THE MANGAKINO GEOTHERMAL SYSTEM: RESOURCE EVALUATION

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ABSTRACT

Aquifer permeability within the Mangakino geothermal system is possibly controlled by reactivation and reopening of old fractures at the intersection of NE-SW trending fault and NW-SE trending fault. The most reliable reservoir temperatures range from 265 °C to 291 °C. The total stored heat in the system is estimated to be between 887 PJ and 2229 PJ. The potential power capacity that can be developed in the system is between 10 and 26 MWe. Geothermal energy could benefit nearby timber operations in terms of: i) reducing raw material and waste disposal costs, (ii) revenue opportunities for processing of residue that was used as heating fuel before, (iii) carbon emission reduction – carbon tax saving, and (iv) higher plant efficiency and lower cost.

1 INTRODUCTION

1.2 Location of Study area

Mangakino is a located next to Lake Maraetai, a hydropower dam operated by Mercury Energy Ltd (MEL). It is about 55 km NW of Taupo and 85 km SE of Hamilton. It lies close to plantation forests (Figure 1). The area consists of flat land surrounded by high terrain plateaus. The main objective of this study was to evaluate the evidence supporting high temperature resources and develop a better understanding of the Mangakino geothermal system for resource assessment.

1.1 Background of Study

Geothermal energy's share in total New Zealand's generated electricity is about 16 percent (Carey *et al.*, 2015), almost all derived from the Taupo Volcanic Zone (TVZ). At least 25 large geothermal systems exist in the TVZ (Figure 2). Waikato Regional Council has divided its geothermal systems into 5 categories based on size, existing uses, and vulnerability of surface features. Mangakino geothermal system is a Development System (Waikato Regional Council, 2011). Several investigations either as regional scale research or as geothermal exploration activity have been conducted in the area. However, the area has not yet been developed since the resource is not confirmed yet.

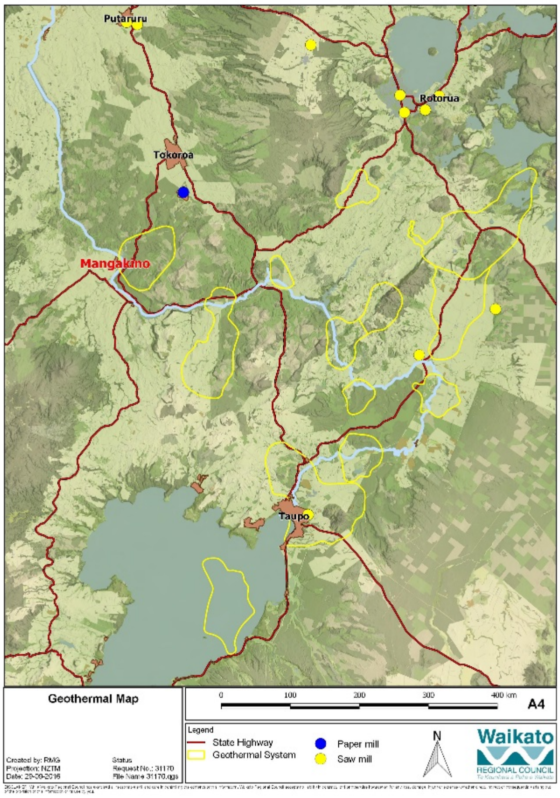

Figure 1. The location of the Mangakino area, with forested areas shown in dark green.

1.3 Previous Works

Various researchers have made different conclusions as to whether Mangakino is a caldera structure or not, citing such evidence as stratigraphy, lack of magnetic signature, and other geological and geophysical data (Martin 1965; Wilson et al. 1984, Fagan 2007; Wilson 1986; Houghton et al. 1995)

The Department of Scientific and Industrial Research (DSIR) prospected the area in 1986, which involved resistivity surveys and the drilling of a well, labelled MA1, to 607 m depth. The results of the investigation suggested the presence of high temperature geothermal systems in the area. The well reached a maximum temperature of 185 °C and tapped bicarbonate-chloride waters.

SKM (2002) calculated that the Mangakino geothermal system has 1500 PJ stored heat resources, which could generate as much as 20 to 90 MWe.

In 2004, an electromagnetic geophysical survey (MT TDEM) sought to identify the best borehole position. The survey results are consistent with previous investigations, indicating an extensive hydrothermal cap. MEL's subsequent drilling and downhole measurements demonstrate a high temperature geothermal resource within the area but with poor permeability. Fagan (2007) suggested there might have been a cooling process since fluid inclusion measurements at 1755 m depth indicated the presence of relict high temperature minerals such as epidote at the level with lower well's measured temperature. In addition, Fagan (2007) reexamined the stratigraphy correlation and hydrothermal alteration within the area using MEL's borehole cutting data.

2 GEOLOGY

2.1 Regional Geology and Tectonic Setting

The TVZ is divided into two areas based on volcanism period, namely the old TVZ (from 2.0 Mega-annum [Ma] or million years ago to 0.34 Ma) and the young TVZ (from 0.34 Ma), which is characterized by the inception of the Whakamaru eruptions.

The young TVZ is rifting at rates between 7 and 18 mm per annum, which started around 0.9 Ma. Eight rhyolitic caldera centres have been recognized, of which two (Mangakino and Kapenga) probably have composite features. Recent age measurement data on ignimbrites inferred from the Mangakino volcanic centre suggests that the Mangakino volcanic activity occurred in two distinct periods, from c. 1.6 to 1.53 Ma and 1.21 to 0.95 Ma. This results in the prognosis that Mangakino was a composite structure (Houghton et al. 1995, Fagan 2007).

Wilson (1995) showed that composite cones occur with lesser volume (< 10 km^3) than those in the andesite-dominated TVZ area. Andesitic volcanism is also represented by: (a) 3 ignimbrites, in the Mangakino, Matahana Basin and Broadlands areas; (b) Buried discrete lava flows or shallow sill complexes intersected in geothermal drill holes; and (c) Mixing components associated with more silicic eruptions.

The hypothesis that Mangakino is a caldera structure is supported by the findings of a gravity study by Stern (1979), which demonstrate a large gravity anomaly within Mangakino, a caldera structure characteristic. On the other hand, the findings also confirmed a lack of magnetic signature which might indicate Mangakino is not a volcanic centre. Bibby et al. (2008) revealed that low magnetic signatures in western part of TVZ might be influenced by the presence of old ignimbrites.

Stratford and Stern (2008) showed that the inferred seismic velocity and density ranges of the anomalous body beneath the Mangakino Caldera are 4 km/s and 2300–2400 kg/m^3 respectively, which are not typical values for a plutonic body. They assumed the subsurface lithology is predominated by the large thickness volcanoclastic. However, a compaction process is supposed to have occurred, which removes porosity and creates higher density rock, which is not observed in the Mangakino area. One explanation is that there might be subsurface high fluid pressure that avoids the compaction and densification process. This condition occurs if there is a 'seal', or a highly welded ignimbrite flow, deposited over the top of the plutonic body, and volatile releases, or melting processes, continue into the caldera. In hydrothermal zones, such as the Mangakino caldera complex, such a seal could exist in fractures and may transform barriers to fluid flow after mineralization (Tenthorey et al. 2003, Stratford & Stern, 2008). Fault activity should be considered during exploration since changing pore pressures could trigger it.

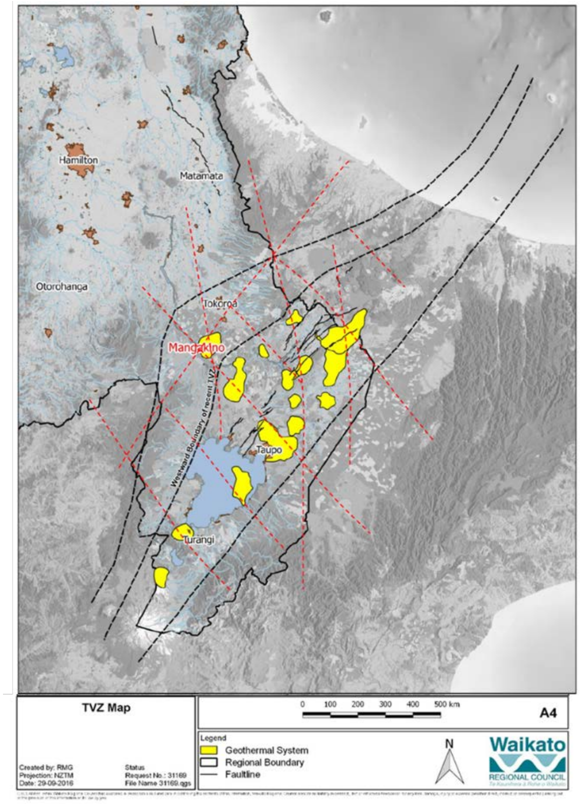

Figure 2. Distribution of geothermal systems in the TVZ (Note red dash line is major structural lineament from Landsat Image Analysis after Tianfeng, 1980)

2.2 MANGAKINO GEOLOGY

2.2.1 Stratigraphy

The surface geology of Mangakino is dominated by Whakamaru ignimbrites as caldera-infilling deposits. A series of rhyolite lava belts and pyroclastic deposits occupies the east side of the area. The rocks are categorized as Ongaroto Group consisting of rhyoltic lavas and pyroclastic rocks. Both rock group units were deposited in the Middle Pleistocene. A small portion of Oranui Ignimbrite Formation, consisting of non-welded ignimbrite and phreatomagmatic fall deposits and reworked ignimbrite, and the youngest Hinuera Formation, a river deposit constituted by cross-bedded pumice sand, silt and gravel with interbedded peat, is deposited at the central area surrounding Lake Maraetai. Those units were deposited in the Late Pleistocene. An older unit, Marshal Ignimbrite (a member of the Pakaumanu Group) crops out in the western and northern areas. This unit was also deposited in the Late Pleistocene. Correlation of subsurface stratigraphy within the Mangakino geothermal system has been carried out by several studies. Grindley and Mumme (1991) correlated the stratigraphy from MA1, the geothermal well drilled by DSIR (see Figure 3 for well locations) with some stratigraphic bore along Mangakino–Waipapa Road (Taupaki Trig/TT) and near Maraetai Dam (WB20). Along borehole MA1 and WB20, the stratigraphy was interpreted consistently from top to bottom as a sequence of Whakamaru Ignimbrite-Lacustrine sediment- Marshal Ignimbrite dipping eastward. However, from WB 20 to TT, they predicted that there might be a major old fault and the dipping transforms to westward without lake bed sediment overlying the Marshal Ignimbrite. Fagan (2007) reconstructed the stratigraphy correlation in the Mangakino geothermal system using the absolute age measurement method and petrography observation of the MEL cutting drilling data. The subsurface lithology is dominated by large ignimbrites, intercalated by lacustrine sediment and intruded by rhyolite lava at some intervals/spots. There is a significant difference in stratigraphy relief at the top boundary of the Rocky Hill Ignimbrite in the central area (MA2 well), indicating an offset which could be caused by a fault (graben) or paleo valley. It can be noted also that in every ignimbrite unit, there are abundant greywacke lithic fragment incursions.

2.2.2 Geological Structure

As a part of the old TVZ, the geological structure in the Mangakino geothermal system tends to be old and inactive and buried beneath the surface. Hence, very limited surface fault structures have been documented. The Regional Geology QMAP Rotorua Sheet (Leonard et al. 2010) only shows surface structure lineaments, mainly the Ongaroto Group of rhyolite lava. However, its geological cross-section provides the subsurface geological structure.

Tianfeng (1980) predicted there are possibly 12 northeast trending main lineaments and 6 northwest lineaments (Figure 2). Two of those lineaments are likely to cross the Mangakino area: the northeast trending Turanga-Hauhau lineament and Northwest trending Mangakino-Wairakei-Ahinawa lineament. The former lineament is influenced by extension rift mechanism whereas the latter is basement faults that may have reactivated by the former lineament.

The lineaments are relatively consistent with the stratigraphy correlation results of Grindley and Mumme (1991). Fagan (2007) predicts there might be a fault existing within the area from the condition of secondary calcite and quartz in Mangakino wells (bent cleavage in calcite at 3192 m in well MA2), supporting a recent deformation event. These structures also influence the geomorphology and drainage pattern within the area through sudden changes of stream/river direction in several places. However, the exact location of the faults needs to be confirmed through a comprehensive study and survey. To sum up, the predicted geology of the Mangakino area is shown in Figures 3 and 4.

In terms of the lateral distribution of the geothermal prospect, these faults might be the controlling main factor in the Mangakino geothermal system. In an old caldera like Mangakino, hydrothermal minerals may accumulate and create 'self-sealed' mechanisms to decrease the permeability, hence inhibiting fluid circulation. The permeability could be maintained by active fracturing. The Mangakino geothermal system seems to be located in a slipping fault intersection setting whose created permeability is still typically less than those in other settings, since the faults tend to just reopen the old existing fractures and not produce new fractures. Hence, the geothermal area tends to concentrate around the fault-intersections (Figure 5).

In terms of the vertical distribution of the geothermal prospect, Bibby et al. (2008) warn that the presence of a large thickness of old low-resistivity ignimbrites (more than 1 Ma) in depth along the western area of the TVZ might lead to misinterpretation of the geothermal prospect as was experienced in Horohoro geothermal prospecting.

3 HYDROTHERMAL ALTERATION AND GEOCHEMISTRY

3.1 Hydrothermal Alteration

Fagan's (2007) hydrothermal study includes alteration intensity (AI) analysis at each level in well boreholes drilled in the Mangakino area. Browne (1995) stated that AI is a semi-quantitative measurement of how completely a fluid and rock interaction has occurred in producing hydrothermal minerals. It is determined using a petrographic microscope by estimating the proportion of the primary mineral replaced by secondary mineral.

Fagan (2007) found that two mechanisms of hydrothermal alteration occur in the Mangakino geothermal system, namely replacement and direct deposition. Replacement is very common in the system. In general, the AI in ignimbrite units is higher than that in lacustrine sediments, among which the Whakamaru ignimbrite is the least altered. Direct deposition is much less common than replacement alteration. The alteration took place through veining, occupying on average 2 % of the host rock. MA4, located near the successful drilling MA1, shows the greatest abundance of veining, replacing 10 % of the host rock in some sections. The most common vein-filling minerals are quartz and calcite. Drilling logs (Fagan 2007) show, based on the distribution of hydrothermal minerals, that the AI is mainly moderate to very intense, ranging from 40–100 % along deeper levels. Whakamaru Ignimbrite, Reporoa Group, and rhyolite intrusion lava are the least altered host rocks. This might reflect the present permeability of the rock because the alteration mineral presence might decrease the permeability by a 'sealing' mechanism within the rock, especially in the area with relatively inactive faults.

Fluid inclusion data from MEL and the alteration mineralogy in the MA2 and MA3 wells indicate the change in the geothermal system (Fagan, 2007). Fluid inclusion data from MA2a, which is MA2 redrilled, (1755–1759 m vertical depth) show two resultant temperatures: secondary calcite is 300–315 ºC and quartz is 165 ºC, which is relatively consistent with the down-hole temperature. Other evidence is the presence of epidote, indicating high temperature conditions (>250) at 2200 depth in MA2, where the measured temperature is 180 ºC). Fagan (2007) also shows that the Whakamaru Ignimbrite and rhyolite intrusion lava are relatively fresh and very limited in alteration, which means that the hydrothermal process was cooling when both units formed.

However, since well MA1 has encountered hotter resources and MA4 shows the occurrence of high temperature mineral (epidote) at a much shallower level, the rejuvenation of an old geothermal process by recent heat injection beneath the surface might be occurring, as happened in the Alto Peak geothermal system in the Philippines (Fagan, 2007). It is possible that such rejuvenation is the influence of reactivated old faults as a result of tectonic dynamics in the TVZ, as proposed by Tianfeng (1980).

The downhole temperature profiles indicate that the heat transfer surrounding wells MA2 and MA3 is greatly influenced by a conductive mechanism, indicating low permeability. This is relatively consistent with the hydrothermal assemblage characteristics within the area. The presence of adularia is low compared to that of albite. This may indicate that there is not enough fluid to produce the alteration series from Andesine (Na, Ca)$AlSi_3O_8$ to Albite $NaAlSi_3O_8$ and Adularia KAlSi3O8. The lack of fluid circulation reflects the low permeability at the time of alteration. On the other hand, the MA1 well shows the convective mechanism, particularly from 230 m depth down, indicating the presence of high permeability within the rock.

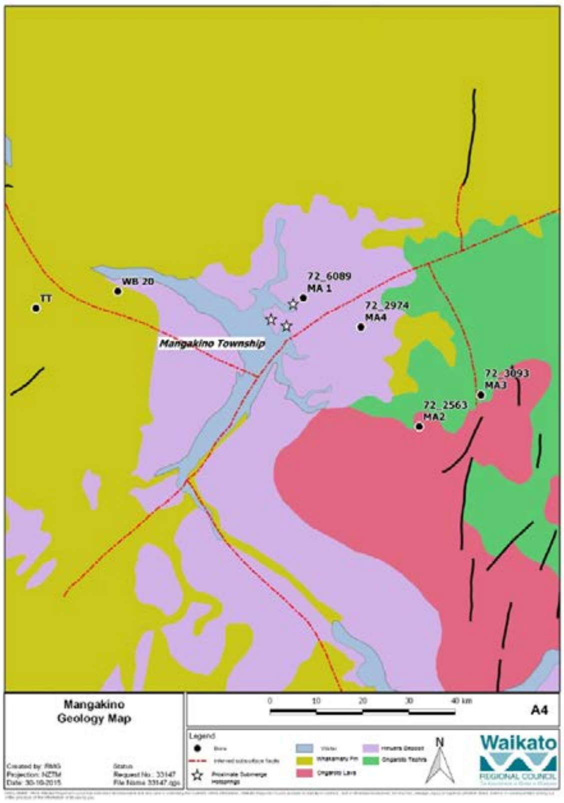

Figure 3. Surface geology of the Mangakino area. Note: red dashed line shows inferred subsurface fault, modified after Tianfeng, (1980), and Grindley & Mumme (1991) GNS Regional Geology QMAP Rotorua Sheet (Leonard et al., 2010).

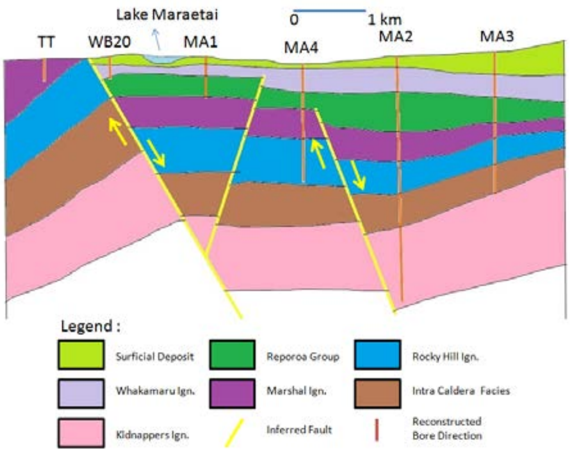

Figure 4. Subsurface geology of Mangakino (modified after Fagan, 2007, and Grindley & Mumme, 1991). (Vertical and horizontal scales are the same).

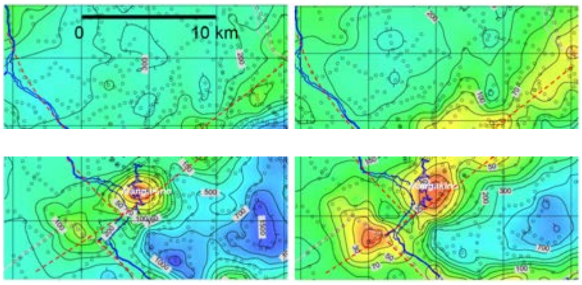

Figure 5. Electricity resistivity map of the Mangakino area: (a) nominal array spacing 500 m; (b) nominal array spacing 1000 m (after Stagpoole & Bibby, 1998) Note : red dash line is inferred subsurface fault after Tianfeng (1980) and Grindley & Mumme (1991)

Table 1. Fluid and gas chemistry data of MA1 sample

Sample label	H (Kj/Kg)	pH	Li	Na	K	Ca	Mg
MA1 (ppm)	177	8.8	8.5	1210	13	1.2	0.24

Sample label	SiO_2	B	Cl	SO_4	HCO_3	$\delta^{18}O$	δ^2H
MA1 (ppm)	264	41	595	35	2090	-5.8	-42

Sample name	G/S $\times 10^6$	CO_2	H_2S	Ar	N_2	CH_4	H_2	He
MA1 (% dry basis)	3000	99.0	0.1	0.0030	0.4	0.62	0.01	0.00014

3.2 Geochemistry

3.2.1 Origin and Classification of Water

The Mangakino geothermal surface manifestations are submerged under Lake Maraetai. Mongillo and Clelland (1984) described the hot spring as clear alkali chloride water with a pH of 8.5, temperature of 98 ºC, and a flow of 2 liters per minute. The water chemistry data in Table 1 come from DSIR's MA1 well survey (Giggenbach, 1994). The $^{\delta18}$O versus $^{\delta2}$H isotope plot indicates that the fluid is derived from meteoric water (Figure 6).

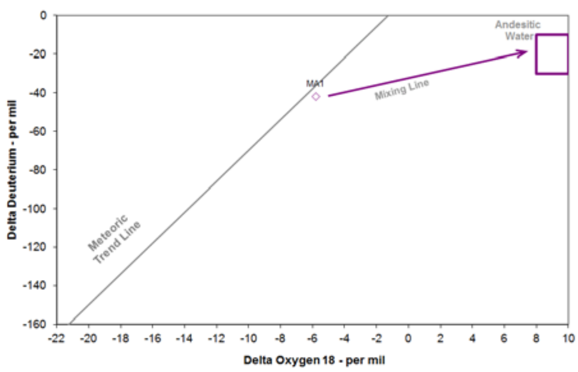

Figure 6. The δ^{18}O versus δ^2H plot for MA1 sample

Based on the SO4-Cl-HCO3 ternary plot, MA1 contains bicarbonate water which can be interpreted as peripheral ground water (Figure 7). Most bicarbonate water, which is typical outflow water, tends to be immature water as a result of Mg mixing from shallower groundwater. One of the possible explanations for such a condition is that this bicarbonate water may be formed as a condensation of the ascending steam/gas, not as an out-flow water. This is consistent with the pressure profile of MA1, which shows constant pressure until 250 m depth (around casing depth), a typical pressure profile for gas/steam. In addition, K species in the water tend to have very little influence on fluid-rock interaction.

The Cl-Li-B ternary plot (Figure 8) shows Mangakino water closer to the B apex than the Cl apex. This suggests that the system is still relatively young. Another possibility is that the high concentrations of boron might be derived from the greywacke lithic fragment incursions scattered within the ignimbrite units in the area.

3.2.2 Origin of Gas

Figure 9 shows the relative concentrations of N2, Ar and He for MA1. Typical groundwater has a specific constant N2/Ar ratio, even after experiencing deep levels circulation and high temperature processes. Meteoric water has negligible He contents and a N2/Ar ratio of about 38. This number will increase due to volcanic or subduction influence as a result of additional N2 from either processes. The MA1 gas tends to fall within a sector of the diagram between the meteoric and magmatic gases with N2/Ar ratio reach 133.

3.2.3. Geothermometry

The N2-CO2-Ar ternary diagram in Figure 10 shows that Mangakino water is close to the line for White Island, which has a CO_2/N_2 ratio of 200 at the Ar corner. The CO_2/N_2 ratio of the MA1 sample is 247. These plots demonstrate that the Mangakino geothermal system may be influenced by subduction processes, especially by the addition of magmatic volatiles to meteoric water.

Geothermometers are normally used to estimate reservoir temperatures based on the following assumptions:

- the concentration of element or species to be used in the geothermometer is controlled only by a temperature-dependent mineral-fluid reaction;
- there is an abundance of the minerals and/or dissolved species to allow the fluid become saturated with respect to the constituents used for geothermometry;
- the reaction attain equilibrium in the reservoir;
- there is negligible re-equilibration as the water flows rapidly to the surface; and
- there is no dilution or mixing of hot and cold waters.

The fluid-rock interaction in the Mangakino area seems much more influenced by Na species through albite precipitation without cation exchange with K species. Hence, the application of K species-basis geothermometers can provide unreliable results. Instead, Na-Ca, Na-Li, chalcedony and quartz geothermometers is used. The geothermometer based on gas ratio is provided as a comparison. The calculation results are shown in Table 2. However, it is important to note that these calculations should be considered with caution since the geothermal fluids are immature waters dominated by mixing with meteoric water.

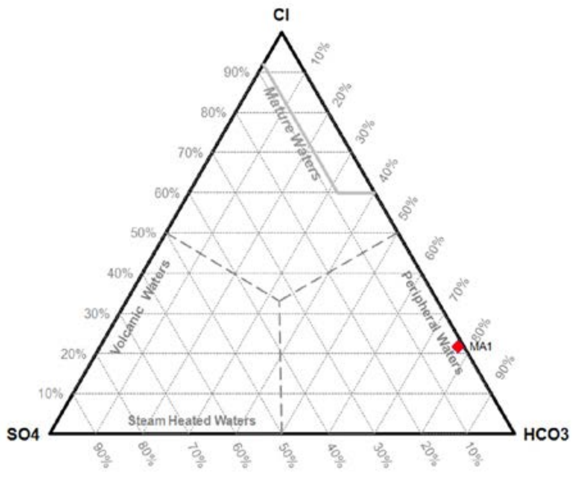

Figure 7. SO_4-Cl-HCO_3 ternary plot for MA1 water

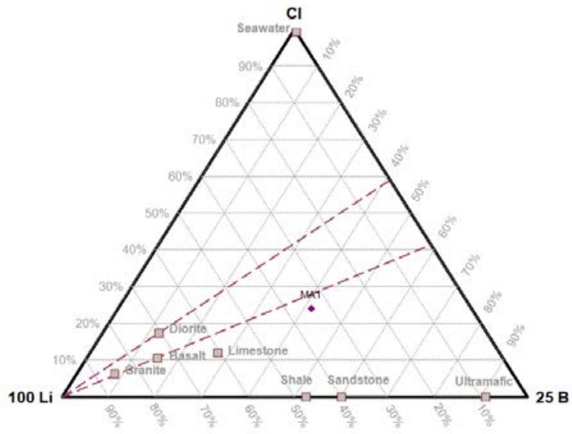

Figure 8. Cl-Li-B ternary plot for MA1 water

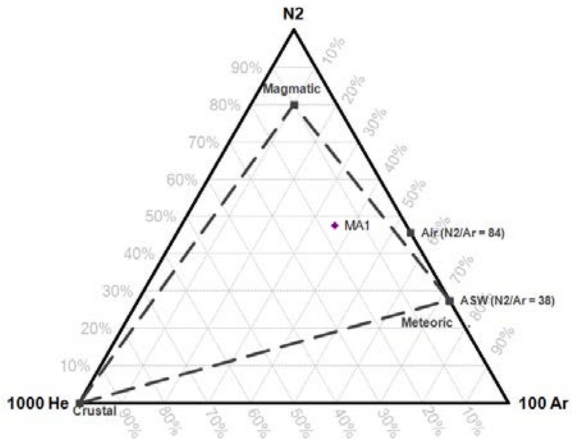

Figure 9. N_2-Ar-He ternary plot for MA1 gas

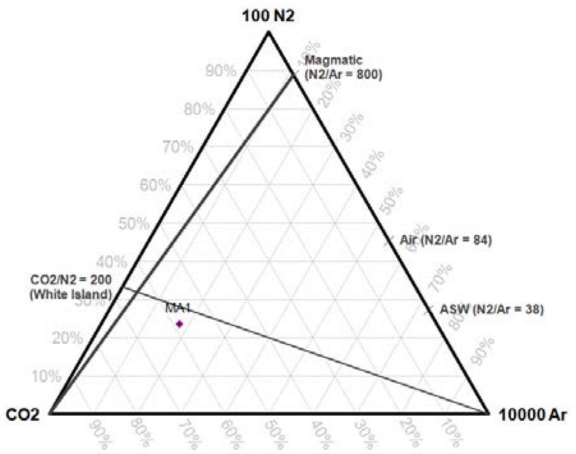

Figure 10. N_2-Ar-CO_2 ternary plot for MA1 gas

Table 2. Indicative reservoir temperatures of Mangakino geothermal system

Geothermometer	Indicative temperature (ºC)	Equation Source
Li-Mg	247	Karakha and Mariner (1989)
Na-Li	269	Kharaka et. al (1982)
Na-Ca	265	Tonani (1980)
Calcedony	182	Fournier (1977)
Quartz Conductive	200	Fournier (1977)
Quartz Adiabatic	184	Fournier (1977)
H_2/Ar	211	Giggenbach (1991)
CH_4/CO_2	291	Giggenbach (1991)

4. POTENTIAL UTILIZATION

4.1. Conceptual Model

In caldera settings, the size of geothermal systems is influenced by the extent of permeable zones beneath the pyroclastic product. When the caldera is overlain by thick, densely welded pyroclastic, the system is limited to the zone near the caldera ring and the crossing faults, contributing to its permeability. Thus, the heat transfer mechanism is mainly conductive while the convective mechanism is only delineated around fault zones (Wohletz & Heiken, 1992). High formation permeability may exist in that system when the pyroclastic has resulted from phreatomagmatic eruptions, whose product shows non-welded or partly welded characteristics. Sometimes, it is characterized by lithic-rich, rather than pumice-rich, fragments.

Hence, the feed zone for Mangakino geothermal system around the fault intersection area is expected to be the Reporoa Group, the middle part of Marshal Ignimbrite, and the middle part of Intracaldera facies, which consists of abundant sandstone fragments. Figure 11 shows a conceptual model of the subsurface geothermal processes in the Mangakino geothermal system.

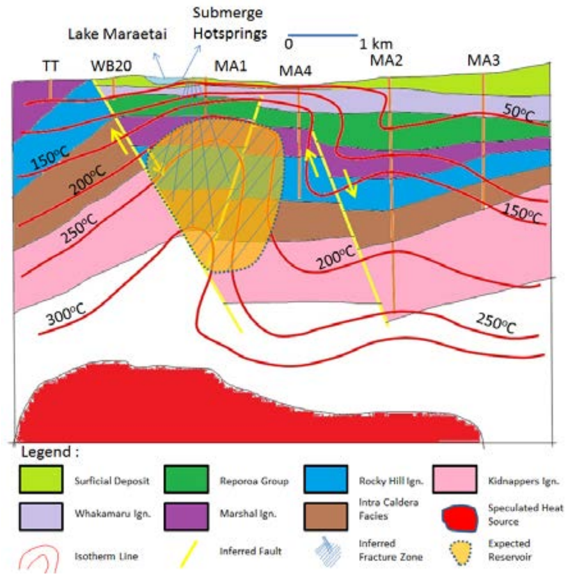

Figure 11.Conceptual model of Mangakino geothermal system (vertical and horizontal scales are the same)

4.2. Resource Assessment

The resource assessment evaluates all data from previous exploration activity. The approach used is the 'probabilistic' Monte Carlo simulation technique. The triangular distribution is mostly used by defining minimum, most likely (modal), and maximum values for each parameter (Figures 12, 13). The estimated ranges for reservoir parameters and type of distributions are given in Table 3.

The assessment uses the stored heat method from the Australian Geothermal Reporting Code Committee (AGRCC, 2010). Monte Carlo simulation with 50,000 trials shows that total stored heat of about 887 PJ at Percentile 10 (P10) (pessimistic scenario), 1392 PJ at P50 (moderate scenario), and 2229 PJ at P90 (optimistic scenario). This means that the most likely value of the total stored heat is 1485 PJ and 1024 PJ, respectively. Thus, the potential power capacity that can be developed from the Mangakino geothermal system is about 10.42 MWe at P10, 16.36 MWe at P50 and 26.18 at P90. The mean and most likely values are 17.44 MWe and 12.03 Me.

4.3 Potential Direct Use

Geothermal energy is used for domestic, industrial and commercial direct heat applications, including greenhouse heating, timber and wood processing.

Geothermal energy could benefit local timber processing operations in terms of: i) reducing raw material and waste disposal costs, (ii) revenue opportunities for adding value to residue currently used as heating fuel, (iii) carbon emission reduction – carbon tax saving, (iv) higher efficiency and lower cost (about 50 % cheaper than other fuel costs) (Suckling et al., 2014).

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The lithology of Mangakino area is dominated by ignimbrite intercalated by a few of sedimentary deposits. The Reporoa Group, Marshal Ignimbrite (middle part), and Intracaldera facies (middle part), which has non–

welded/weakly welded characteristics with abundant lithic fragments, are expected to be the potential feed zone. The permeability in those units might have been enhanced by reactivation of old and inactive subsurface structures through reopening mechanisms near the fault intersection areas where the geothermal upflow in Mangakino concentrates.

Table 3. Estimated ranges of Mangakino reservoir parameters and their type of probability distribution

Parameter	Min	Max	Most likely	Units	Probability Distribution	Remarks (Source)
Area (A)	3	9	3	km2	Triangular	Minimum and maximum value is the area with resistivity value 30 Ω on GNS resistivity map nominating array 500 m and 1000 m, respectively (Staagpoole and Bibby, 1998)
Thickness (h)	0.65	1.75	1.75	km	Triangular	Minimum and maximum value is the thickness with low vertical resistivity and the thickness from Reporoa Group to Volcanic sandstone in Intracaldera facies respectively. (Fagan, 2007)
Reservoir Temperature (Ti)	265	291	265	°C	Triangular	The minimum and maximum value is the temperature indicated by Na-Ca and CH4/CO2 Geothermometer respectively. (Section 3. Geothermometer this report)
Rock Density (ρr)	2274			kg/m3	Constant	Measurement Data in Fagan (2007)
Heat Capacity (Cr)	0.9			KJ/kg.K	Constant	SKM (2002)
Cut Off Temperature (Tf)	180			°C	Constant	Zarrouk and Moon (2014)
Porosity (ϕ)	0.158				Constant	Measurement Data in Fagan (2007)
Water Saturation (Sw)	1				Constant	Assumption no steam present, SKM (2002)
Recovery Factor (Rf)	0.1				Constant	Low Confidence Assumption
Conversion Efficiency (ηc)	0.1				Constant	Zarrouk and Moon (2014)
Plant Capacity Factor (F)	0.9				Constant	Zarrouk and Moon (2014)
Power Plant Life (PL)	30			years	Constant	General Assumption

Fagan's (2007) hydrothermal alteration study suggests Mangakino system has been cooled in some area near MA2 and MA3. However, there may be s a rejuvenation process, especially near MA1 and MA4, which may be simultaneously with the reactivation of the old fault. These processes might have correlations with the recent regional tectonic and volcanic activity because the analysis of Cl-Li-B, N_2-Ar-He and N_2-Ar-CO2 ternary plots indicates that the geothermal system of Mangakino is a young system which is influenced by additional magmatic volatile.

The Cl-SO_4-HCO_3 ternary plot of the MA1 sample suggests that the water is bicarbonate water resulting from steam condensation, as indicated by the Na-K-Mg plot and downhole pressure profile. Based on isotope analysis, the water originated from meteoric water. The fluid-rock interaction at Mangakino seems to be controlled by Na species through albite precipitation and less by cation K species. Hence, the application of K species-basis geothermometers such as Na-K-Ca, Na- K, or Na-Mg is not appropriate. For resource estimation, the most reliable temperatures are those indicated by Na-Ca and CH_4/CO_2 geothermometers, which range from 265 °C to 295 °C.

The resource assessment in this study used the stored heat method combined with the Monte Carlo simulation technique. The analysis estimated the total stored heat to range from 887 PJ at P10 (pessimistic scenario), to 2229 PJ at P90 (optimistic scenario). Thus, the potential power capacity that can be developed in the Mangakino geothermal system is about 10 MWe at P10 to 26 MWe at P90. This more refined potential power capacity is on the lower range of that predicted in the SKM (2002) analysis which was between 20 MWe at P10 and 90 MWe at P90 that was carried out before exploration drilling of 2004-2005. This work indicates that the Mangakino geothermal system might not be very attractive for large scale electricity generation. However, timber industry has high potential for geothermal energy use in New Zealand. Mangakino is located close to some of the country's largest wood processing plants in Tokoroa. Geothermal energy could benefit timber operations in terms of: i) reducing raw material and waste disposal costs, (ii) revenue opportunities for processing of residue that was used as heating fuel before, (iii) carbon emission reduction – carbon tax saving, and (iv) higher efficiency and lower cost.

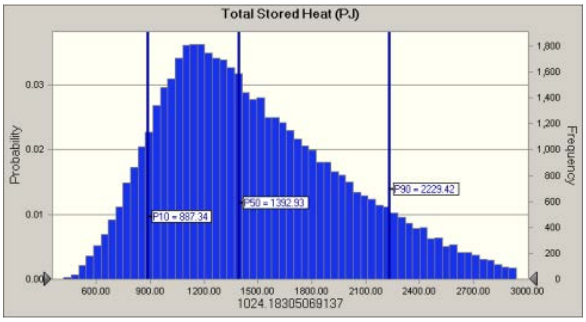

Figure 12. The probability distribution of total stored heat in the Mangakino geothermal system

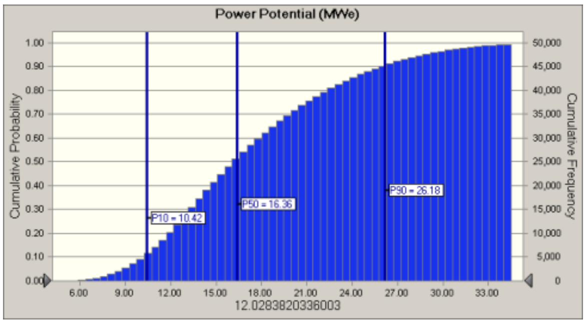

Figure 13. The probability distribution of Power potential capacity in the Mangakino geothermal system

5.2. Recommendations

It is recommended to carry out more detailed geological structural analyses, especially in low resistivity areas. If necessary, a detailed micro seismic survey can be done to proxy subsurface structure as fluid path. Once the analysis shows positive result about the availability of high permeability zone, one or more slim-hole drilling programs of about 1000 m depth near the MA1 well should be carried out for resource confirmation.

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