A REVIEW OF THE HYDROGEOLOGY OF THE TAUHARA DOMESTIC BORES, TAUPŌ, NEW ZEALAND.

Jesse L. Lebe[1]

[1]Waikato Regional Council, Private Bag 3038, Waikato Mail Centre, Hamilton 3240

Jesse.Lebe@waikatoregion.govt.nz

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ABSTRACT

Five hundred and twenty-four domestic bores have been installed for water and space heating in Taupō township, mainly within the resistivity boundary of the Tauhara geothermal field. Geochemistry data indicate that the dominant water type extracted from the allocated aquifer is steam-heated waters. Due to minimal data existing on the lithological conditions of the bores, lithostratigraphic data from well THM-18 is used for interpreting the subsurface stratigraphy of the allocated aquifer area. No significant variations in temperature-elevation relationship are observed at different geographical areas across Taupō township. Elevation and bore depth measurements suggest that the Oruanui Formation is the most common lithological unit from which hot fluids are extracted. The Upper Huka Falls Formation is intersected by fewer bores and records lower temperatures than the overlying Oruanui Formation. Fluids exceeding 160 °C were encountered in the Middle Huka Falls Formation, however the formation is a less practical drilling target than the Oruanui Formation aquifer for future domestic bore drilling due to its situation at significantly greater depths. The Oruanui Formation is the most productive and most ideal target zone for future fluid extractions due having a reliable high temperature resource at a relatively shallow depth. Future monitoring of the bores could create a better understanding of the relationship between the domestic bores and surface geothermal features and streams, which have seen a general decline in discharge in recent years.

1. INTRODUCTION

1.1 Tectonic setting

Taupō township is situated in the central Taupo Volcanic Zone (TVZ), a volcanically active rifting-arc margin

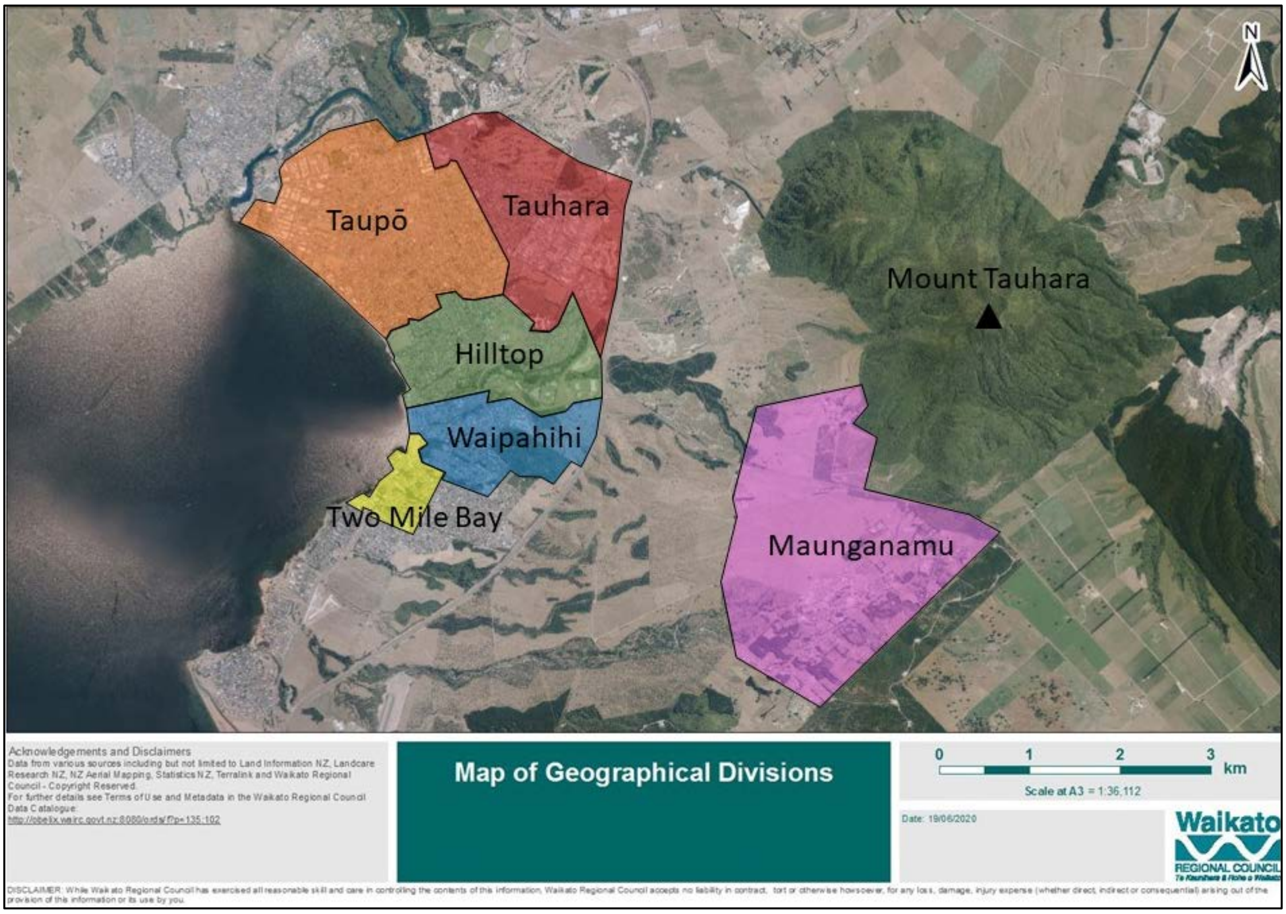

Figure 1 Map showing the geographical divisions of areas with domestic bores in Taupō and Maunganamu. Areas correlate with the actual administrative boundaries of the township, but the extent of Taupō, Tauhara and Maunganamu have been limited to a smaller area for this study based on bore distribution.

associated with the northwest subduction of the Pacific Plate underneath the Australian Plate, offshore the eastern margin of the North Island (Cole, 1990; Wilson et al., 1995; Wilson and Rowland, 2016). Due to its regional geological setting, the TVZ has a relatively high thermal gradient of ~50 °C/km (Reyes, 2007) and host geothermal systems with natural heat discharges exceeding 30 MWth (Bibby et al., 1995; Hochstein, 1990). The urbanised area of Taupo township lies at the northeast margin of Lake Taupo, and 524 domestic bores are known to exist across the area in 2020 (**Figure 1**). In exception to bores at Maunganamu, all other bores lie within the resistivity boundary of the Wairakei-Tauhara geothermal system (Daysh et al., 2015), directly to the south of the Tauhara geothermal field.

The earliest domestic bores were recorded by Occupational Safety and Health (OSH) under the Department of Labour, who also conducted inspections and monitoring of the bores. Minimal studies were undergone (Curtis, 1988; Morris, 1995) outside of OSH and its predecessors, but has since stopped all inspections in 2004. The domestic bores do not record stratigraphy data, keeping understandings of the bore-aquifer relationships at a minimum. Understanding the interaction between the bore and the aquifer fluids is critical, as nearby hot springs and geothermal streams have collectively been observed to have lesser discharges or have stopped discharging, especially as both the bores and features may share fluid from a common aquifer. This study aims to review the hydrogeological relationship using existing data.

2.METHODOLOGY

2.1 Water chemistry analysis

Domestic bores were observed for the availability of downhole water chemistry measurements, and only bores with complete data for the anions chloride (Cl^-), sulphate (SO_4), and bicarbonate (HCO^-_3) were used for analysis. Eight bores were found to have recorded all three key parameters. A water type analysis was conducted by comparing the relative anion percentages for each water sample.

2.2 Assumptions on lithostratigraphy

Geological data were rarely retrieved during domestic bore drilling processes, and when recorded only show the shallower unconsolidated sediments. Despite a more recent study providing a more accurate lithostratigraphy for the geothermal system (Rosenberg et al., 2020), data from existing pressure-temperature monitoring and geotechnical wells recorded by Rosenberg et al. (2009) are used for this study due to their proximity to the area with domestic bores. As some lithological formations show variable stratigraphic thicknesses in different bores, and due to the lack of detailed stratigraphic information available for this study, one bore is used as a representative of the subsurface stratigraphy. Lithological data from bore THM-18 [2779633, 6276647] just north of Otumuheke Stream in the north of Tauhara is selected to represent the subsurface stratigraphy. Despite THM-18 not being centre to the geographical distribution of the bores (**Figure 2**), it reaches a relatively great depth of 717 m, and intersecting the common sedimentary and volcaniclastic sequences and aquifers, which will be discussed in **Section 4**. Spa Andesite lavas were encountered below the Lower Huka Falls Formation in THM-18 and may

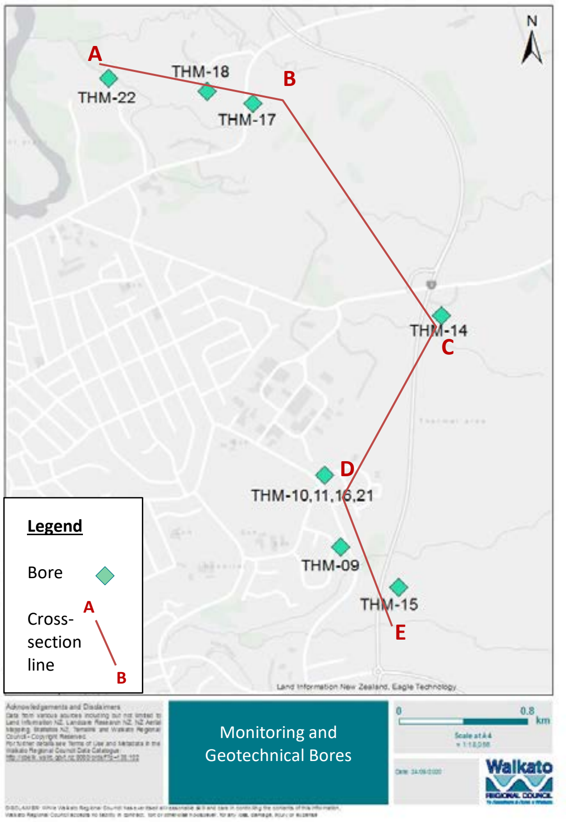

Figure 2 A map showing the bores from Rosenberg et al. (2009), which are used for understanding the geology related to the domestic bores.

be influence the hydrogeology, however as this unit is non-continuous, it is ignored in order to simplify the model.

An assumption is made for this investigation that the thickness of lithological formations observed at THM-18 are consistent, and that all formations extend into the area of aquifer underlying the domestic bores. It is also assumed that breccias and non-extensive lava flows from the Taupo Group (Rosenberg et al., 2020) and structural displacements do not intersect the stratigraphy. The hydrological properties of the observed formations are also assumed to be homogeneous throughout the area to simplify interpretations. The surface bore-head elevations are uninfluenced by the assumptions made. Based on stratigraphic log data, the undefined top-sections of the stratigraphy are assumed to be composed unconsolidated sediments.

2.3 Relative bore depth-elevation conversion

The surface elevations for the domestic bores vary due to the topography of the urban area, so bore depth data does not provide an accurate way of relative depths and intersected lithological zones. *Vertical Datum 2016* (NZVD2016), and then the converted value deducted by the maximum bore depth to obtain the bore depth relative to the datum:

$$\textit{Elevation at max. depth} =$$

$$\textit{wellhead elevation in NZVD2016} - \textit{Max. bore depth}$$

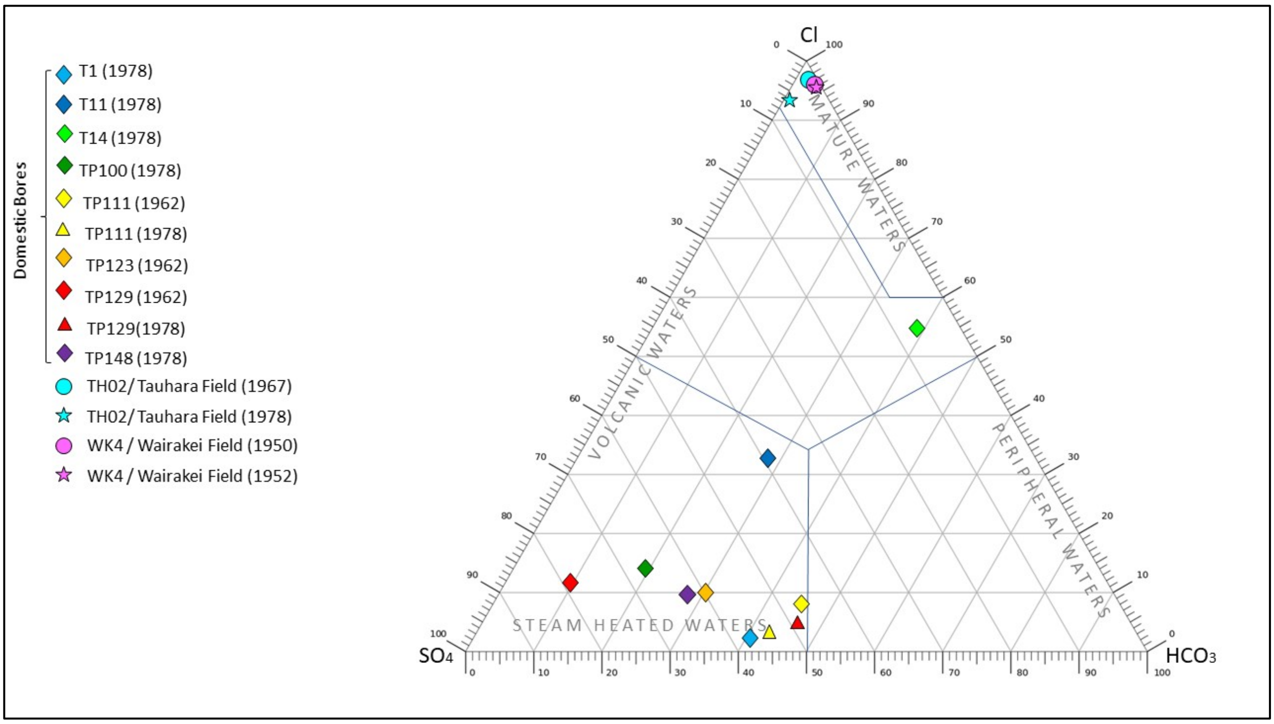

Figure 3 Historical water type ternary diagram with water chemistry measurements taken from domestic bores, and two bores from Tauhara and Wairakei.

Of the 506 bores available to analyse, only 189 bores have a recorded bore-head elevation known to WRC, derived *from 20m Digital Elevation Model* with an accuracy of 6 m. Elevation for another 284 bores were successfully estimated from satellite data, bringing the total number of bores with elevation data to 473 out of 506. Despite the numerical reduction and increased error margins for the elevation of analysed bores, the use of elevation in NZVD2016 was still preferred, as it allowed for the relative comparison between maximum bore depth, with the lithology and fluid conditions at the maximum depth horizon.

3. WATER CHEMISTRY

The relative percentages of the anion chloride (Cl^-), sulphate (SO_4), and bicarbonate (HCO^-_3) is used for observing the type of geothermal water from a fluid sample (**Figure 3**). A major limitation from the water chemistry study is the absence of more recent samples. Water chemistry of the bore fluids may have changed through time, and so the analysis only presents a historical study that is unreliable for representing recent conditions. Only a small number of domestic bores have existing data for all three geochemical parameters, limiting the sampling population for geochemical analysis.

From eight analysed bores (**Figure 4**), seven bores show steam-heated water chemistry. TP129 initially had the highest observed SO_4 percentage of all water samples in 1962, but by 1978 had shown almost equal amounts of SO_4 and HCO_3 constituents, inferred to represent local mixing with meteoric waters. T14, which lies furthest to the south in Waipahihi, is the only bore that shows chemistry trending towards mature waters but being still showing a mixed mature-peripheral chemistry, consistent with a study undertaken by Allis et al. (1989). The water chemistry samples taken from bores in Tauhara and Wairakei (**Figure 3**) show very mature compositions with significantly greater chloride percentages compared to the bore water samples, as commonly observed in upflow zones. Samples from most domestic bores show steam-heated water chemistry, consistent with a study by Morris (1995) who also observed the same water type, associated with the Oruanui aquifer.

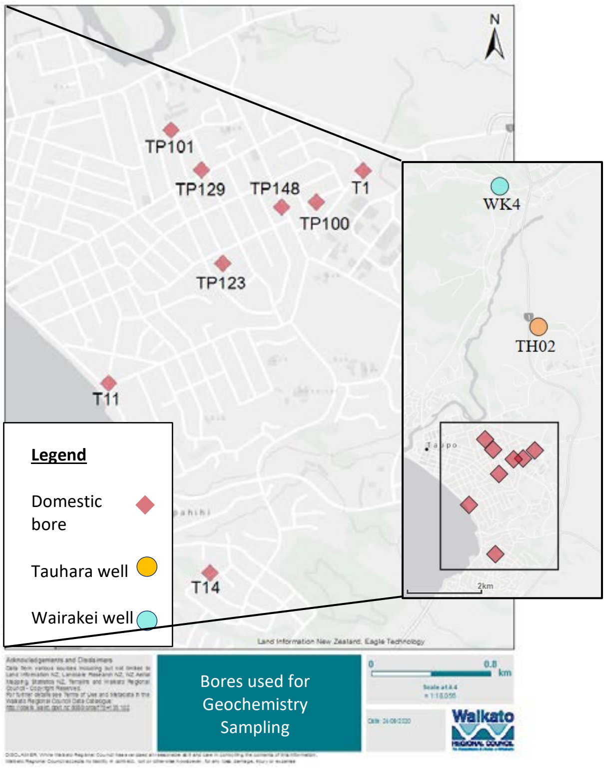

Figure 4 Location of bores with analysed water chemistry data.

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4. SUBSURFACE DATA

4.1 Bore measurements

The Tauhara domestic bores have a variety of depths (**Figure 5**), with the shallowest measuring only 1.5 m deep, and the deepest being 250 m. Many bores reach depths of 20 – 69 m, with few exceeding 100 m. There is an observed concentration of bores <25 m deep on properties located proximal to the Lake Taupō shore in southwest Hilltop and north Waipahihi, around the Waipahihi Stream. There are known alkali-chloride springs in this area; the Taharepa Springs (TH16) and Rocky Point Spring (TH17) in Hilltop, and Waipahihi Stream, Waipahihi Source Spring (THF6), and Otumeheke Stream (THF99). A smaller population of bores >25 m deep is also observed on the east-northeast section of the allocated aquifer, close to the industrial area of Tauhara. Bores between 25 – 75 m are well distributed across the allocated aquifer, representing their greater population compared to bores with other depths. Bores exceeding 75 m in depth are also scattered across the area, with no clusters observed. Overall, there is no observed correlation between bore depth and location, except around the Waipahihi Stream area, where surface geothermal manifestations are recorded.

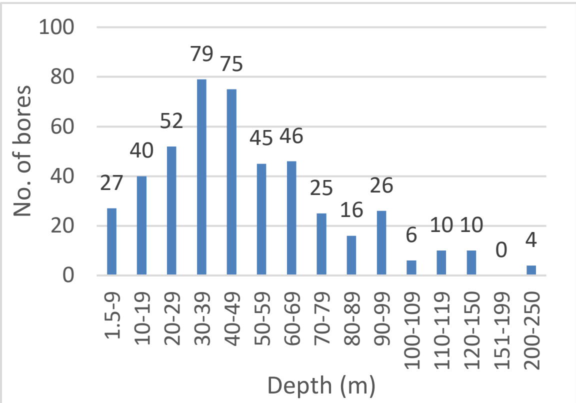

Figure 6 Range of bore depths from 506 locations observed on *Located* and OSH Reports.

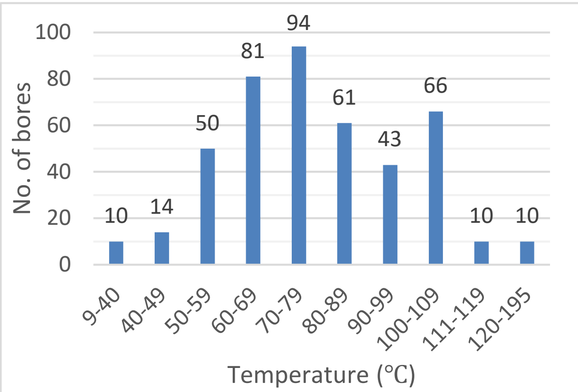

Figure 5 Maximum measured bore temperature from 506 locations observed from *Located* and OSH Reports.

The maximum temperatures encountered after drilling vary from bore to bore, with a minimum recorded temperature of 9 °C, and a maximum record of 195 °C (**Figure 6**). Measurements below 50 °C are likely to correspond to groundwater or steam-heated water feeds, instead of a chloride-rich fluid originating from a deep reservoir. From the data, these relatively cool bores make up 5.3% of measured bores with data, similar to the 3% recorded by Curtis as the percentage of cold water bores (Curtis, 1988), which may suggest a minor increase in numbers constructed over time. A significant number of bores encounter maximum temperatures between 60 and 89 °C, with the greatest number of measurements ranging between 70 °C and 79 °C. As 40 °C is generally the minimum temperature required for effectively generating heat for a domestic bore, the data shows that there is a relatively high chance of encountering sufficient temperatures.

4.2 Geology

Data on domestic bore geology were rarely retrieved during domestic bore drilling processes, and when recorded only show the shallower unconsolidated sediments. As previously mentioned in **Section 2**, the subsurface geology is assumed to be laterally homogeneous throughout the area for simplification, but other bores also record valuable lithological information. THM-16 is at Crown Rd in east Tauhara, and is situated within the Crown Bowl, a subsidence bowl occurring at the site of a paleo-hydrothermal eruption vent. This subsidence bowl (**Figure 7**) is characterised by the occurrence of the Crown Breccia (CXB), which consists of tuffaceous clasts from the Oruanui Formation (O) and Waiora Formation (W), clastic clasts from the Huka Falls Formation, and a sand-rich matrix with significant clays (Rosenberg et al., 2009). Swelling clays, predominantly smectite and kaolinite at shallower depths and mixed-layer illite-smectites at greater depths, constitute between <5 – 40% of Crown Breccia rock samples. The thickness of the Crown Breccia at THM-16 is 167 m and overlies a 522 m thick sedimentary and volcaniclastic sequence of the Waiora Formation. The stratigraphic sequence at THM-16 and the other Crown Bowl bores (THM-10, 11, 21) not only differs from that at THM-18 due to the presence of the Crown Breccia, but also from the absence of Huka Falls Formation deposits, which is well developed at the THM-18 and bores to the north of THM-14. The top of the Waiora Formation is also encountered at a deeper elevation of -186 m at THM-18 compared to 235 m at THM-16 and is underlying Spa Andesite which is absent elsewhere. THM-18 is preferred to THM-16 as a reference bore for interpreting the hydrological relationship between subsurface lithology and the domestic bores. Despite THM-16 being situated closer to many domestic bores, its lithology is greatly influenced by local hydrothermal alteration. The unique lithology at Crown Bowl is not observed outside of the subsidence bowl, and hence is interpreted as not being representative of the geology underlying the properties with domestic bores, or the general shallow aquifer in the area.

4.3 Bore-aquifer relationship

Three rock units have been identified by Rosenberg et al. (2010) acting as shallow aquifers in the Tauhara geothermal field. The Taupo Pumice, which belongs to the Taupo sub-group (T), is the shallowest known aquifer unit, and is an unconfined aquifer found at surface levels at the Crown Bowl, THM-9, throughout the Waipahihi Stream, and around the margins of Lake Taupō. Due to its very high permeability, meteoric waters preferentially percolate through Taupo Pumice and enter the underlying Oruanui Formation, with which this unit shares a hydraulic link (Rosenberg et al., 2010). However, as Taupo Pumice is

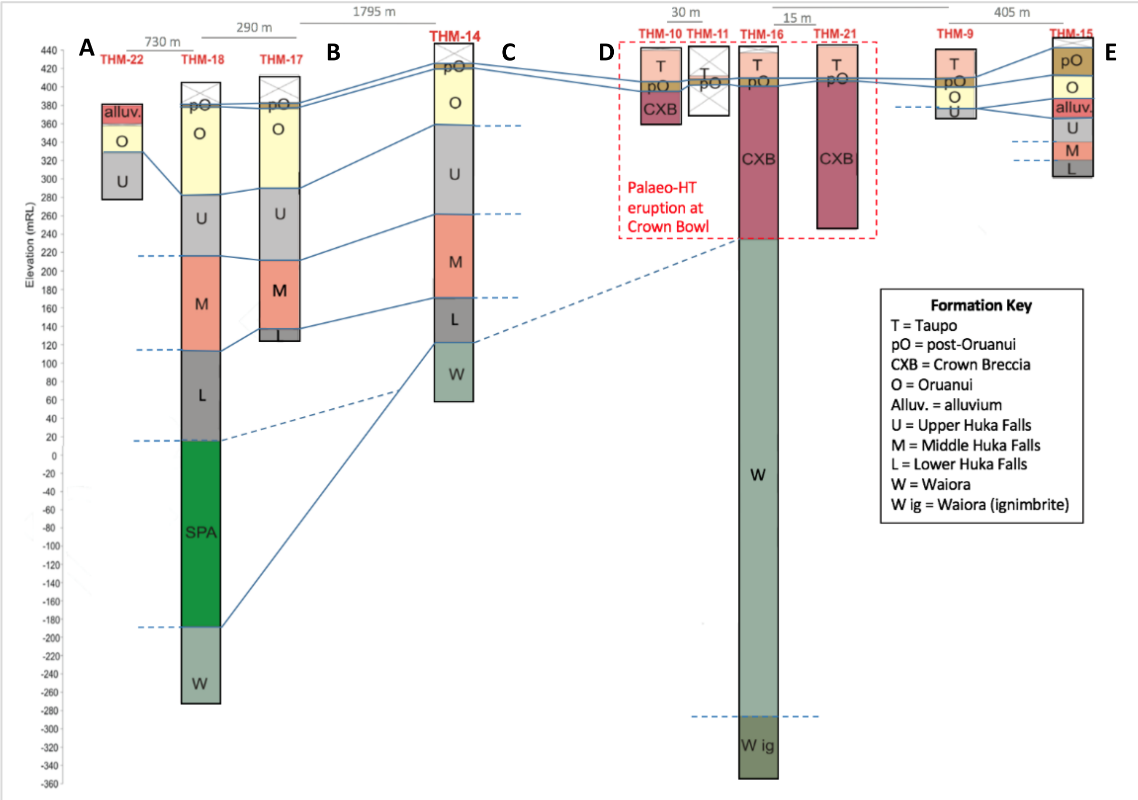

Figure 7 A geological cross-section constructed using monitoring and geotechnical bores along points A – E on Figure 2. Modified from Rosenberg et al., 2009.

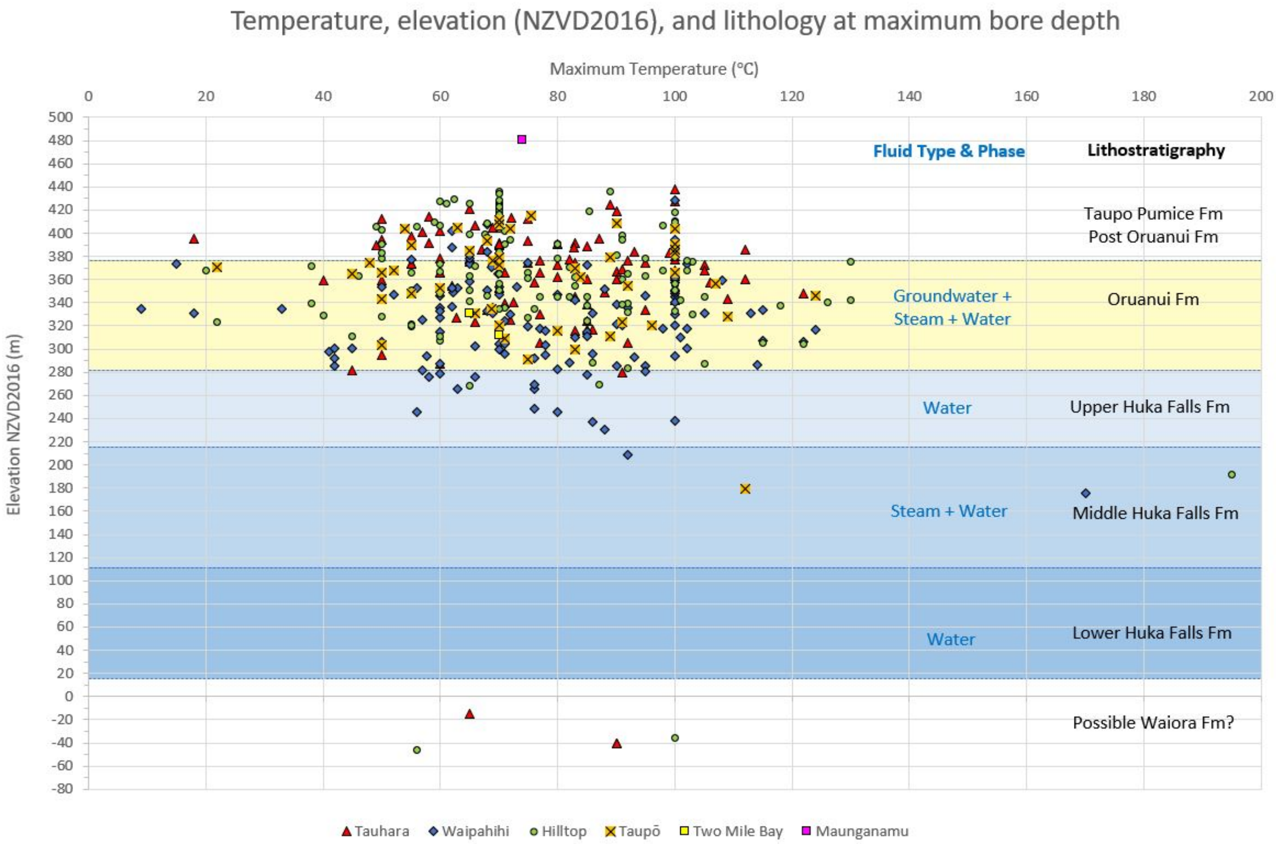

Figure 8 Diagram showing the relationship between elevation at maximum bore depth in NZVD2016, maximum temperature, stratigraphy, and fluid phase in 473 bores. Stratigraphy and water phase zones adapted from Hunt and Graham (2009).

found at the surface, it is inferred to mainly interact with colder waters of meteoric origin and could not provide enough water that is hot enough for domestic use.

The Oruanui Formation (**Figure 7**) is composed of multiple sequences pyroclastic materials, some of which are permeable. The main recharge for this aquifer comes from meteoric waters, but the unit also receives relatively deep-sourced hot geothermal fluids. It is suggested by Rosenberg et al. (2010) that the Oruanui Formation may exist as a confined aquifer in locations where the Post-Oruanui Formation and less permeable sequences within Oruanui Formation overlie the aquifer. The third shallow aquifer is associated with the Tauhara Dacite. This aquifer has been encountered in bores relatively proximal to Mt Tauhara, and its thickness decreases distally from the mountain. Due to its local extent at Mt Tauhara, this aquifer is not given any significant focus in this investigation.

The productivity of the domestic bores does not seem to be influenced by fluid extraction for electricity generation further north in the field. It has been suggested by previous studies (Allis et al., 1989; Curtis, 1988) that the southern part of the Tauhara geothermal field, which includes the bore-populated area, possesses higher aquifer permeability associated with more porous lithology and a higher degree of fracturing. The two shallowest aquifers are also stratigraphically situated above the cap rock (**Figure 8**), which is the Huka Falls Formation, which may be why the deep reservoir further north is not or minimally affected. Hence, the upflow and outflow in the southern part of the geothermal field may be contemporary to the known zones to the north, where fluid extraction for power generation is taking place, and is separated by the less permeable geology as discussed by Curtis (1988). The domestic bores tap into the aquifer where permeability is inferred to be higher than in the north.

The conversion of maximum bore depths into elevation, and the assumption that the lithology and stratigraphic succession from THM-18 is laterally homogeneous in the allocated aquifer allows for the lithology of bores to be interpreted. It is observable (**Figure 8**) that the most common geological unit encountered at the maximum depth of bores, and therefore tapped for hot fluids is the Oruanui Formation. Bores intersecting these formations have recorded fluids at a wide range of temperature, between 9 °C and 130 °C. Lower temperature measurements are probably caused by the bores tapping into groundwater, the bore being a groundwater bore, or waters cooled by near-surface interactions. The undistinguished zone with Taupo Pumice Formation and Post-Oruanui Formation is also observed to be encountered at the bottom of bores, although it is unlikely for the Taupo Pumice Formation to retain its waters due to very high porosity conditions. There are two linear trends at temperature measurements of 70 °C and 100 °C intersecting the Post-Oruanui Formation and Oruanui Formation (**Figure 8**). This may be due to aquifers being confined, reducing external influences, and allowing for the fluid temperature to remain stable at the two temperature points.

Significantly fewer bores intersect the Upper Huka Falls Formation, most of which occur at Waipahihi. This is consistent with the role of this formation as an impermeable cap (Rosenberg et al., 2009). Bores in the inferred Upper Huka Falls Formation zone records a maximum temperature many bores exceeding 100 °C. Four bores intersect into the inferred Middle Huka Falls Formation zone, with two bores showing temperatures between 80 °C and 120 °C, and two bores exceeding 160 °C. The upper third of the Upper Huka Falls Formation is comprised of predominantly volcaniclastic sandstones with pumice pebbles, with thinly bedded intercalated siltstones the dominant lithology below the sandstones. Pumice pebbles in the sandstones could provide porosity and permeability in an otherwise impermeable aquitard zone if intergranular connectivity between the pebbles exist. Other possible permeable zones within this aquiclude include bedding contacts on sandstones and siltstones, and on fractures.

The two hottest bores are situated in Waipahihi and Hilltop which show that exceptionally high temperatures can be encountered at depth. However, there are four known bores drilled below the inferred lower boundary of the Lower Huka Falls Formation but only encountering temperatures of 100 °C or lower, showing that drilling deeper is not always more productive. Two Mile Bay and Maunganamu each have data from only two bores. These show different results to the other geographical areas. Bores in Two Mile Bay show temperatures of 65 °C and 70 °C, at elevations of 331 m and 312 m respectively. The two bores show temperatures slightly below the area mean of 76.6 °C, but there is not enough data from Two Mile Bay to conclude the area has below-average fluid temperatures. Despite only having a low number of data, measurements from Maunganamu offers valuable information, as it lies at some distance from all other bores and may access a completely different local aquifer. The area has a bore with the highest recorded elevation at maximum depth, at 480.6 m (NZVD2016), while reaching temperatures just below the area mean. However, these bores are hot enough for domestic use, and is possibly related to a different heat source.

Temperature and elevation diagrams show that the Oruanui Formation aquifer is sufficiently hot for domestic utilisation, with some bores recording temperatures exceeding 100 °C in Tauhara, Waipahihi, Hilltop, and Taupō (**Figure 5**). This zone has both steam and water resources, with known steam zones feeding into bores in Tauhara. One minor issue with this aquifer is the recorded low temperatures <40 °C, but there are only 11 bores with such low temperatures, so this is a minor issue. Most bores tapping into the Taupo Pumice Formation and Post-Oruanui are also sufficiently hot for the required use, with the most productive zone being approximately between elevations of 380 – 440 m NZVD2016. However, only one bore in Tauhara encounter fluid >100 °C, so Oruanui Formation is more ideal when targeting greater temperature ranges. Due to its shallower stratigraphy, the Post-Oruanui Formation is also more influenced by shallow groundwaters and meteoric waters (Cattell et al., 2015), which makes it less reliable in generating consistent heat in the long run.

5. CONCLUSIONS

There is no clear justification for trying to drill as deep as possible into the Huka Falls Formation and the Waiora Formation, despite very high temperatures having been encountered at depth. The Oruanui Formation can provide enough and reliable heat distribution for domestic use at shallower depths or higher elevations, helping minimise drilling risks, economical costs, and uncertainties. Despite the Post-Oruanui Formation also recording high enough heat, the formation is more easily influenced by cooling processes, and so provides a greater long-run risk for heat sustainability. The Oruanui Formation is a relatively low-risk and economically viable target zone for drilling a domestic bore compared to other formations.

Geothermal surface features such as hot springs and geothermal streams are present within the Taupō township area, with the Waipahihi Valley features being situated and some most prominent features situated proximal to the area populated by the domestic bores are those of the Waipahihi Valley. The geochemistry of features along the Waipahihi Valley show relatively high chloride (Cl) concentrations for the area (Luketina et al., 2015), and show alternating trends between mature and transitional mature-peripheral waters between 1900 – 2003, a water type typically indicative of upflow zones in flat-terrain or extensional geothermal systems (Giggenbach, 1988), consistent with the system type at Wairakei-Tauhara. However, features such as the Iron Bath Spring or THF1 [NZMS-260 U18: 2779839 E, 6273199 N] which once deposited sinter stopped discharging since the late 1980s, when the use of domestic bores was already established. Another depleted feature is the Kathleen Spring or THF91 at [NZMS-260 U18: 2779566 E, 6276024 N] the northwest of the allocated aquifer area, which has stopped flowing since 1997, with both rainfall variations and extraction from aquifers noted as the possible causes.

Further studies and the frequent monitoring of the bores could help create a better understanding of the relationship between fluid uptakes, the aquifers, and hydrology of the system, while also providing better help for future management and planning of the intermediate aquifer. This is an especially interesting issue as many features, including geothermal streams, have shown a decrease in discharge over the years, with the role of bore extraction still uncertain in the depletion events. Efforts to achieve a better understanding of the hydrological relationship between the domestic bores and nearby surface features are required to ensure that domestic bores extract fluids from the aquifer sustainably.

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