZ): Do chloride fluxes provide an accurate measure?* (No. GEO-PROC-95-02). Wellington, NZ: Kelburn Research Centre, IGNS; Taupo, NZ: Wairakei Research Centre, GNS, 1995

Ellis, A. J. (1970). Quantitative interpretation of chemical characteristics of hydrothermal systems. *Geothermics*, *2*,(1970) 516-528.

Ellis, A. J. (1977). Chemical and isotopic techniques in geothermal investigations. *Geothermics*, *5*(1-4) (197, 3-12.

Ellis, A. J., and Mahon, W. A. J. (1977). *Chemistry and geothermal systems.* (No. 553.79 E4).

Giggenbach, W. F. (1986, November). Graphical techniques for the evaluation of water/rock equilibration conditions by use of Na, K, Mg and Ca contents of discharge waters. In *Proceedings 8th New Zealand Geothermal Workshop,* 37-44.

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

Jones, B., Renaut, R. W., and Rosen, M. R. (2000). Trigonal dendritic calcite crystals forming from hot spring waters at Waikite, North Island, New Zealand. *Journal of Sedimentary Research*, *70*(3), 2000, 586-603.

Kaya, E., O'Sullivan, M. J., and Hochstein, M. P. (2014) A three dimensional numerical model of the Waiotapu, Waikite and Reporoa geothermal areas, New Zealand. *Journal of Volcanology and Geothermal Research*, ***283*** (2014*),* 127-142.

Mongillo, M.A. and L. Clelland (1984), Concise listing of information on the thermal areas and thermal springs of New Zealand, in New Zealand Department of Scientific and Industrial Research Geothermal Report. 1984. p. 1-228.

Stagpoole, V. M., and Bibby, H. M. Electrical resistivity map of the Taupo Volcanic Zone, New Zealand; nominal array spacing 500 m, 1:250 000, version 1.0. Institute of Geological & Nuclear Sciences geophysical map 11. Institute of Geological & Nuclear Sciences Limited, Lower Hutt, New Zealand (1998a)

Stagpoole, V. M., and Bibby, H. M. Electrical resistivity map of the Taupo Volcanic Zone, New Zealand; nominal array spacing 1000 m, 1:250 000, version 1.0. Institute of Geological & Nuclear Sciences geophysical map 12. Institute of Geological & Nuclear Sciences Limited, Lower Hutt, New Zealand (1998b).

Stewart MK 1994. Groundwater contributions to Waikite geothermal fluids. In: Soengkono S, Lee KC ed. Proceedings of the 16th New Zealand Geothermal Workshop 1994. Pp. 109-114.

Waikato Regional Council 2011. Waikato Regional Plan: (Reprinted December 2011 – incorporating Variations No.2, No.5 and No.7) ed, Waikato Regional Council.

White PA, Moreau M, Rae AJ, Power JF, Davids B 2018. Evolution of Geothermal -Groundwater Circulation system in the THE Quaternary Taupo Volcanic Zone: Example of the Upper Waikato River catchment, New Zealand. Proceedings the 39th New Zealand Geothermal Workshop. Rotorua, New Zealand.

Zarrouk, S.J. and McLean K., 2019. Geothermal Well Test Analysis: Fundamentals, Applications and Advanced Techniques. ISBN: 9780128149461 Academic Press.