Investigating Influences on Hydrothermal Fluid Flow in the Taupō Volcanic Zone with Numerical Models Constrained by Magnetotellurics

Sophie Pearson-Grant[1], Edward Bertrand[1] and Lucy Carson[2]

[1] GNS Science, 1 Fairway Drive, Avalon, Lower Hutt 5010, New Zealand

[2] Wairakei Research Centre, GNS Science, 114 Karetoto Road, RD4, Taupō 3384, New Zealand

s.pearson-grant@gns.cri.nz

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ABSTRACT

There are 23 high-temperature geothermal fields in the central Taupō Volcanic Zone (TVZ), discharging ~4200 GW of heat. Magnetotelluric (MT) surveys over large areas in the central TVZ have detected eight low-resistivity anomalies (i.e. plumes) in the brittle part of the crust. These plumes are interpreted as upwelling hot geothermal fluids with high conductivity compared to the surrounding cold-water-saturated meta-sedimentary basement rocks. The upper extents of these conductive plumes correspond well with the surface expressions of most geothermal fields, but not all.

We have used TOUGH2 numerical modelling software to explore regional influences on subsurface geothermal fluid circulation. We created simplified models with uniform geology and:

1. localised heat sources at 5 km depth as modelled from MT data.
2. surface elevation variations based on the water table (a muted reflection of topography).
3. a combination of influences 1 and 2.

We then compared resulting modelled zones of high temperature at 500 m depth with geothermal field boundaries as delineated by DC resistivity measurements.

Modelled upflow zones correspond extremely well with some of the known geothermal fields, such as Tikitere and Ngatamariki. In other areas, e.g. Waimangu and Rotokawa geothermal fields, modelled upflow zones are in the right geographic regions but have different lateral extents.

Beneath the Haroharo Volcanic Complex in the Okataina Volcanic Centre, a conductive plume and modelled upflow do not underlie any areas of hydrothermal activity at the surface. Here, we hypothesise that mapped or previously unidentified geological structures such as faults or volcanic domes may be influencing regional geothermal circulation. Some fields are not explained by MT anomalies or topographic effects, and these will be the subjects for future studies.

1. INTRODUCTION

The TVZ in the North Island of New Zealand is one of the most geothermally active regions on Earth. It discharges ~4200 GW of heat through 23 high-temperature geothermal systems (Bibby et al., 1995). These systems are concentrated in the centre of the TVZ (Figure 1) and appear to have been stable for 10s of thousands of years (Milicich et al., 2018). There are still questions however about the longevity, locations and potential connections between systems at depth, which are important for geothermal exploration and managing fluid extraction sustainably.

Previous numerical modelling has suggested that permeability distribution, localised heat sources, and surface topography may be strong influences on hydrothermal fluid flow in the TVZ (Dempsey et al., 2011; Kissling & Weir, 2005; Pearson-Grant et al., 2022; Pearson-Grant & Bertrand, 2021; Ratouis & Zarrouk, 2016). In this paper, we build on these studies with generalised models of the TVZ constrained by magnetotelluric (MT) data.

1.1 Magnetotelluric Surveys

For more than 20 years, broadband MT data have been measured in the TVZ to image the electrical conductivity (or inversely resistivity) structure of the crust and upper mantle. Since any rock that contains interconnected high-temperature fluid, or that is partially molten, becomes orders of magnitude more conductive (i.e. less resistive), MT data are very sensitive to the presence of fluids and melt in the subsurface.

Initially, regional MT surveys in the TVZ were designed to image resistivity structure at 30-40 km depths to investigate rifting processes and structure (e.g. Heise et al., 2007, 2010). More local surveys were also undertaken at geothermal field-scale to investigate shallow structures (upper 3 km) motivated by power development (Heise et al., 2008). Since 2009, GNS Science have made MT measurements across large areas of the TVZ at 2 km site-spacing to research heat transport processes in the brittle part of the crust (e.g. Bertrand et al., 2012, 2013, 2015, 2022; Heise et al., 2016). These more recent MT data form arrays that were specifically designed to image connections between the locations of the geothermal fields and the underlying magmatic systems that supply the heat.

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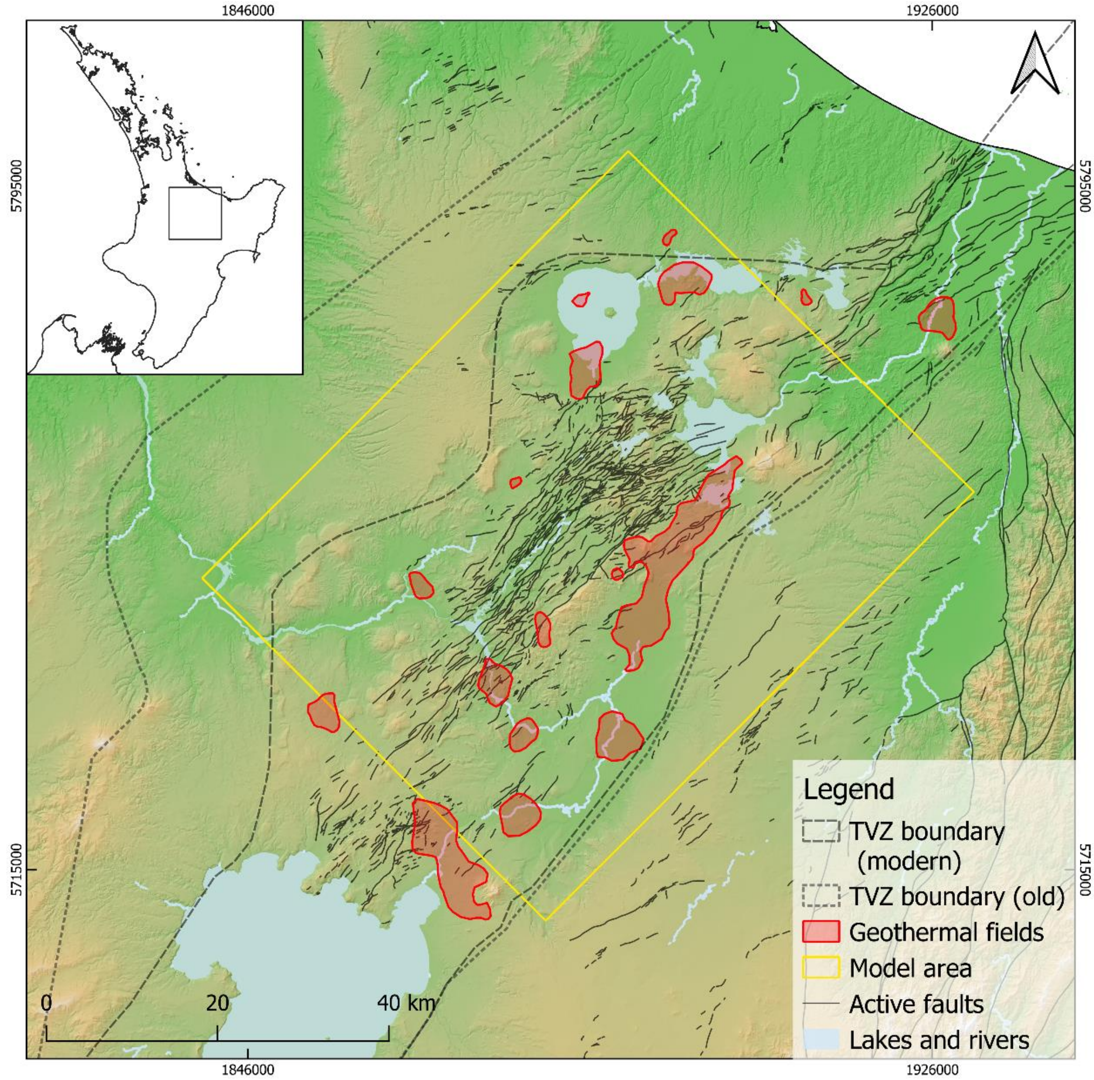

Figure 1 Location map showing the model area, boundaries of the TVZ (Wilson et al., 1995) and active faults (Langridge et al., 2016). Geothermal field locations are derived from DC resistivity data (Bibby et al., 1995). Inset: map of North Island of New Zealand.

Published resistivity inversion models from subsets of these MT array data (Figure 2; Bertrand et al., 2015, 2022) have imaged eight low-resistivity plumes in the TVZ crust – with all but one of these plumes connecting at shallow depths to the location of a known geothermal field. The one exception is located beneath the Haroharo Volcanic Complex in the Okataina Volcanic Centre (Figure 2), where a low-resistivity plume does not reach the surface and may represent a 'blind' deep geothermal resource in the TVZ (Bertrand et al., 2022). Young (resistive) rhyolite lavas overlie this plume and likely pose an impermeable barrier to upward fluid flow. A similar situation may occur (in-part) northwest of Ohaaki, where there is offset between the low-resistivity plume in the basement rocks and the surface expression of the geothermal field (Bertrand et al., 2013).

Importantly, by imaging the electrical resistivity structure of the basement rocks in the TVZ crust, ascending pathways of heat transport from the underlying magmatic systems are revealed. Understanding the variability observed in these pathways and implications to the geothermal systems can then be investigated by hypothesis testing using generalised numerical models.

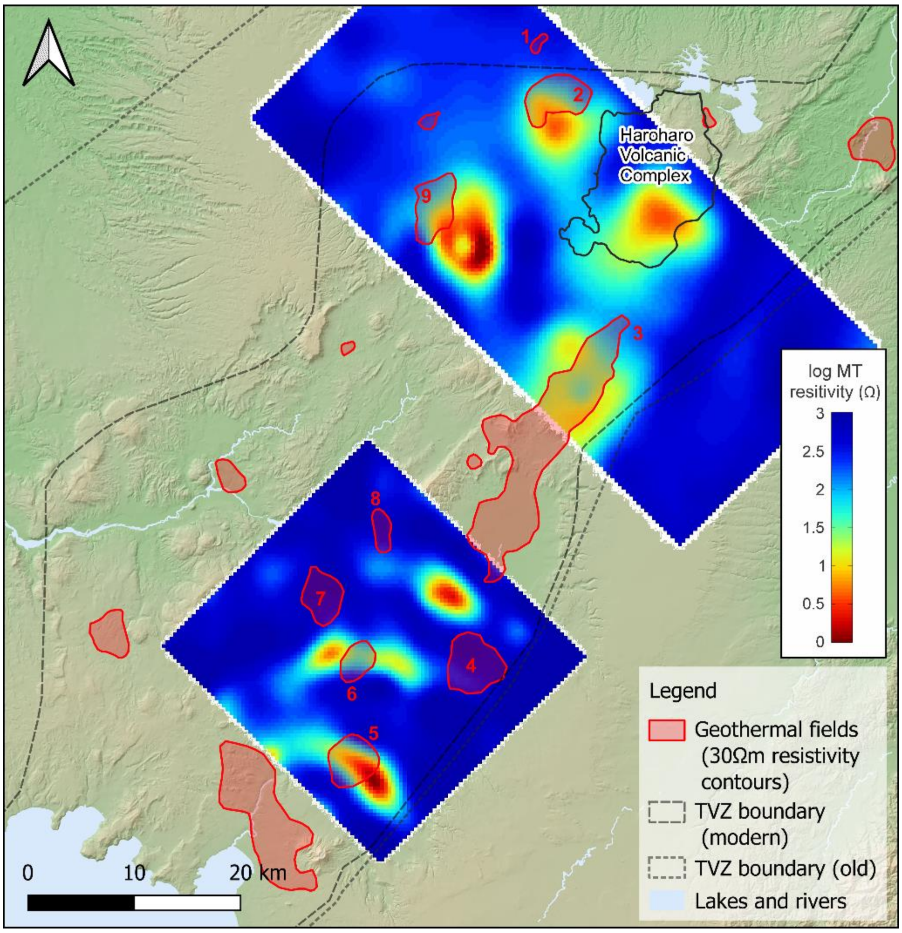

Figure 2. Map of the central TVZ with published resistivity inversion models overlaid in the white-outlined boxes (Bertrand et al., 2015, 2022). The resistivity inversion models image localised low-resistivity zones in the crust. Red shapes and labels correspond to surface locations of geothermal fields (Bibby et al., 1995). 1=Taheke, 2=Tikitere, 3=Waimangu, 4=Ohaaki, 5=Rotokawa, 6=Ngatamariki, 7=Orakei Korako, 8=Te Kopia, 9=Rotorua.

2. METHOD

We used TOUGH2 software to create heat and fluid flow models of the TVZ (see Figure 1). Leapfrog Geothermal was used to turn a simple geological model (Alcaraz et al., 2012) into a block model that could be used in TOUGH2. The model area covers 57 km by 71.5 km and extends to 5 km depth below sea level. Grid blocks measure 500 m by 500 m horizontally, and 250 m vertically (Figure 3).

The models are fully saturated, and their top boundaries follow the water table. The water table was calculated from the topography (Westerhoff et al., 2018), with a model height of between 0 and 1000 metres above sea level (Figure 3). The model grid is rectangular, but results are only shown for areas where MT models are available (see Figure 2). Geology was uniform, with a permeability of 5 x 10^{-15} m^2 based on previous work (Pearson-Grant & Bertrand, 2021).

A heat source of 700 mW/m² at the base of the uniform-heat models was used as a representative average of the TVZ (Bibby et al., 1995). To simulate localised heat sources corresponding to MT anomalies, elevated heat flux of 2200 mW/m² was put into the base of models in the areas where MT resistivity was less than 30 Ωm at 5 km depth (see Figure 2). 200 mW/m² was used everywhere outside the localised heat sources for these models, to give an average heat flux of 700 mW/m² across the TVZ.

We ran the models for 50,000 years, by which time model temperatures and pressures had stabilised. Resulting model temperatures at 250 mbsl were compared with geothermal field locations derived from DC resistivity data (Figure 1)(Bibby et al., 1995; Pearson-Grant & Bertrand, 2021; Stagpoole & Bibby, 1998).

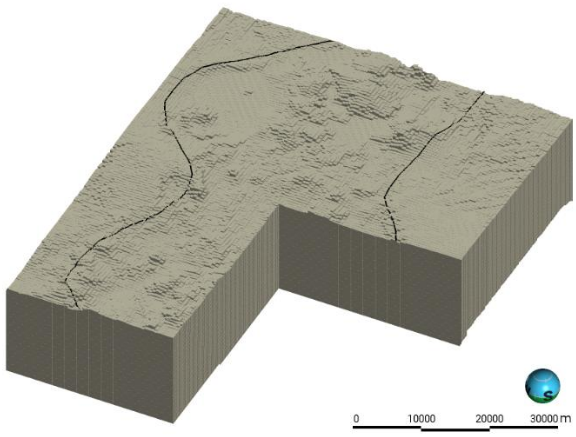

Figure 3. Numerical model grid, showing TVZ boundaries in black. The model grid has three times vertical exaggeration.

3. RESULTS

A uniform model with homogeneous geology, uniform heat flow into the base, and flat top surface results in many small upflows that do not correlate with observed geothermal system locations (Figure 4a). If the top surface of the model follows the water table (a muted reflection of topography), upflows occur under all of the geothermal systems other than Te Kopia, but also in many other areas (Figure 4b). If the top surface of the model is flat but heat sources are localised to zones of low resistivity at 5 km depth, upflows occur near many of the fields but are often offset (Figure 4c). If the top surface of the model follows the water table and there are localised deep heat sources, elevated model temperatures occur at the same locations as many of the geothermal systems and there are only three upflow zones that do not overlap a geothermal system (Figure 4d).

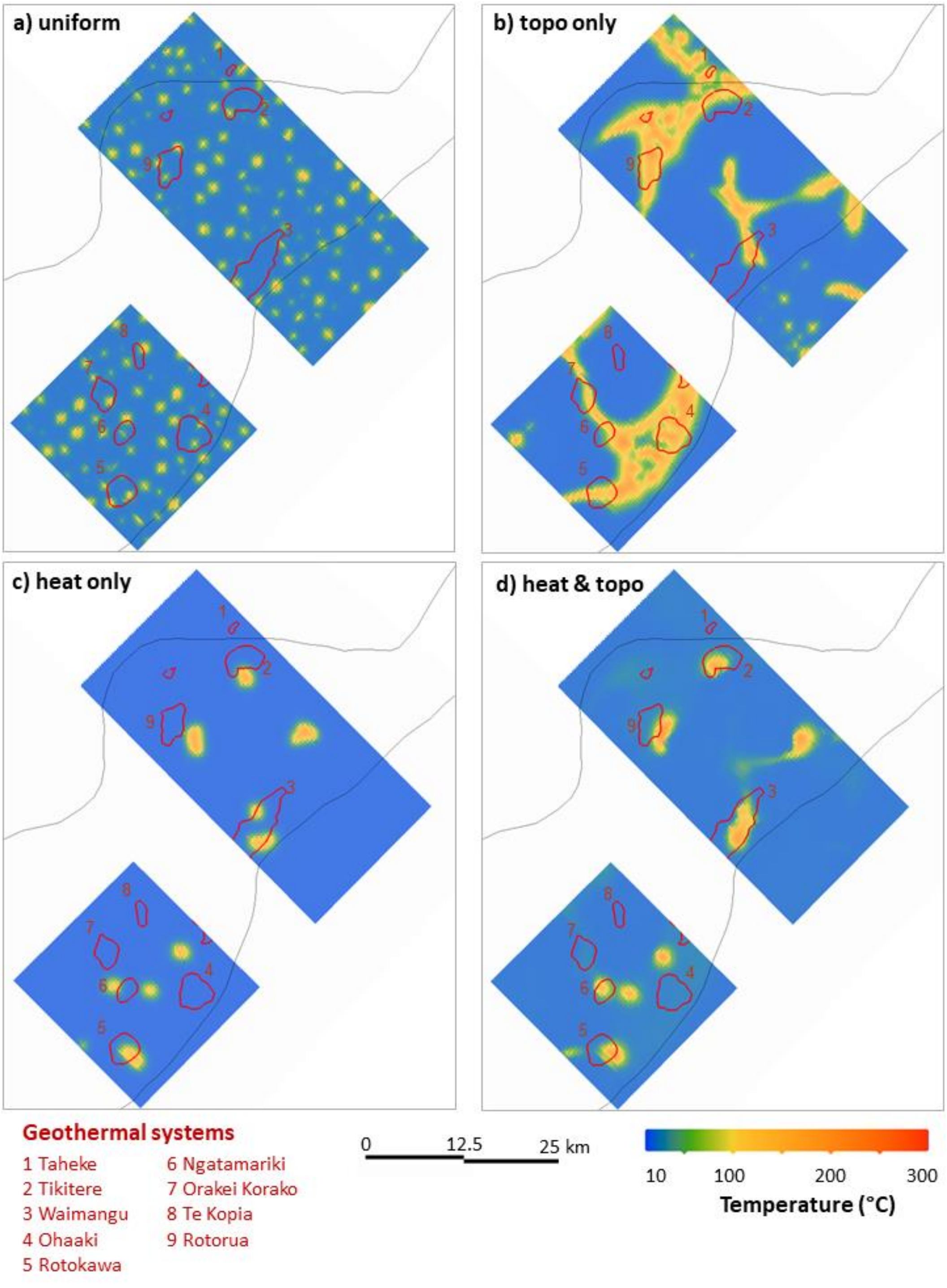

Figure 4 Depth slices of shallow model temperature results for models with homogeneous geology. a) With flat top surface and uniform deep heat input. b) With top surface of the model following the water table, but uniform deep heat input. c) With localised deep heat input following MT anomalies at 5 km depth (see Figure 2), but flat top surface. d) With localised deep heat input and top surface following the water table. Red outlines and numbers correspond to major geothermal systems, black outlines to young TVZ boundaries.

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4. DISCUSSION

4.1 Fields where model temperatures and resistivity correlate.

Several fields show an extremely good correlation between elevated model temperatures and low resistivity zones (Figure 4d). These are: Tikitere (2; Figure 5), Waimangu (3), Rotokawa (5), Ngatamariki (6), and Rotorua (9). The modelled upflows at Rotokawa and Rotorua overlap the field boundaries but are offset a little to the southeast (Figure 4d).

Model temperatures are very slightly elevated near Orakei Korako (7), but far less than at the other fields (Figure 4d).

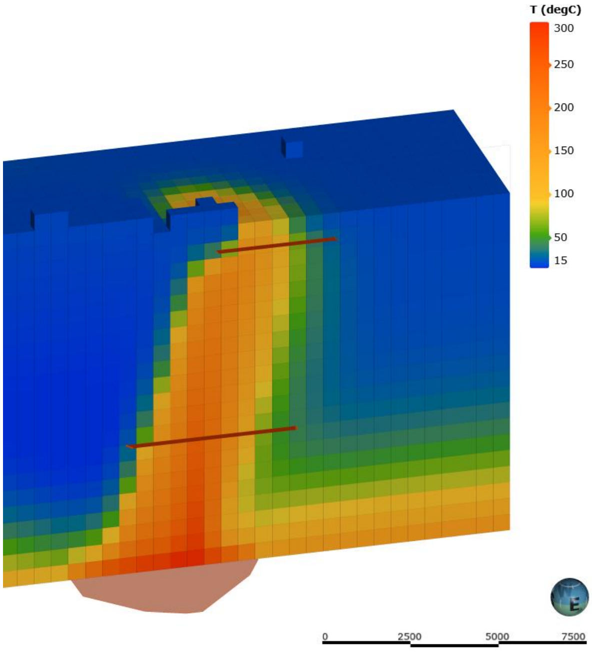

Figure 5 Example model temperature results at Tikitere. Red lines correspond to DC and MT low-resistivity anomalies at 500 m and 3 km depth respectively. The red polygon represents a localised heat source corresponding to a low-resistivity MT anomaly at 5 km depth. Model grid has five times vertical exaggeration.

4.2 Fields where model temperatures and resistivity do not correlate.

At Taheke (1) and Ohaaki (4), upflow is only observed when the top surface of the model follows the water table, and the model is otherwise spatially uniform (Figure 4b). When localised heat sources are included in the base of the model, temperatures in these areas are not elevated (Figure 4d). At Te Kopia (8), upflow does not occur in any of the models (Figure 4). This suggests that the models are not capturing major influences in these areas, for example deep heat flow may be elevated compared to background, and/or local geology may be blocking or redirecting fluid flow.

There are three zones of elevated model temperature that do not occur at the same locations as known geothermal systems (Figure 4d). One of these is thought to be related to the Ohaaki system (Bertrand et al., 2013; Kissling et al., 2016), and one of them is adjacent to Ngatamariki geothermal system. The third, located beneath the Haroharo Volcanic Complex, does not underlie a known geothermal system and MT models suggest that fluid upflow in this region is arrested before it reaches the surface (Bertrand et al., 2022). It is hypothesized that the young lava domes that overlie this low-resistivity plume are relatively impermeable, and force fluid flow to spread laterally rather than ascending vertically to the surface (Bertrand et al., 2022; Miller et al., 2022; Pearson-Grant et al., 2022). Future work will explore this hypothesis.

4. CONCLUSION

The effects of topographic loading and localised heat sources inferred from MT can explain the surface expressions of five geothermal systems out of the nine within the studied area (Figure 4). This implies that the other fields are affected by other factors, for example at Ohaaki there is an MT plume offset to the northwest that is thought to be redirected by local geology. At Haroharo Volcanic Complex, there is no shallow evidence of geothermal activity but there is a low resistivity zone and elevated model temperatures that again may be influenced by local geology. These regions will form targets for future study.

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