NUMERICAL MODELLING OF THE INFLUENCE OF GEOLOGY AND GROUNDWATER RECHARGE ON GEOTHERMAL SYSTEMS IN THE CENTRAL TVZ

S. C. Pearson-Grant[1], S. D. Milicich[1], P. A. White[2] and W. M. Kissling[1]

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

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

s.pearson-grant@gns.cri.nz

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ABSTRACT

Geothermal activity in the Taupo Volcanic Zone (TVZ) is focused into 23 high-temperature geothermal systems that have varying geological, geographical and physical properties. We have created numerical models of a central part of the TVZ to assess the roles that geology and groundwater recharge play in determining the locations and characteristics of geothermal systems.

Our model grid extends from Ngatamariki in the southwest to Waiotapu in the northeast. The grid blocks are 500 m by 500 m horizontally, and 250 m vertically. We began by creating a model with homogeneous permeability and uniform heat input into the base. We then explored the effects of different rock properties and recharge conditions.

In this way, we can determine the influences of geology and recharge on hydrothermal fluid flow in the central TVZ, and determine the levels of detail useful to simulate the location, temperature and mass/heat flow of geothermal systems in our study area. Ultimately, these models will provide the basis for answering broad questions about the geothermal systems in the TVZ, for example why geothermal systems are located where they are, and whether they are interconnected at depth.

1. INTRODUCTION

The 23 high-temperature geothermal systems in the Taupo Volcanic Zone provide electricity, tourist attractions, direct use, and cultural value (Carey et al., 2015; White and Chambefort, 2016). They are therefore an obvious target when studying geothermal fluid circulation in New Zealand. As many of these systems are within a few kilometres of each other (Figure 1), understanding how and why they develop has implications on both field and regional scales. In this study, we create the first regional-scale numerical model of heat and fluid flow based on actual TVZ geological structures to try to understand regional-scale geothermal processes in the TVZ.

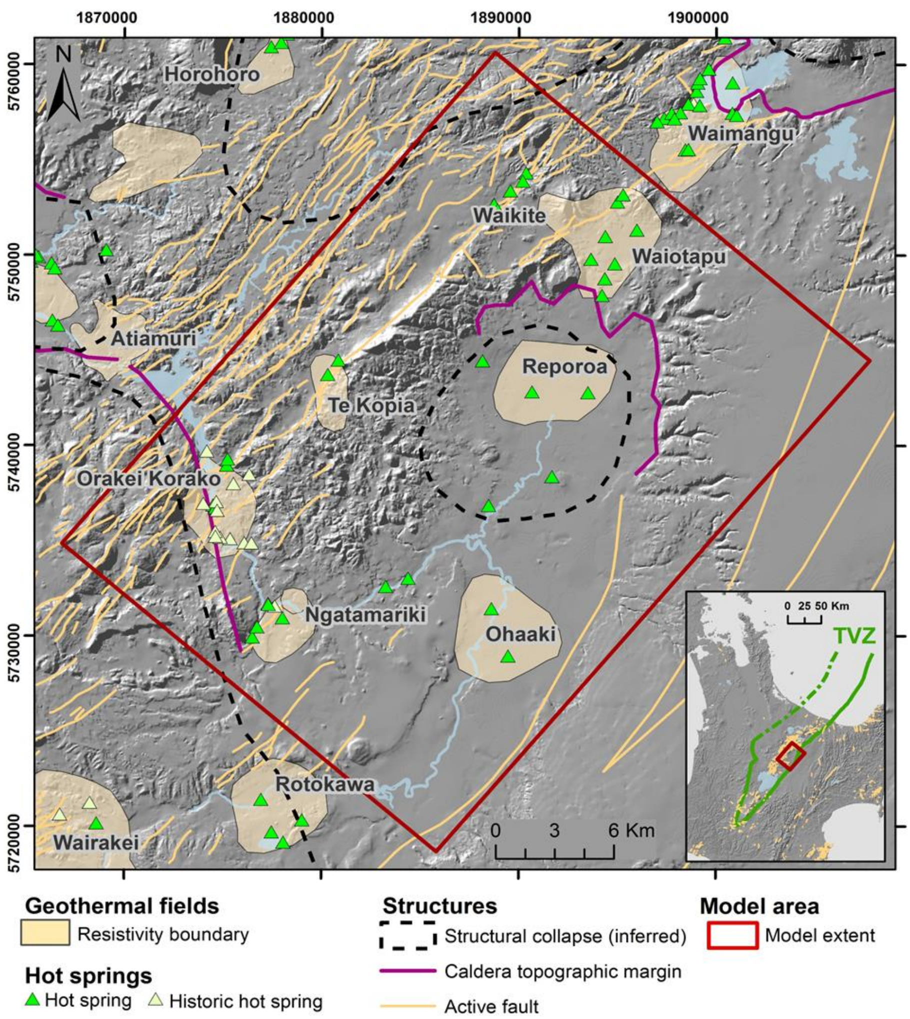

Figure 1: Map of the model extent with major caldera structures (Leonard et al., 2010), active faults (Langridge et al., 2016), hot spring locations, and geothermal systems as described in Milicich et al. (2017). Inset map: North Island, New Zealand, showing the model extent in relation to the Taupo Volcanic Zone (TVZ; Wilson et al., 1995).

Previous numerical modelling studies have focused on individual field scale, or on TVZ scale. Numerous numerical modelling studies have been carried out on individual geothermal fields, to aid in management of producing fields, and/or to better understand heat and fluid flow processes in a field (e.g., Wairakei (Mannington et al., 2004), Rotokawa (Clearwater et al., 2016), Rotorua (Ratouis et al., 2017) Tauranga (Pearson et al., 2012)). On a larger scale, several numerical models have looked at convective processes in a TVZ-like setting. Kissling and Weir (2005) developed a model that subdivided the TVZ into 16 semi-rectangular zones of varying permeability and heat flow. Dempsey et al. (2011) modelled a three-zone temperature source with a statistically varying permeability distribution. Kaya and Widyanti (2015) simulated a varying heat source and a permeability distribution that was initially based on broad geological structures, but was then modified and subdivided. All three studies achieved spatial distributions of the geothermal systems that were qualitatively similar to those observed, but maximum temperatures were generally underestimated.

In this paper, we present the initial results from a numerical model that is based on a hydrogeological model of a central portion of the TVZ. The complexity of this model will be built up over time, and it will be used to explore a range of questions, for example:

- Are the extents of geothermal systems predominantly linked to structural boundaries, or to the natural separation of convective cells?
- What is the nature of connection between neighbouring geothermal systems?
- Can convective cells be stable on the timescales inferred for geothermal systems in the TVZ?
- What rock properties are feasible to allow fluid upflow at the mass rates and temperatures that we observe in the geothermal systems?
- Does shallow groundwater recharge affect the locations and rates of geothermal circulation?

2. STUDY AREA

Our study area extends from Ngatamariki in the south-west to Waiotapu in the north-east and comprises an area of approximately 870 km^2 (Figure 1). Within this area there are two producing geothermal fields (Ohaaki and Ngatamariki) and five undeveloped systems (Waiotapu, Waikite, Reporoa, Te Kopia, and Orakei Korako). This area was chosen because we could not include sufficient resolution to model the entire TVZ, while at the same time ensuring that both geological and groundwater variations were adequately represented. The area hosts hot springs, geysers, collapse calderas, faults, and groundwater catchment zones, making it ideal to study the effects of geological structures and recharge on regional fluid flow.

Previous work has taken publicly-accessible data and turned it into a hydrogeological model suitable for modelling heat and fluid flow (Milicich et al., 2017). The resulting Leapfrog model can be used to directly populate a TOUGH2 heat and fluid flow model. In the Leapfrog hydrogeological model, geological maps, borehole data, cross-sections and a geological basement model based on gravity data were used to create a simplified geological model. The geology was simplified by grouping rock types with similar fluid flow properties (hence hydrogeological model), resulting in seven layers (Figure 2). Additionally, nine faults were identified that are laterally extensive or host significant fluid flow. These will not be incorporated into the numerical model until later. Permeability and other rock property data were also collated where available.

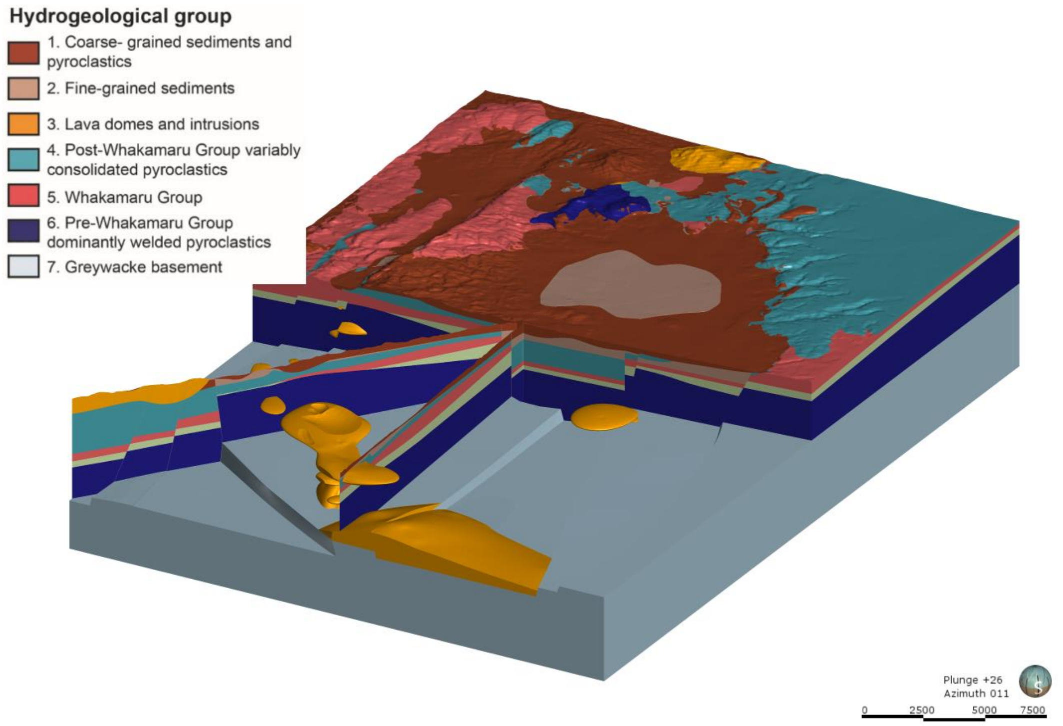

Figure 2 Hydrogeological model of our study area, showing the seven groupings of rock types according to hydraulic properties (Milicich et al., 2017).

3. METHODOLOY

TOUGH2 was used for the numerical modelling as it is the default industry standard in New Zealand. Leapfrog was used to turn the hydrogeological model into a numerical model. A model was created covering 25 km by 34 km and extending to 5 km deep. Grid blocks were 500 m by 500 m horizontally, and 250 m vertically. The top boundary of the model followed the topography, with a maximum height of ~960 m. For the purposes of this initial, simple study the surface was assumed to be the water table and the model was fully saturated with water. A uniform heat source at the base of the model of 700 mW/m^2 was used as a representative average of the TVZ (Bibby et al., 1995). The model was run for 1 million years, by which time an approximate steady state was achieved.

To begin with, we created a model with homogeneous permeability to explore the effects of recharge at the top boundary condition. A layer of water as the top surface is often used to ensure that there is an adequate supply. This means that pressure conditions can find a natural equilibrium and are not forced by the model boundary conditions. However, this provides an essentially infinite supply of water into the system and allows an infinite amount to escape. These fluid inflows and outflows are responses to pressure variations resulting from the developing convective system, which limit this exchange, but this still may not be physically realistic. To limit this potentially infinite supply, the permeability of the top rock can be made very low, or the top layer can be filled with air. However, in this case the lack of fluid supply into the top of the model combined with the initial pressure conditions can limit fluid flow within the model. Both of these boundary conditions have limitations, and the reality is probably somewhere in the middle. Therefore, we tried both as the opposite extremes.

As well as exploring the effects of recharge at the top boundary condition, we varied the rock properties within the model to determine their effect on hydrothermal fluid flow. Homogeneous, isotropic rock properties were modelled to explore what permeability ranges would result in TVZ-like geothermal systems. The permeability range included was based on the literature as discussed in Milicich et al. (2017). In future, the permeabilities of the different rock types will be explored, for example using the ranges found in the literature as a proxy for the variability found within a layer.

4. RESULTS

Model results show that convection is predominantly along topographic lows (Figure 3). Maximum temperature of the model is between 30 and 374°C depending on the permeability (Table 1).

Results show that the model is essentially insensitive to the top boundary condition. Both infinite recharge and a no-recharge boundary condition give almost the same maximum temperature (Table 1) and convection patterns.

The models are highly sensitive to permeability (Table 1). With a permeability of 1 x 10^{-15} m² or less, fluid cannot flow fast enough to remove the heat that is being added at the bottom boundary. Therefore, heat accumulates and the system reaches the limit that TOUGH2 can simulate of 374°C. Otherwise, as permeability increases, the maximum temperature in the model decreases (Figure 4).

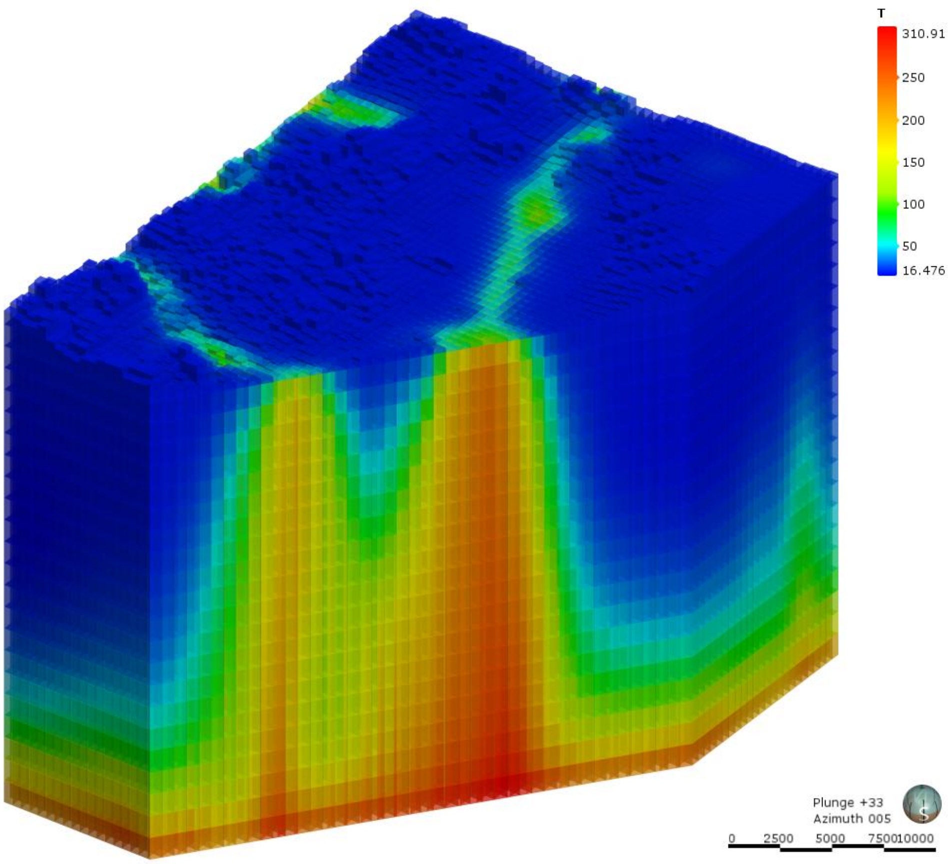

Figure 3 Cross-section of model temperatures with a permeability of 1.2 x 10^{-15} m². Hot upflow is predominantly along topographic lows. Figure is five times vertical exaggeration.

Table 1. Effects of permeability and recharge boundary conditions (Top BC) on maximum temperature (max T) in the model and convection patterns.

Permeability (m^2)	Top BC	Max T (°C)	Notes
1×10^{-15}	Infinite recharge	374	Temperature reached TOUGH2 limit after 80k years
1.2×10^{-15}	Infinite recharge	311	Convection in topographic lows
2×10^{-15}	Infinite recharge	276	Convection in topographic lows
5×10^{-15}	Infinite recharge	246	Extensive convection
1×10^{-14}	Infinite recharge	172	Laterally continuous convection
8×10^{-12}	Infinite recharge	31.5	Onset of convective plumes along topographic lows, converged after 11k years
2×10^{-9}	Infinite recharge	30	Cold, conductive, converged after 63 years
1×10^{-15}	No recharge	374	Sparse convection in topographic lows
2×10^{-15}	No recharge	275	Convection in topographic lows
5×10^{-15}	No recharge	243	Extensive convection
1×10^{-14}	No recharge	173	Laterally continuous convection

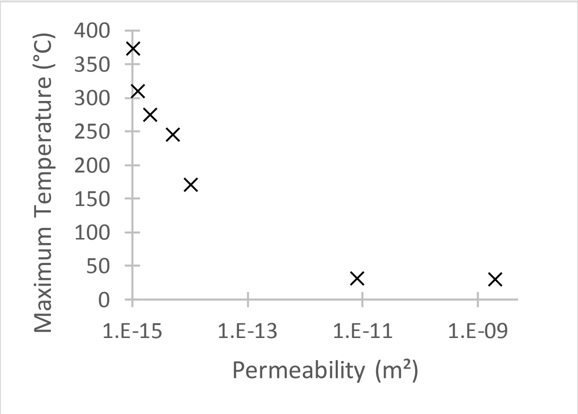

Figure 4 Log of permeability against maximum temperature in the model.

5. DISCUSSION

The models in this study are extremely simple, with a single homogeneous rock-type and uniform heat at the base. However, they give surprisingly promising results (Figure 5). Topography is included in the model and this appears to be a key control (Figure 3). Convective upwelling occurs below topographic lows. This is consistent with the 2-D modelling of Ratouis et al. (2016), as well as the qualitative observation that geothermal systems in the TVZ tend to occur near the river (Figure 1). This may be due in part to the fact that there is a smaller column of water and rock at the topographic lows creating smaller overpressure at depth and therefore encouraging upflow in those areas. Topographically driven fluid flow has also been found to concentrate heat into valleys at the alpine fault (Sutherland et al., 2017).

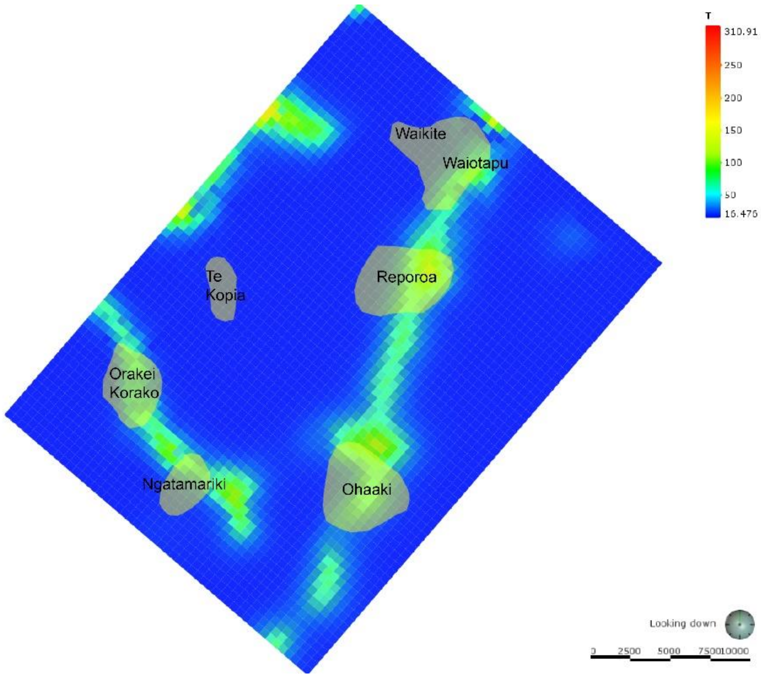

Figure 5. Model results. Warmer colours correspond to hotter near-surface temperatures, while blues are colder, as shown in the scale bar. The tan shapes are the geothermal systems as shown in Figure 1.

Even with such a simple model, 5 of the 6 geothermal systems in our study area are located over convective upwellings (Figure 5). We find it interesting that many of the features that are often thought to be fundamental to a TVZ geothermal system (e.g. caprock, fracture network, localized heat sources) are not invoked here. This suggests that those features may not be necessary for the initial formation of TVZ geothermal systems. In fact, they may develop as a result of the system, for example fractures developing due to fluid flow and caprock forming due to hydrothermal alteration. These processes may then iteratively build on each other to give the present-day details.

The models show that there is only a relatively small permeability range that results in a distribution of the geothermal systems similar to that observed in the TVZ. Too low a permeability and fluid cannot flow and the system gets too hot. Too high a permeability and convection becomes vigorous and widespread and so the fluid upwellings become too cold. A permeability between 1×10^{-15} m² and 2×10^{-15} m² appears to give the most TVZ-like results when only one permeability and a uniform heat source are used. This is in the range suggested by Rowland and Simmons (2012). The maximum temperatures in these models are between 276 and 374°C, which is in the range of 265 to 335°C observed at geothermal fields throughout the TVZ (Rowland and Simmons, 2012).

The modelling suggests that convective heat transfer in the TVZ is relatively insensitive to recharge from the near-surface, as no recharge or an infinite reservoir both give similar results. This is an unexpected result. It may be partly explained by the fact that pressure conditions mean that the infinite reservoir actually provides very little recharge into the model's relatively large volume of geothermal fluid. At the same time, over 1 million years, a permeability of 1×10^{-20} m² is not a true no recharge condition as it still allows some small flow into and out of the system. This will be explored further, as will the effects of naturally-occurring spatial variations of rainfall.

Although most of the geothermal systems occur where the model suggests there should be convective upwellings (Figure 5), the location of Te Kopia geothermal system cannot be explained in the same way. Additionally, the hot areas in the model are much more laterally extensive than those observed in the TVZ. There are many factors that may contribute to this, which we hope to explore in future work. Possible factors include variable recharge, faulting and caldera structures, formation of caprock, different rock types giving permeability contrasts, variable properties within rock types, and hydrothermal alteration.

6. CONCLUSION

Topography appears to be a major influence on the location of geothermal systems in the TVZ. Convective upwellings occur in topographic lows. Even with a single, uniform rock type and a uniform heat source at depth, many of the hot upwellings occur in the same locations as geothermal systems of the TVZ. However, convective upwellings are more extensive than the systems observed in the TVZ, and Te Kopia is not in a topographic low and cannot be explained by this mechanism. Future work will explore the effects of faulting, caldera boundaries, variable recharge and different rock types on fluid upflow.

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