Long Term Production in TVZ Geothermal Systems using a 2D Source to Surface Model

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ABSTRACT

A 2-D 'Source to Surface' regional-scale heat and fluid transport model of the central TVZ is described and used to investigate the nature of the high-temperature geothermal systems and long-term fluid production and reinjection from them. The model represents a 10 km-deep NW-SE cross-section across the TVZ with simplified geology including a 20 km wide 'rift'. At the base of the model a 'hotplate' heat source has a temperature of ca. 700ºC and produces a heat flux of 0.7 Wm^{-2}.

The (horizontal) permeability of the rifted basement is the key factor in the model. This is described as a function of depth, and the free parameters in this function allow a) the hotplate temperature to be set independently of the prescribed heat flux, b) sufficient shallow permeability to support widespread convection in the upper few km of the model, and c) control of the temperature distribution within the rift so that high-temperature geothermal systems form and temperature proxies for rift-scale geophysical constraints are satisfied. Another essential feature of the model is that the geological units outside of the rift must have low permeability (~10^{-16} m^2) to prevent excessive cooling from cool fluid flowing into the rift.

The model suggests that the high-temperature geothermal systems in the TVZ are transient surface expressions of an unsteady rift-scale convective hydrothermal system. Temperatures in the geothermal systems can reach ca. 300ºC at 2 km depth. The models respect constraints from geophysics, with the depth of the shallowest melt close to 10 km and the maximum depth of seismicity at 9 +/- 1 km.

The model describes the complete hydrothermal system underlying the geothermal systems and its principal geological controls. For this reason, it can be used to investigate the effects of fluid production and reinjection on timescales longer than the normal plant life of 30-50 years. We give some simple examples of this.

1. INTRODUCTION

1.1 TVZ and Modelling Background

The Taupo Volcanic Zone's (TVZ) geothermal systems contribute almost 20% of New Zealand's total electricity supply. With the transition away from fossil fuel generation, existing geothermal generation capacity will need to be expanded, but little is known about the sustainability of the geothermal systems on timescales longer than typical plant lives of 30 - 50 years or the impact of fluid production on the wider TVZ hydrothermal system.

The Taupō Volcanic Zone (TVZ; Figure 1) of Aotearoa/New Zealand is a continental volcanic rift that exhibits high convective heat-flow sustained by deep magmatic processes (Cole 1990; Wilson et al., 1995; 2009; Villamor et al., 2017; Figure 1). This high heat flow is manifested near the surface as high-temperature geothermal systems. These are an important energy source for New Zealand (e.g., Bibby et al., 1995; Hochstein, 1995, White et al., 2016). The shallow parts of these systems (less than 3 km deep) have been intensively studied for geothermal energy production, but the connection with fluid and heat transport deeper in the crust is not well understood.

No previous models of the TVZ hydrothermal system (e.g., Kissling and Weir, 2005, Dempsey et al., 2013) were true 'source to surface' models, that is, including a heat source with a realistic temperature and heat flux for the TVZ and a model domain sufficiently deep to encompass the entire hydrothermal system. Also, these models did not respect important constraints from geophysics and could not produce high-temperature geothermal systems with typical maximum temperatures of ~ 200ºC compared to those of > 300ºC in the TVZ.

In this paper we develop a 2-D source to surface model of the hydrothermal system within the central TVZ which addresses these issues. We focus on the central Taupō Rift (Villamor et al., 2017; black outlined area in Figure 1) because it is outside of the presently active caldera volcanoes Ōkataina and Taupō, where shallow magma is expected. In the central Taupō Rift, subsidence and faulting have caused a basin to develop that is infilled by ~ 2-3 km of low-density shallow volcanics and bordered by low-permeability basement rock to the north-west and south-east. The region hosts hydrothermal fluid circulation and associated geothermal activity (Figure 1) driven by high heat flow from melt in the lower crust. Due to its history of hosting transient hydrothermal activity (Brathwaite, 2003; Drake et al., 2014; Loame, 2016; Kissling et al., 2018), its role in providing deep fluid recharge to the wider region of the TVZ, the absence of recent volcanism and its well-understood geophysics (Bibby et al., 1995), the central Taupō Rift provides an ideal setting for assessing heat and fluid transport mechanisms from the deep heat source (~ 10 km) to the surface.

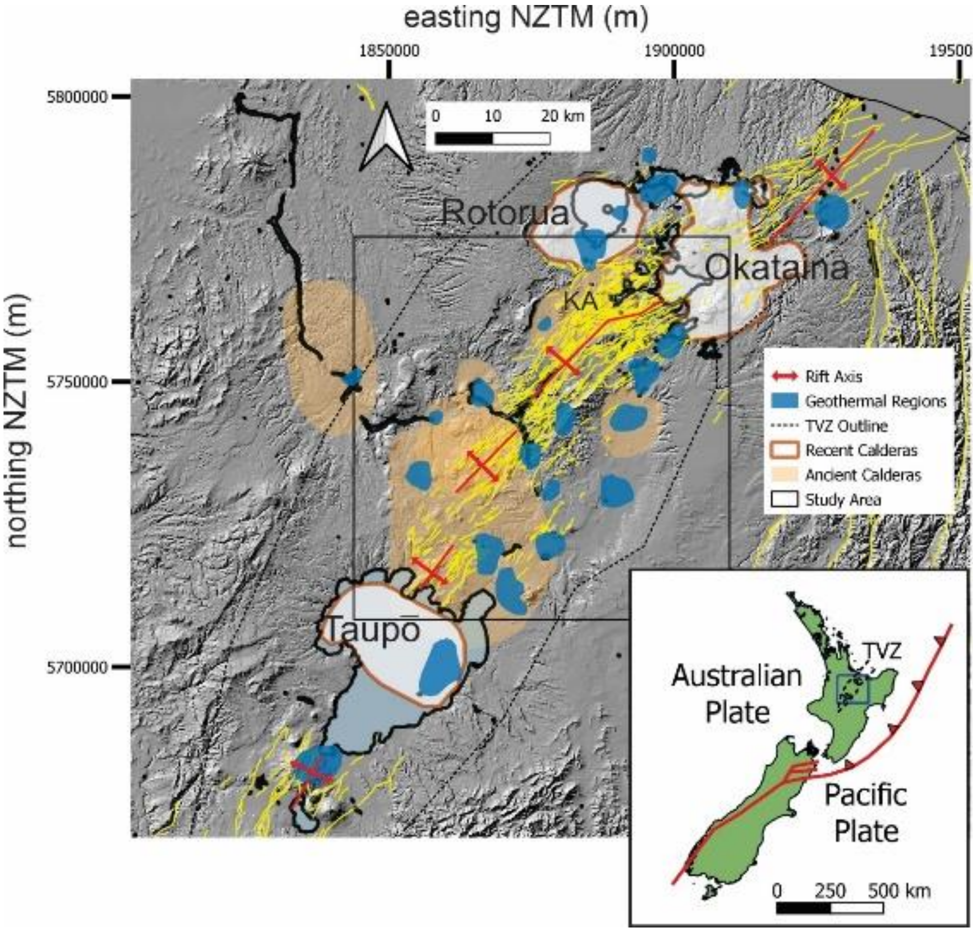

Figure 1: Map summarising main features of the Taupō Volcanic Zone (TVZ), North Island, New Zealand. Inset shows tectonic setting with plate boundary between Australian and Pacific lithosphere (red lines) and the location of the Taupō Volcanic Zone (TVZ).

1.2 Constraints on TVZ models

The TVZ has one of the highest thermal outputs of any comparable arc setting on Earth at ~ 4200 ± 500 MW, with an average heat flux of ~0.7 Wm^{-2} (Bibby et al., 1995). Approximately 20% of this occurs as rhyolitic volcanism, with the system as a whole erupting ~20,000 km^3 of rhyolitic magma in the last 2 Myr (Hochstein, 1995, Wilson et al., 1995), together with minor amounts of andesitic and basaltic lavas. The remaining 80% of the TVZ thermal output occurs through roughly 23 high-temperature geothermal systems (Bibby et al., 1995; Figure 1). Temperatures in these systems are typically 250°-300°C in the upper 1-2 km (e.g., Grant and Bixley, 2011). Modern and fossil geothermal systems are distributed across the rift although preferentially concentrated near both margins (e.g., Figure 1; Bibby et al., 1995; Kissling et al., 2018) and individual systems may last 10s-100s of thousands of years (e.g., Rae et al., 2015; Browne, 1979; Drake et al., 2014) although there is much uncertainty in these estimates.

As expected for a region with such high heat flow, the maximum depth to which earthquakes occur within the TVZ is (on average) quite shallow (Bryan et al., 1999; Bannister et al., 2015). While the depth and distribution of seismicity in the TVZ can be complex and swarm-like (e.g., Illsley-Kemp et al., 2021; Bannister et al., 2015; 2022), Bannister et al., (2015) found that most seismicity in the region between the active Taupō and Ōkataina calderas occurred at depths shallower than 8-10 km, with some patches of deeper seismicity at > 10 km depth.

The seismogenic zone is expected to correspond to the region where rocks are velocity weakening (i.e. they can slip unstably). For a greywacke gouge, the upper temperature limit for unstable sliding occurs at ca. 400°-450°C (Boulton et al., in prep.), though it also depends on sliding velocity. Assuming the TVZ basement is dominated by quartzo-feldspathic rocks to mid-crustal depths, this suggests that the seismogenic depth limit of ca. 9 km should correspond to a temperature of ca. 450°C.

2. HYDROTHERMAL MODELING CODE, TGNS

TGNS (Kissling, 2014) is an implementation of an integrated finite-volume algorithm for solving the equations which describe the flow of water and heat in hydrothermal systems. It shares many features with the well-known code TOUGH2 which is used extensively by the geothermal industry worldwide (Pruess, 1991). Unlike TOUGH2, TGNS uses thermodynamic properties of water substance (density, enthalpy, dynamic viscosity) as described by the IAPWS-95 formulation (Wagner and Pruβ, 1995). This is based on a general expression for the Helmholtz free energy, from which all desired fluid properties can be calculated. The fluid properties are therefore by construction thermodynamically consistent. This an important and non-trivial requirement when solving mass (water) and energy (heat) conservation equations in systems like the TVZ where the dominant process is the transport of heat across large ranges of pressure and temperature. IAPWS-95 is currently the best available description of the thermophysical properties of water and steam, and covers the full range of pressure and temperature required for our modelling.

3. MODEL DESCRIPTION

The model domain used in this paper is 50 km wide by 10 km deep and represents a 2-D cross section perpendicular to the NE-SW strike of the central Taupō rift. The domain is divided into 50,000 computational elements arranged in a 500 x 100 array, with each element being a 100 x 100 m x 100 m cube. Details of the model are shown in Figure 2. The geological layout and heat source in the model do not change during the simulations.

The Taupō Rift is assumed to be 20 km wide, and bounded to the NW and SE by low permeability basement units. These are assigned an isotropic permeability of 10^{-16} m^2 (Upton and Sutherland, 2014) and extend to 10 km depth. Between these, in the 'rifted basement', the permeability decreases with depth. The upper 2 km of the rift comprise higher permeability shallow volcanics. The permeability of these is well-characterised as they host many of the geothermal systems used for electricity generation in the TVZ (e.g., Grant and Bixley, 2011). We use a horizontal permeability of 50 x 10^{-15} m^2, with the vertical permeability a factor of ten lower, as suggested by Wooding (1978).

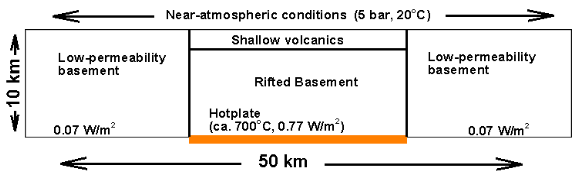

Figure 2: Layout of the model, showing dimensions, geological units, and boundary conditions. The 'magmatic' heat source, indicated by the orange band, underlies the rift and is centered in the model domain. An additional background conductive heat flux is applied across the bottom boundary.

To provide a realistic heat source for the models, the regional conductive heat flux is augmented with an additional 'magmatic' heat flux of 0.7 Wm^{-2} (Bibby et al., 1995), corresponding to the average heat flux over the TVZ. This distributed uniformly over the central 20 km-wide rift and is motivated by the hotplate concept for the TVZ heat source (Wooding, 1978; McNabb 1993). The temperature of the hotplate source is estimated to be ca. 700^o-750^oC based on its location ~5 km above intruded primitive basalt (Gamble et al., 1993; Gelman et al., 2013). The most physically-based heat flux boundary condition is used in the model and the target temperature of ca. 700-750 ^oC is achieved by adjusting the permeability profile in the basement rock (Kissling et al., 2023).

To start the simulations an arbitrary but well-defined initial condition for the temperature and pressure distributions in the model domain is required. A convenient choice for this is a steady-state hydrostatic fluid pressure distribution with an associated conductive temperature gradient. To generate this a representative regional heat flux of 0.07 Wm^{-2} (Studt & Thompson, 1969; Thompson, 1977) is applied on the lower boundary of the model,

The depth variation of permeability in the rifted basement is the key factor in this model. Elsewhere (Kissling et al., 2023) we have argued that high temperature geothermal systems cannot be produced in a model where the deep basement permeability is constant, and that such models are not consistent with rift-scale geophysical constraints. To remedy this problem, here we propose a three-parameter family of curves which describe the depth dependence of $\log_{10}$(permeability) as a power law :

$$\log_{10}(k(z)) = A + B\,(z-z_1)^{\gamma} \qquad (1)$$

where A and B can be determined from permeabilities (k_1 and k_2) specified at two depths (z_1 and z_2) and the power-law exponent γ.

4. NATURAL STATE MODEL RESULTS

The determination of the free parameters describing the permeability distribution in the rifted basement which satisfies all geophysical constraints and produces high-temperature geothermal systems is described in detail in Kissling et al., (2023). To summarise these briefly, we find viable solutions which satisfy the constraints all occur for the power-law exponent $\gamma < 0.4$ and $-\log_{10}(k_2)$ between 16.6 and 17.0, while $-\log_{10}(k_1)$ can take values in the range 13.5 ± 0.5. This region of the parameter space covers average hotplate temperatures from 700^oC to 1000^oC. Generically these models produce unsteady, irregularly convecting hydrothermal systems with transient plumes of hot fluid which are interpreted as high-temperature geothermal systems.

In this paper we will discuss a single viable model where, using the notation from the last section, (z_1, z_2) are 2 km and 10 km and (k_1 ,k_2) are $10^{-13.5}$ and $10^{-16.8}$ m^2 respectively. The power-law exponent γ is 0.25. Figure 3 shows the temperature distribution in the model. The average temperature across the hotplate is ~750^oC and the model is consistent with the inferred maximum depth of seismicity of ~9 km (represented by 450^oC proxy) and the presence of partial melt at 10 km depth. There are two high-temperature geothermal systems, one in the interior of the rift and the other, much larger, which is associated with the 'eastern' rift margin. These geothermal systems have temperatures of > 250^oC at 2 km depth, and are transient features in the wider rift-scale vigorously convecting hydrothermal system. A representative timescale for the temperature fluctuations in the model is ~10^5 years. However, even for much shorter times, these fluctuations are visible in the modelling results. Figure 4 shows the temperature differences which occur in the model in a period of ca. 100 years due to the migration and/or subsidence of the geothermal plumes. The red/green areas show local heating/cooling resulting from the migration of the plumes in this time.

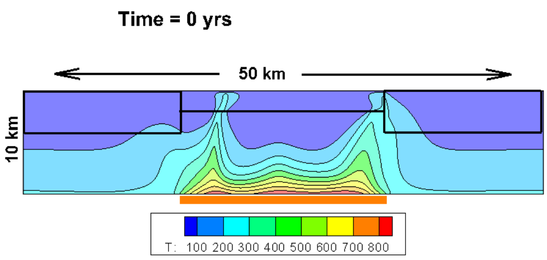

Figure 3: Temperature snapshot in the model. The two plumes have temperatures > 250ºC at 2 km depth and are part of a rift-scale vigorously convecting hydrothermal system. This temperature distribution provides the initial condition for the production/reinjection model discussed in the next section.

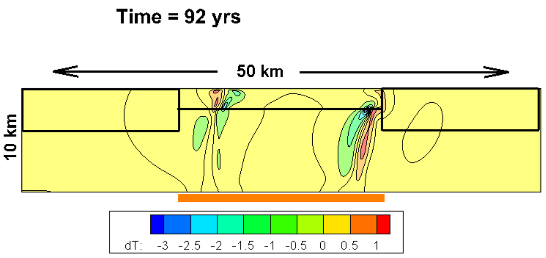

Figure 4: Temperature differences which occur in the natural state model in the absence of any fluid production or reinjection. The red/green areas show local heating/cooling caused by the migration of the plumes.

5. A PRODUCTION/REINJECTION MODEL

In this section we will examine a simple scenario where geothermal fluid is produced from each of the geothermal systems shown in Figure 3, and full reinjection occurs in the central rift between the fields. The production wells are labelled P1 and P2, and the reinjection well R1. The wells each consist of a single 100 m-on-a-side cubic model element. Fluid production from P1 and P2 occurs at a rate of 1 kg/s and the reinjection into R1 is at 2 kg/s with a fluid enthalpy of 350 kJ/kg (~80ºC). These rates are comparable to the total fluid output of each of the geothermal systems. All fluid production and reinjection occurs within the upper rifted basement at a depth of 2.1 km and the production and reinjection lasts for a period of 200 years.

The purpose of this model is to investigate some of the possible effects of long term fluid production and reinjection on the geothermal systems which cannot be investigated with traditional geothermal models. Typically, these models are truncated both at shallower depths, say 3-5 km, and within a few km of the field boundaries and so cannot correctly represent the 'far field' boundary conditions correctly.

Figure 5 shows the temperature distribution in the region of the left hand plume in (top panel) the initial state of the model and (bottom) after 100 and 200 years of fluid production and full reinjection. There is obvious degradation to the central high-temperature upper core of the geothermal system, which has been substantially cooled by the fluid production. Evidently, this implies that such fluid extraction (and reinjection) cannot be continued indefinitely. Interestingly, the peak of the 300ºC contour (marked with an x) is unchanged, suggesting that the deeper upflow is largely unaffected by the fluid extraction.

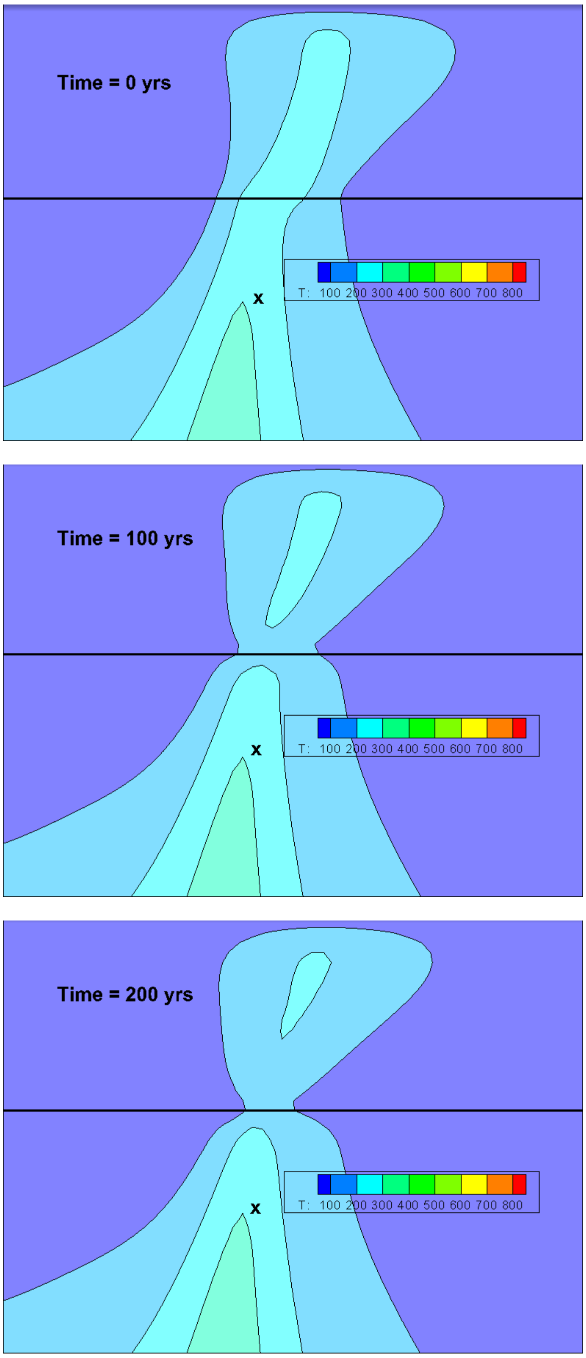

Figure 5: Temperature distribution in the initial state (top), after 100 years (middle) and 200 years (bottom) fluid production and full reinjection. The horizontal line is boundary between the (upper) shallow volcanics and the deeper rifted basement. These panels reveal a disturbance to the high temperature core of the geothermal system caused by the fluid extraction.

To see how the field might recover after 200 years of fluid extraction all fluid production and reinjection is stopped at this time. Figure 6 shows the temperature distribution at 300 and 500 years, that is 100 and 300 years after the cessation of fluid production.

At 100 years (top, Figure 6), two changes are apparent. First, the high-temperature central core of the upflow within the shallow volcanics has continued to shrink. Secondly, the peak of the 200ºC contour in the deeper plume in the basement has risen by ~500 m post-production, relative to its former depth during the production period.

At 300 years post-production (bottom, Figure 6), the upper part of the geothermal system within the shallow volcanics has continued to cool, but the 200ºC contour in the lower, deeper plume, has risen a further ~500 m, showing the recovery is ongoing but far from complete. The depth to the 300ºC contour remains unchanged.

Longer model runs reveal a similar situation, with further recovery of the 200ºC temperature contour into the shallow volcanics. The timescale for complete recovery of the geothermal system, to something similar to that shown in the top panel of Figure 5, appears to be greater than 1000 years.

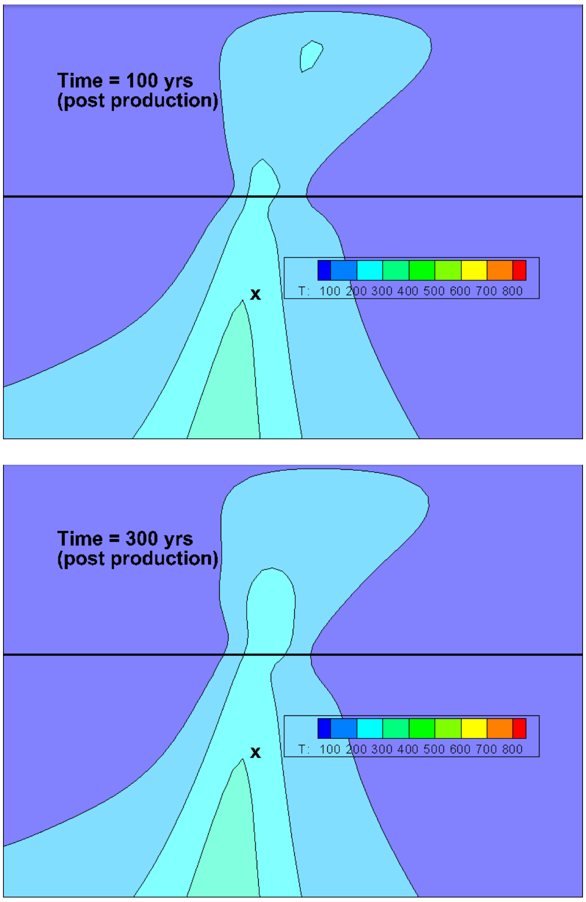

Figure 6: Temperature distribution 100 years (top) and 300 years (bottom) after the cessation of fluid production and reinjection.

Figure 7 shows pressure histories for the three wells. Note the initial pressure increase at well R1 is ~180 bars, although detail of the early transient response of the three wells cannot be seen on the plot. In fact, the three wells return to close to their initial pressures by 500 years. A similar model run but with no reinjection shows that the pressure support occurring in this model is 7.5 bar for P1, and 11 bar P2 after 200 years.

Figure 8 shows the corresponding temperature histories for the three wells. The temperature at reinjection well R1 stabilises at ~ 80ºC, corresponding to the assumed enthalpy of the reinjected fluid (350 kJ/kg) and falls only slightly after reinjection ends. The two production wells show declines of ~100ºC over 200 years and return to close to initial temperatures by the end of the simulation. A model run without full injection shows that reinjection causes cooling in production wells P1 and P2 of 2ºC and 11ºC respectively after 200 years.

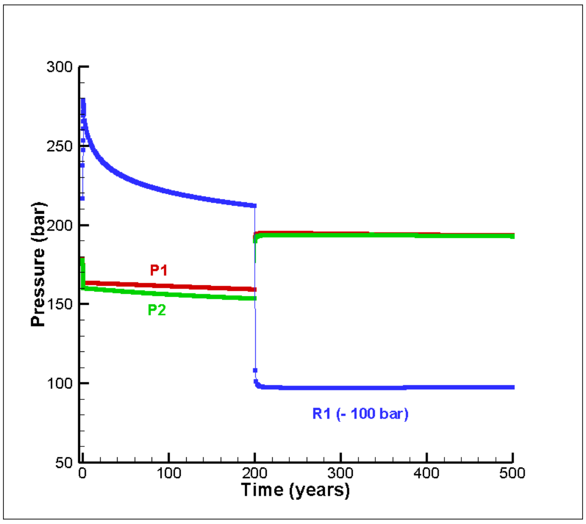

Figure 7: Pressure histories for the three wells. The earliest part of the transient responses cannot be seen but all wells return to close to their initial pressures soon after the cessation of production and reinjection at 200 years.

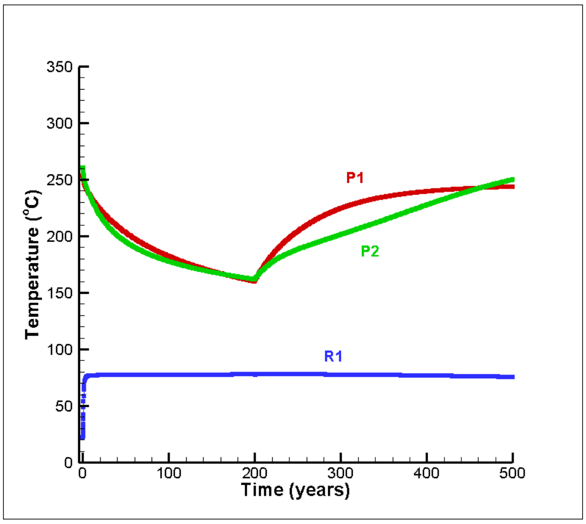

Figure 8: Temperature histories for the three wells. For the reinjection well (R1) the temperature stabilises at ~ 80ºC, corresponding to the enthalpy of the reinjected fluid (350 kJ/kg). The production wells P1 and P2 show steady declines of ~100ºC over 200 years.

6. DISCUSSION AND CONCLUSION

This paper has described the first source to surface models of heat and fluid flow in the TVZ hydrothermal system, in a 2-D setting, with particular emphasis on the Taupō Rift in New Zealand. The key feature of the models is the variation of permeability with depth in the 'rifted basement'. This is described in terms of three parameters – the permeabilities at the top and bottom of the rifted basement and a power law exponent. Valid solutions have low permeabilities (~10^{-17} m^2) at 10 km depth which ensures hotplate temperatures in the range 700°-1000°C, but sufficient permeability in the upper few km (10^{-13} – 10^{-14} m^2) to allow the formation of transient high-temperature geothermal systems which are part of a rift-scale, vigorously convecting hydrothermal system. The models respect temperature proxies for the maximum depth of seismicity, and presence of partial melt at depths greater than ca. 9 km.

Using this model as a starting point, we examine the effects of a simple production/reinjection scenario where fluid is produced from two geothermal systems and reinjected in the central rift, several km from the geothermal systems. Fluid production and reinjection takes place in the upper rifted basement, and lasts for 200 years, significantly longer than existing TVZ geothermal plants. We find a significant perturbation occurs in the high-temperature core of the geothermal system, and show that even distant reinjection can provide significant pressure support for the production well. Allowing the geothermal systems to recover for a further 300 years after stopping fluid extraction shows temperatures at the wells depths recover to within 10°C of their initial values, but the upper ~ 1km of the geothermal system is estimated to take longer than 1000 years to recover.

One caveat of this work is that the modelling is carried out in a 2-D setting. Unfortunately, at present it is not possible to use 100 m resolution (as we do here) in a 3-D setting for a significant part of the TVZ hydrothermal system as the models become impractically large with several tens of millions of elements. However, models of 10-30 km along-rift sections of the TVZ might be practical, with 'only' a few million elements. This would allow similar studies of long-term production and reinjection to be carried out to provide insights into the long-term sustainability of the TVZ geothermal systems.

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