OPTIMAL SETTINGS FOR DIRECT GEOTHERMAL USE INVESTIGATED WITH NUMERICAL MODELLING

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ABSTRACT

Geothermal energy has been used in the central part of the North Island of New Zealand since people first settled there. Traditionally it was used for bathing and cooking. During the 20th century, uses expanded to include heating and cooling of buildings, green houses and aquaculture farming. Direct geothermal use tends to be located in areas where there is a known heat source with easily accessible heated water; many of New Zealand's direct use applications are focussed within the Taupo Volcanic Zone, or in areas with hot springs such as Hanmer Springs in the South Island. With the New Zealand government's ambitious targets to reduce fossil fuel dependencies, clean and efficient sources of energy will become increasingly important. Determining the potential, and potential limitations, of low-temperature geothermal energy will be important to help in establishing the contribution that it can make to the nation's energy ambitions.

This project aims to identify the ideal settings for low-temperature heat extraction. We will use numerical modelling to determine what rock properties and thermal characteristics result in usable low-temperature geothermal systems. We will distinguish key settings that are suitable for different direct use technologies such as ground-source heat pumps, residential warm water extraction or direct heating for small-scale commercial industry. We can then start to build up a map of the most promising types of geothermal use for different regions in New Zealand.

1. INTRODUCTION

Geothermal energy (subsurface heat) is available throughout New Zealand's varied geological settings. High-temperature geothermal systems (>225°C) are localised and generally have magmatic sources, such as in the Taupo Volcanic Zone. Low-temperature systems (<150°C) are found on the North and South Islands, and are usually related to young volcanism, deep faults or tectonic features (Climo, Milicich, & White, 2016). The temperature of the geothermal system dictates its potential use (Figure 1), although cascaded use allows for multiple applications to be run from one source, as fluid temperature decreases after each use.

Electricity generation from high-temperature systems is the most publicly recognized use of geothermal resources (Doody & Becker, 2010). However, Māori have used hot springs for bathing and cooking since their migration to New Zealand (Climo, Milicich, & White, 2016). Direct use applications expanded during the 20th century to include industrial processes, heating and cooling of buildings, green houses (agriculture), and aquaculture farming.

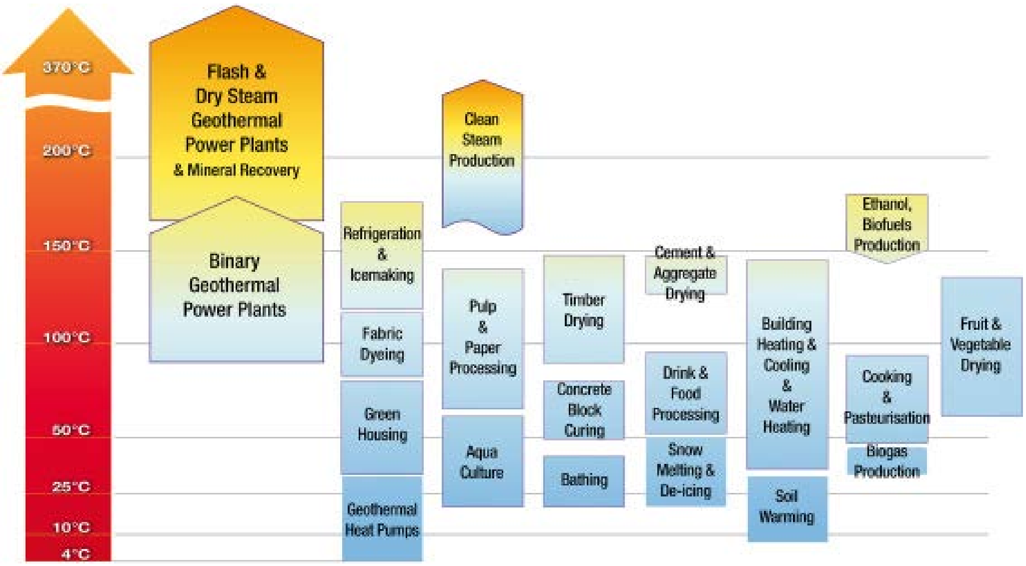

Figure 1 Diagram showing potential uses for geothermal resources as a function of the temperature required for the process (Climo, Milicich, & White, 2016).

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Directly using geothermal energy in homes and commercial operations can be much less expensive than traditional fuels (e.g. gas, coal, wood products). It can be as much as 80% cheaper than fossil fuels (U.S. Department of Energy, 2004). It is thought to be at least twice as efficient as converting geothermal energy for electricity generation (Lund & Toth, 2020). It is also clean, producing almost no air pollution. Although direct geothermal use has increased over the decades, in New Zealand this has predominantly been in regions of high-temperature geothermal systems and in places using waste heat from electricity production. There is considered to be significant untapped potential in other areas.

New Zealand's 2019 Zero Carbon Act has set a target to reduce net emissions of greenhouse gases to zero by 2050 (Ministry for the Environment, 2019). Electricity generation is currently ~80% renewable, with a target of 100% by 2035 (Daysh, et al., 2020). There is an increasing emphasis on direct geothermal use to complement renewable electricity generation. In this paper we will summarise direct use in New Zealand and explore geological and thermal conditions that are optimal for direct use of warm water as part of the country's move to a low carbon future.

2. DIRECT USE IN NEW ZEALAND

New Zealand has the fifth largest direct energy use in the world if geothermal (ground source) heat pumps are not included (Lund & Toth, 2020). It equates to almost 10,000 TJ/year, over half of which is used for industrial wood-processing at Kawerau (Daysh, et al., 2020).

A comprehensive history of direct use in New Zealand can be found in Climo et al. (2016). In the past few years, direct use has gained significant momentum with the New Zealand Geothermal Association's Geoheat Strategy for Aotearoa NZ 2017-2030, and with central, regional and local government initiatives (Climo, et al., 2020). The total energy used has increased from 8,500 TJ/year in 2015 to 9,700 TJ/year in 2019. Geothermal heat pump use has increased from 70 TJ/year in 2015 to 400 TJ/year in 2019 (Daysh, et al., 2020).

The majority of geothermal direct use is in the Waikato and Bay of Plenty regions, close to the high-temperature systems of Rotorua and Taupo (Figure 2). Elsewhere in the country, bathing is the primary application of direct geothermal use. Other uses include space heating, tourism, and ground source heat pumps (Daysh, et al., 2020) (Figure 3). Much of the recent increase in ground source heat pump use is in Christchurch as the city rebuilds after the 2010 / 2011 Canterbury earthquakes (Seward & Carey, 2020).

There are more than ten identified low-temperature geothermal systems in New Zealand (Soengkono, Bromley, Reeves, Bennie, & Graham, 2013), and more than 100 hot springs of which less than 20% are estimated to be used (Thain, Reyes, & Hunt, 2006). Fluid flow has been modelled at the Tauranga and Whitford low-temperature systems, where the warm water resources (<70°C) have a range of uses including bathing, agriculture, frost protection, aquaculture, and heating (Pearson, Alcaraz, & Barber, 2014; Molière, 2010). At Tauranga, heat is primarily conducted through the rock to shallow depths where increased permeability allows fluid extraction (Pearson-Grant & Burnell, 2018; Pearson, Alcaraz, & Barber, 2014). At Whitford, heat flow is predominantly conductive but with fractures that allow convection of warm water towards the surface (Molière, 2010). This paper presents a smaller-scale model based on central Tauranga, which will be used to determine what rock properties and thermal settings allow low-temperature geothermal fluids to flow close enough to the surface to be extractable.

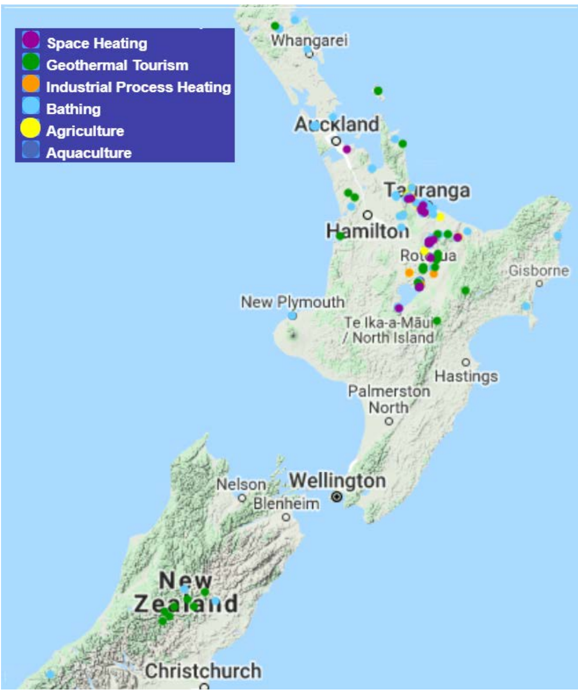

Figure 2 Map showing the locations of different types of direct use in New Zealand (from https://data.gns.cri.nz/geothermal/wms.html).

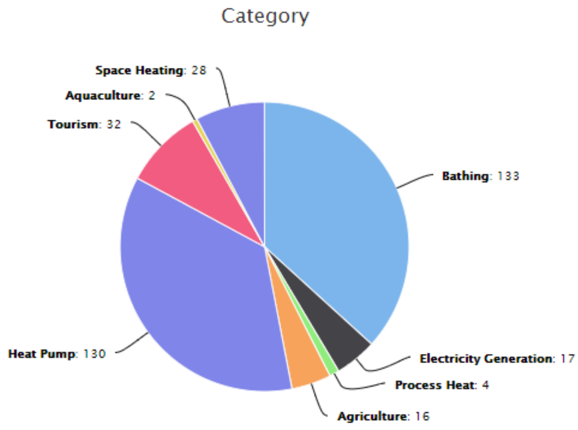

Figure 3 Number of installations of different types of geothermal use in New Zealand (from https://data.gns.cri.nz/geothermal/charts.html).

3. NEW ZEALAND'S THERMAL REGIMES

Ambient heat flow through the continental crust in New Zealand is around 50-60 mW/m², which is consistent with mature continental crust that has cooled since rifting in the Late Cretaceous (Allis, Funnell, & Zhan, 1998). Much of New Zealand has higher heat flow than this however (Figure 4). Slightly elevated heat flow is thought to be the result of Late Neogene tectonism (Allis, Funnell, & Zhan, 1998). Higher heat flow, of over 80 mW/m², is found in several regions in the North and South Islands (Figure 4; Coussens, et al., 2018; Pandey, 1981; Allis, Funnell, & Zhan, 1998; Zarrouk & Moore, 2007), the most extensive of which are described in this section.

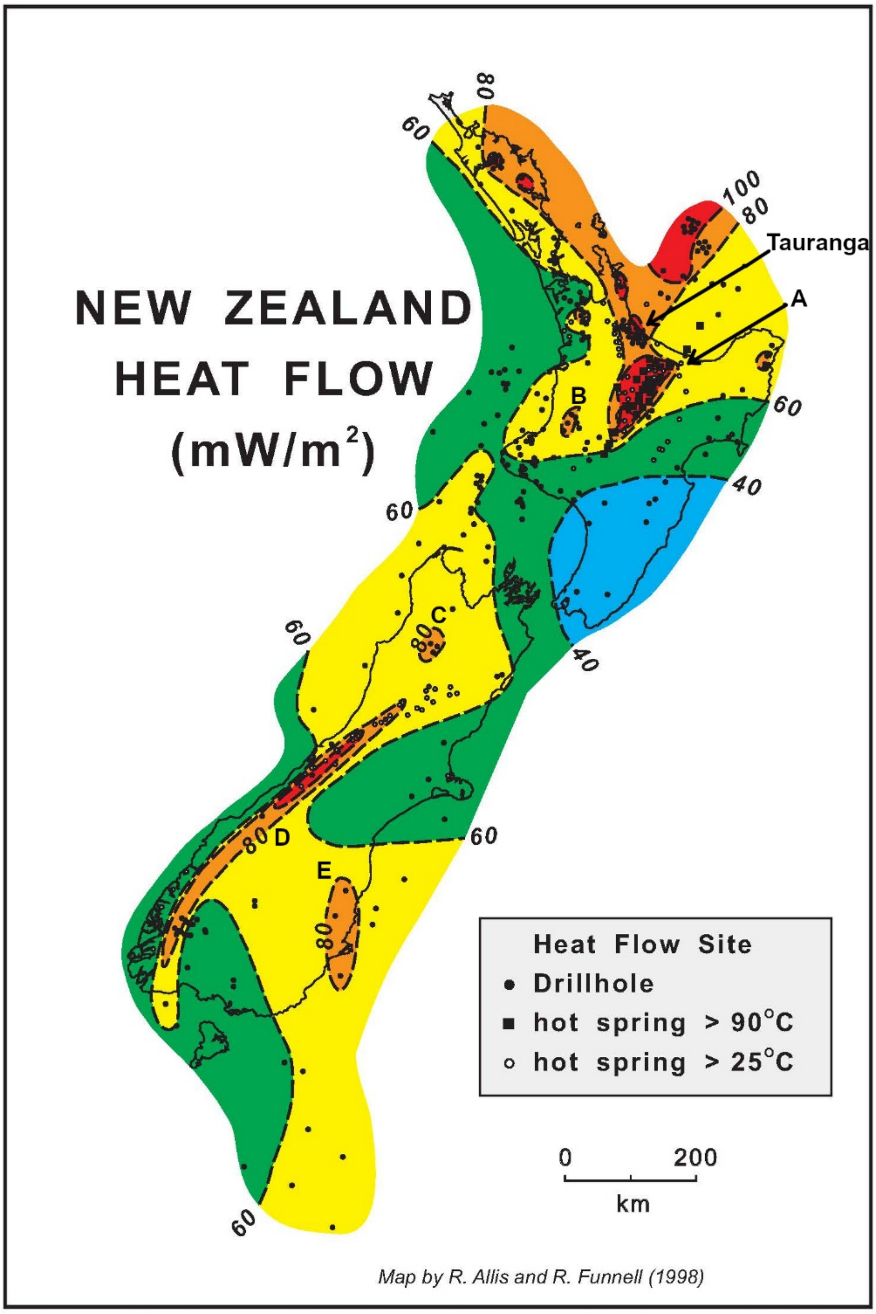

Figure 4 Heat flow map of New Zealand, adapted from Allis, Funnell, & Zhan (1998). Areas with anomalously high heat flow are A) Taupo Volcanic Zone, B) Taranaki Basin, C) Murchison, D) Southern Alps, and E) Dunedin.

The region with the highest heat flow in New Zealand is the Taupo Volcanic Zone in the central North Island (Figure 4-A), and its off-shore extension into the Havre Trough. Average heat flow in this area is 700 mW/m² due to convective fluid flow related to extensive volcanism and rapid magma production along with a thin crust (Bibby, Caldwell, Davey, & Webb, 1995). Pliocene-Recent rhyolitic volcanism has caused adjacent high heat flow through the Coromandel Peninsula into eastern Northland (Allis, Funnell, & Zhan, 1998).

Uplift and erosion have resulted in elevated heat flow in the Taranaki Basin in the North Island, and around Murchison and along the Southern Alps in the South Island (Allis, Funnell, & Zhan, 1998; Townend, 1999)(Figure 4 – B to D). The central Southern Alps is an interesting example, where rapid exhumation has resulted in temperatures of at least 200°C at <5km depth (Allis, Funnell, & Zhan, 1998). High heat flow in the southeast part of the South Island coincides with the Late Miocene Dunedin basaltic volcanic complex (Allis, Funnell, & Zhan, 1998) (Figure 4-E). All of these areas could be considered as prospects for increased direct geothermal heat use.

5. CASE STUDY: TAURANGA

Tauranga in the Coromandel Volcanic Zone in the North Island of New Zealand (Figure 4) was the site of volcanic activity until ~2 million years ago. It now hosts a warm-water resource that is extracted from by several hundred users (Pearson-Grant & Burnell, 2018). The maximum measured downhole temperature is 67°C at 750 m depth (Pearson, Alcaraz, & Barber, 2014).

As with most low-temperature geothermal systems, heat transfer within the Tauranga system appears to be predominantly conductive. Temperature profiles are typically roughly linear, as temperature increases with depth according to the geothermal gradient (e.g. Figure 5, wells d,e). However, in the centre of the field where the hottest temperatures and shallowest producing wells are found, heat transfer appears to be convective. In this case, there is a threshold where the temperature does not increase as rapidly with depth because the fluid can flow relatively freely (e.g. Figure 5, wells a-c). It can be difficult to extract fluid from conductive systems as permeabilities are often too low for fluid and heat to be replenished, whereas fully convective systems generally need a vigorous heat source to maintain fluid temperature. Understanding the thermal and fluid flow processes within low-temperature systems is fundamental to determining the characteristics of systems that have extractable heated water, and what the effects of extraction would be.

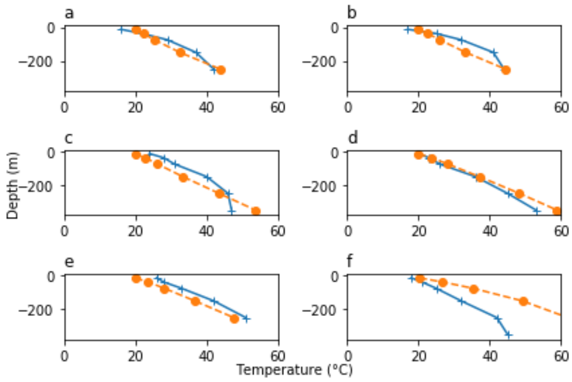

Figure 5 Temperature profiles in the Tauranga region, shown in blue. Orange symbols show modelled temperatures, with primarily conductive heat transfer.

In this study, we focus on a 5km by 5km region in central Tauranga where both conductive and convective heat transport processes appear to be operating. We created a TOUGH2 model (Figure 6) to try to determine the permeability, heat flow and thermal conductivity ranges likely for this system. The TOUGH2 modelling process and parameters are described in (Pearson-Grant & Burnell, 2018). We then used PEST and PEST++ suites (Doherty, 2015; White, Hunt, Doherty, & Fienen, 2020) to begin to explore the range of model parameters that can sufficiently reproduce measured temperature profiles with depth in local boreholes (Figure 6).

5. RESULTS AND DISCUSSION

Figure 5 shows the model-to-measurement fit using the parameter values estimated through calibration of a field-scale model in Pearson-Grant & Burnell (2018, Table 1). Observed temperature profiles that suggest conductive heat transfer are replicated well. Observed profiles that suggest convective heat transfer, on the other hand, are not. This indicates that the convective thermal process is not being captured in the model and that the northern part of the model must have variations in geology or heat flow compared to the southern part. By estimating subsurface properties in this portion of the model separately to those elsewhere using PEST's Gauss-Levenberg-Marquardt algorithm, an improved fit to the convective profiles could be achieved; however, the corresponding fit to conductive profiles got worse (Figure 7). This suggests that the current range of model parameters need modifying to better capture the thermal processes and their variability in this system.

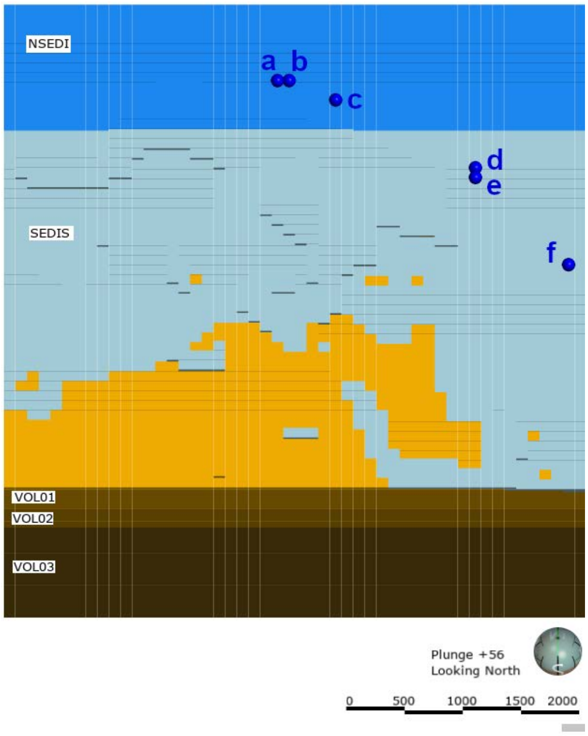

Figure 6 Model grid looking obliquely down from the south. Different colours correspond to different rock types as labelled (see Table 1). Locations of wells with temperature-depth profiles in the Tauranga region are labelled in blue.

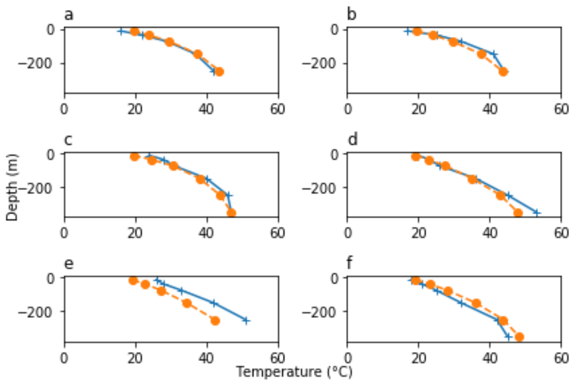

Figure 7 Temperature profiles in the Tauranga region when the rock and thermal properties in the northern part of the model are estimated separately to those elsewhere. Modelled temperature profiles (orange) are generally closer to measured (blue).

Table 1 Model parameters for original field-scale calibrated Tauranga model, compared to calibrated parameter values found when the model is divided into northern and southern areas. Rock types can be seen in Figure 6, with N indicating those under the northern part of the model. Permeability, thermal conductivity and heat flow values were best-fit estimates from the modelling process so far.

Model	Rock type	Permeability (m²)		Thermal Conductivity	Heat Flow
		Lateral	Vertical	(W/mK)	(mW/m²)
original	SEDIS	2.50E-14	2.50E-15	1.25	2.00E+02
south	SEDIS	1.00E-16	2.23E-16	1.00	1.02E+02
north	NSEDI	1.00E-13	2.81E-16	1.00	1.02E+02
original	VOL01	2.50E-14	2.50E-15	1.80	2.00E+02
south	VOL01	4.56E-16	1.31E-16	1.00	1.02E+02
north	NVOL1	2.22E-16	2.91E-15	2.19	1.02E+02
original	VOL02	1.00E-14	1.00E-15	1.80	2.00E+02
south	VOL02	1.00E-13	4.37E-16	2.50	1.02E+02
north	NVOL2	1.00E-16	2.38E-15	2.50	1.02E+02
original	VOL03	1.00E-16	1.00E-17	1.80	2.00E+02
south	VOL03	3.26E-17	2.23E-18	2.50	1.02E+02
north	NVOL3	7.66E-17	3.67E-17	1.00	1.02E+02

Table 2 Parameter ranges for Monte Carlo simulations. The vertical permeability was higher in the northern part of the model to encourage enhanced fluid flow, all other parameters were given a uniform range across the model.

Parameter	Rock type	Units	Minimum	Maximum
Lateral permeability	SEDIS	m²	5.00E-15	5.00E-14
Lateral permeability	VOL01	m²	5.00E-15	5.00E-14
Lateral permeability	VOL02	m²	5.00E-15	5.00E-14
Lateral permeability	VOL03	m²	1.00E-17	1.00E-15
Vertical permeability	S SEDIS	m²	5.00E-16	1.00E-14
Vertical permeability	S VOL01	m²	5.00E-16	1.00E-14
Vertical permeability	S VOL02	m²	5.00E-16	1.00E-14
Vertical permeability	S VOL03	m²	1.00E-18	1.00E-16
Vertical permeability	N SEDIS	m²	5.00E-15	5.00E-14
Vertical permeability	N VOL01	m²	5.00E-15	5.00E-14
Vertical permeability	N VOL02	m²	5.00E-15	5.00E-14
Vertical permeability	N VOL03	m²	1.00E-17	1.00E-15
Thermal conductivity		W/mK	1.2	2.5
Heat flow		mW/m²	120	250

To explore the range of plausible rock and thermal properties that might give rise to processes such as those observed in the Tauranga system, we carried out a Monte Carlo simulation using the PEST++ suite. Specifically, we created 50 different versions of the model with realisations of model parameters from a "prior" Bayesian stance, defining the upper and lower bounds based on expert knowledge and previous modelling efforts (Pearson, Alcaraz, & Barber, 2014; Pearson-Grant & Burnell, 2018). These bounds were then reduced to limit the occurrence of boiling, which there is no evidence for in Tauranga and which increased the computational time significantly. We evaluated each realisation by running the model forward.

We then compared the resulting probability distributions of modelled temperatures and temperature profiles with observations (Figure 8). By assessing the extent to which these probability distributions encompass observed values, we can start to explore how well the model can predict these quantities of interest – beyond that possible by assessing model-to-measurement misfit in a deterministic sense (e.g., Figure 5). To the south of the model area, observed temperatures fall within the range of modelled temperatures (Figure 8a), but in the north no combination of heat flow, permeability and thermal conductivity within our ranges results in the model getting hot enough (Figure 8b). Therefore, our ranges for parameter estimates need to be increased.

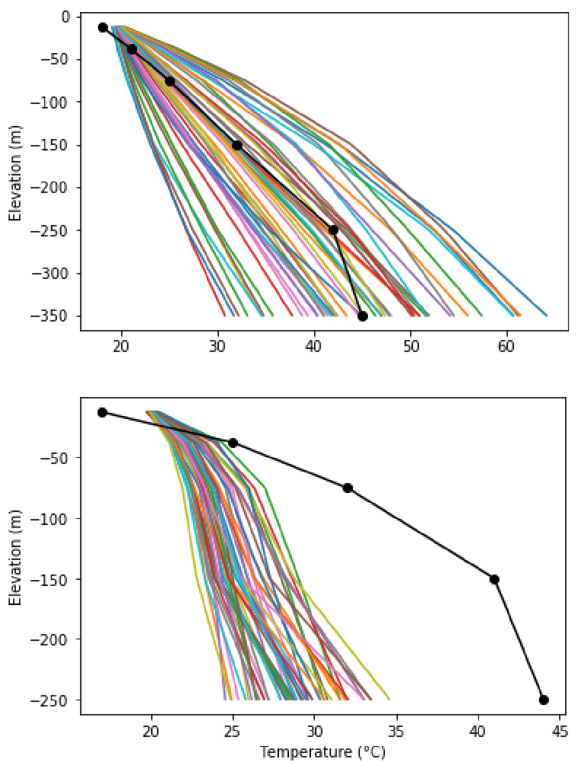

Figure 8 Temperature profiles with depth for all 50 model realisations (coloured lines) and measured observations (black circles and lines). Top) well f, Bottom) well b.

6. SUMMARY AND FUTURE DIRECTIONS

Low-temperature systems are primarily conductive, but this can make fluid extraction for direct use unfeasible. Fractures combined with reasonably high heat flow at depth, or increased permeability near the surface, can create a system that allows direct fluid extraction. Our models are the first step to determining what permeability and heat flow combinations are optimal for direct use.

To use New Zealand's low-temperature geothermal systems for direct use, we need to better understand their thermal settings. In central Tauranga for example, there is some convection that allows warm fluid to reach shallow depths. Field-wide modelling struggles to replicate this, particularly when calibrated on temperatures alone.

There are several steps that we have identified that may help the model to more closely represent this complexity that we will address moving forward. The first is to modify the ranges of model parameters based on the Monte Carlo simulation, particularly in the northern half of the model. The second is to calibrate the models against the temperature gradient in wells with downhole temperature profiles, to ensure that the dominant convective or conductive process is correctly captured. The third is to calibrate against pressure or water level data. In Tauranga, the available data is limited to seasonal changes in water level in response to extraction, but this can provide valuable insight (Pearson-Grant & Burnell, 2018).

We will further extend the parameter estimation and uncertainty analysis framework to make more generic models. With these, we will explore the full range of rock and thermal characteristics that are appropriate for a low-temperature geothermal system. We can apply this to the known systems in New Zealand, to determine which are likely to have warm water that can be extracted directly for local use and to look for other regions where we might expect similar properties.

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