MODELLING DEEP PRODUCTION AND INJECTION USING A REGIONAL SCALE MODEL OF A TVZ-LIKE GEOTHERMAL FIELD

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ABSTRACT

The rock-mechanics code SULEC and the fluid flow code TOUGH2 have been combined to produce a thermal/fluid flow model of a two-dimensional west to east section across the TVZ which connects processes which occur at ~100 km depths to those which produce plumes of high temperature fluids within a few kilometers of the surface.

The model predicts that the brittle-ductile transition occurs at ~7-9 km depth, and that permeabilities in the brittle crust above this of ~1 mD) are sufficient to support convective plumes which transport heat and fluid to the surface. We provisionally interpret these plumes as TVZ-like geothermal fields because of their similarity to them in terms of their total heat and mass flows, their temperatures and their narrow width (~ a few km).

By construction, the model represents the complete hydrological system associated with the convective plumes and can be used to address questions concerning the long term sustainability of these as renewable energy sources. In particular, we model very deep (~5 km) fluid extraction (with no reinjection) for a period of 150 years, and examine the effects of this on the geothermal field itself, on its surface heat and mass flows, and on neighbouring fields.

1. INTRODUCTION

1.1 Model Background

In this paper, we draw on techniques described in Kissling and Ellis (2011), where a partial coupling of the thermo-mechanical code SULEC (Ellis *et al.*, 2011) and TOUGH2 (Pruess, 1991) is used to model the formation of hydrothermal systems above an evolving continental rift. Here we investigate the consequences of sustained, very deep extraction of hot water from one of these modelled hydrothermal systems. Our aim is to begin to address some of the engineering and environmental challenges that will be faced by the New Zealand geothermal industry in the future when such extraction is considered.

An extended version of the geothermal simulator TOUGH2 (Pruess, 1991) is used for all fluid flow calculations. TOUGH2 is a fully implicit integrated finite difference code which solves the time dependent equations of mass and energy conservation in a porous medium, supplemented with appropriate constitutive relationships for the density, enthalpy and viscosity of liquid water and steam. The transport of fluid is described by Darcy's Law. The version of TOUGH2 used for the modelling in this paper contains a realistic description of the properties of water for pressures to 3700 MPa and temperatures to 1400°C. These are adequate to cover the expected pressure and temperature ranges in our SULEC model domain (maximum depth 120 km), in the presence of partially melted upper mantle material.

To recap from Kissling and Ellis (2011), SULEC is a thermo-mechanical code which has be used to model the evolution of continental rift for a period of ~ 10 Myr. The rifting rate is set at 1 cm/yr, similar to that observed in the TVZ (e.g. Wallace *et al.*, 2004). SULEC predicts crustal thinning from 30 km to ~15 km directly above the rift, together with the development of localised shear zones on the 'TVZ' margins. Furthermore, a localised (~20 km in horizontal extent) heat flow anomaly forms at the base of the crust which provides the heat source for our modelled hydrothermal systems.

2. DETAILED MODEL

2.1 Model Description

For this paper we have chosen a single snapshot in time from the SULEC output (at 7.9 Myr), as shown in Figures 1 (distribution of rock types) and 2 (temperatures). Table 1 shows the permeabilities used in this study for each rock type. Typically, permeabilities of ~1 mD are necesssary to promote the formation of convective plumes in the brittle crust.

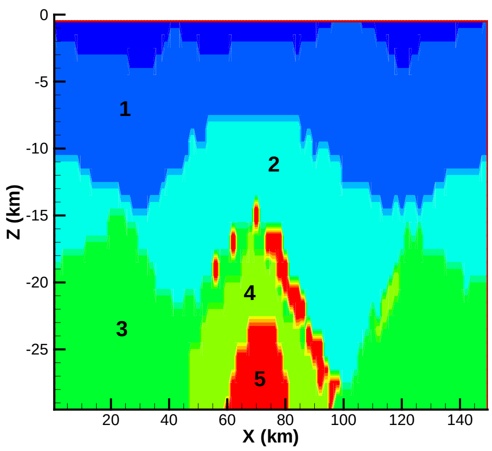

Figure 1: Distribution of rock types in the model, from SULEC output after 7.9 Myr simulated rifting. 1) brittle crust, 2) ductile crust, 3) brittle mantle, 4) ductile mantle, 5) rocks with >10% partial melt. The brittle ductile transition separates rock types 1 and 2. The darker blue at the top is an 'atmospheric' layer used in the TOUGH2 model.

Table 1. Summary of permeabilities used in the TOUGH2 model.

Rock Type/Number	Permeability (m^2)
1 Brittle crust	10^{-15}
2 Ductile crust	10^{-16}
3 Brittle mantle	5×10^{-17}
4 Ductile mantle	5×10^{-18}
5 Partial melt (>10%)	10^{-18}

The temperature distribution is calculated using TOUGH2 (for ~50 kyr) for this model is shown in Figure 2. This shows several features which correspond closely to the geothermal fields in the TVZ:

- There are three high-temperature plumes in the central region of the model which are long-lived (at least several kyr)
- Each of the plumes has a temperature of >330°C within about 2 km of the surface.
- The plumes reside in the brittle crust above the brittle-ductile transition and are within ~20 km of each other.
- The horizontal extent of each plume is just a few kilometres with a central high temperature core about 2km wide.

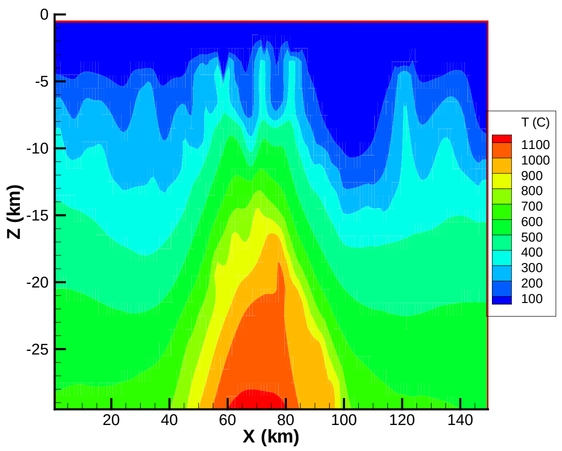

Figure 2: Temperature distribution in the model, after 50 kyr of simulation time using TOUGH2.

Figure 2 also shows some 'unproven' features of the TVZ hydrothermal system. In particular, between the plumes cool surface waters descend to depths of ~5-10 km and below this there is a relatively rapid transition to temperatures rather higher than 300°C. This is significant as it is this relatively cool water which ultimately provides the deep recharge for the three hydrothermal systems.

2.2 Deep Production

We have used our model to investigate the effects of long term production of deep fluid on the whole of the geothermal system and the surrounding region. In the past, most detailed 'production' models of individual geothermal fields have had, for practical purposes, fixed lower boundaries at a depth which is generally well above the brittle-ductile transition. These models are not able to represent the correct deep-field response to fluid extraction or the correct deep recharge to the system in either its natural or developed states. No such limitation exists for the model presented here.

We choose the right-hand most of the three hydrothermal plumes (at X = 82 km) to be our 'production' geothermal field, which we shall henceforth call DPF, for 'Deep Production Field'. Because the present model is only 2D, it is difficult to translate the natural state flows of water and heat in this system into those of an equivalent TVZ geothermal field (which of course exists in 3D). To make at least a rough comparison possible, the rates of heat and mass transported to the surface, and the production rates used later in the paper, are all referenced to the natural state flows in the DPF system. For example, an extraction rate of 100% means that the production rate from the field is equal to the natural mass flow rate from DPF.

Figure 2 shows that DPF consists of a plume ~5 km across, with a central core about 2 km wide where the temperature exceeds 300°C. This core is the natural location for production of fluid from DPF. For this, two wells, A and B, are placed 1 km apart (in fact in adjacent model elements), with feeds at 5 km depth within the core. Figure 3 shows the initial temperature profiles for wells A and B. The temperatures at production depth are 337°C and 360°C respectively. Note that in both cases the temperature gradient increases immediately below the feed points because the brittle-ductile transition occurs there, just below 6 km deep. Production from this model at any greater depth would therefore occur from within lower permeability ductile crustal rock (see Table 1), but this has not been considered in this paper.

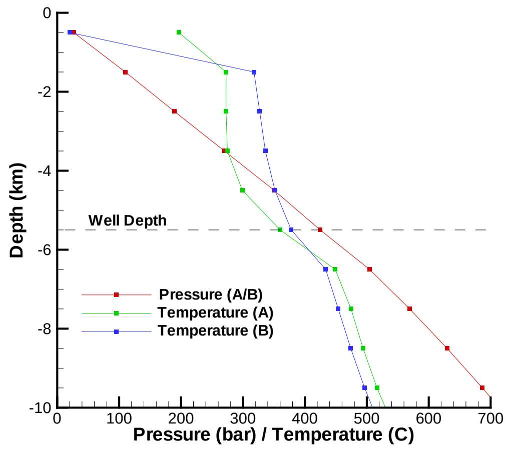

Figure 3: Initial temperature and pressure profiles for wells A and B. The increase in temperature gradient which occurs just below 6 km depth marks the location of the brittle-ductile transition in the crustal rocks.

Different models are run for Q = 0, 100, 200, 300 and 400% of the natural mass flow rate, as described previously. In each case production is continued for a period of 150 years, and there is no reinjection. This is several times the lifetime of any operational geothermal power station in New Zealand, but is relevant from the standpoint of assessing the long-term sustainability of the geothermal resources. The largest production rate (400%) is comparable to that at Wairakei (Mannington *et al.*, 2004). By simulating such a long period of production, we can begin to answer the questions:

- What is the sustainable production rate for DPF ?
- How does DPF recover after the cessation of production?
- How are the surface heat/mass flows affected?
- Can we detect any influence of the long term production from DPF on its neighbouring geothermal fields ?
- Is there any induced recharge at DPF due to the long term production?

3. RESULTS

3.1 Sustainability

We first remark that in all models, the production rate is able to be sustained for 150 years. Figure 4 shows the temperature and pressure drawdowns at the 'feeds' of wells A and B after 150 years, as a function of production rate. Clearly the pressure drawdowns are quite substantial relative to the initial pressure; however, the production rates seem able to be maintained with relative ease. In contrast, the temperature rundowns in both wells are rather modest, probably reflecting both the relatively large lower crustal permeabilities used in the model (1 mD), and the close proximity of a large volume of high temperature rock below the brittle-ductile transition which provides a conductive 'buffer' to maintain the well temperatures.

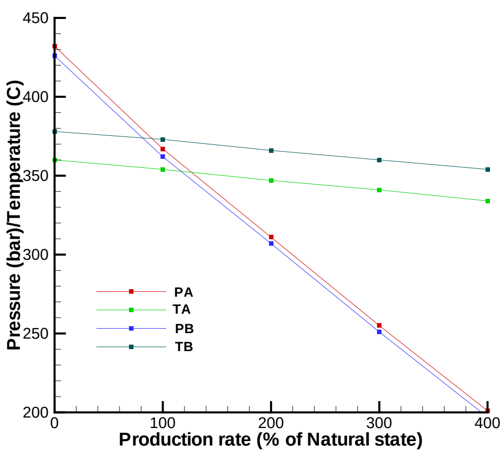

Figure 4. Final temperatures and pressures in wells A and B after 150 years continuous production, as a function of production rate.

The reason that such high production rates can be maintained from DPF for a long period of time is less clear. An obvious question is: Where does the produced water come from? To help answer this, Figure 5 shows a contour plot of the fluid pressure difference (a proxy for mass change, and defined as 'final pressure – initial pressure'), for Q=300% at 150 years, superimposed on the temperature contours at the same time (as also shown in Figure 2).

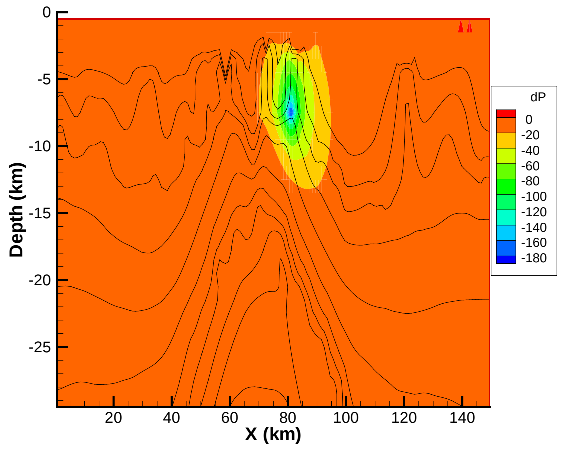

Figure 5: The fluid pressure difference (bar) across the model generated after 150 years production at 300% of the natural state flow. The black contours show the initial temperature.

We see the green/blue areas where the largest pressure decrease occurs are localised within the high temperature plume of DPF, and indicate that most of the produced fluid, as expected, comes from within the plume itself. However, the pressure decrease also extends horizontally beyond the plume into both the cold surrounding region to the right and leftward into the neighbouring central plume. Vertically, it extends upward into the plume from the production depth and also propagates downward into the ductile crust. One implication of this lateral spread is that the effects of the very high production rates in DPF might be felt in neighbouring geothermal fields, and this will be discussed in a later section of this paper.

So far, we have assumed that the permeability within the brittle crust is uniform and (probably) higher than in the actual deep TVZ (see e.g. Ingebritsen and Manning, 2010). Further numerical experiments using a (more realistic) reduced permeability (0.25 mD) in the lower 2 km of the brittle crust show larger local pressure declines within DPF but essentially the same effects in the neighbouring central and western plumes. This suggests, at least if these simple permeability distributions are realistic, that sustainable production cannot be maintained at the highest rates considered here without the risk of field-to-field interactions.

3.2 Surface heat and mass flows

As with present-day shallower production from geothermal systems, one possible environmental effect of very deep production is changing the outflows of geothermal heat and water at the surface. In Figure 6 we show the heat and water flows to the surface after 150 years of production, for the (1 km wide) elements directly above wells A and B. The flows have been normalised to 1 by dividing by the initial mass and heat flows above well A. For A, there is an initial decrease in both mass and heat flows, which reach zero at about Q=150%. Thereafter the mass and heat flows grow again, with the heat flow eventually surpassing the 'natural state' heat flow while the mass flow reaches about 60% of its initial value. The excess heat flow as the production rate increases occurs because of the greater proportion of steam in the flow. For B the behaviour is different. Following a similar decline to A in heat/mass flows at low production rates, beyond Q=100% there is essentially no mass flow and the heat flow is entirely conductive.

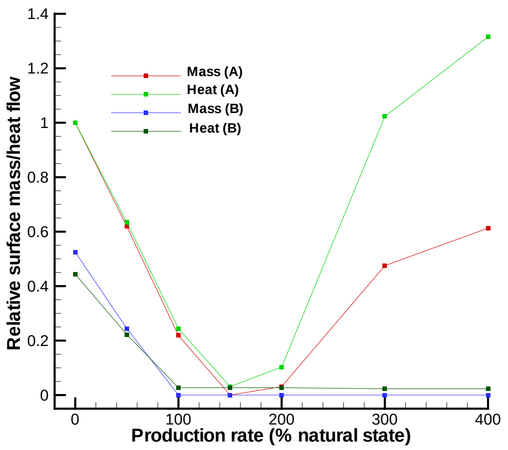

Figure 6. Surface mass and heat flows after 150 years of production, as a function of production rate. Points on the graph are obtained by integrating the upward flows of heat and mass at the rock/atmosphere interface across the top of the plume (DPF).

3.3 Influence on neighbouring plumes

One major concern for future deep geothermal developments is the potential influence of long term fluid production on neighbouring geothermal fields. Referring back to figure 2, we see there are two hydrothermal plumes to the 'west' (left) of DPF, which we label the 'west' and 'central' plumes respectively. Figure 7 shows the changes in surface mass flow from these fields after 150 years of production from DPF, as a function of production rate. The effects on the central plume are largest, with the mass flow from this plume reducing to zero for the highest production rates from DPF (greater than Q=300%). For the western plume, the effect of production at DPF is smaller because of its greater distance from DPF (22 km, against 10 km for the central plume), but amounts to a reduction of approximately 10% in the natural flow.

In figure 7 the curves labelled 'deep crust' refer to the previously mentioned (subsection 3.1) model with 0.25 mD permeability in the lower 2 km of the brittle crust. For the central plume the decline in mass flow is less than the 'uniform permeability' model, but is still significant. For the western plume, the surface flows are initially smaller anyway due to the reduced 'connection' to the surface, but there is still no discernable effect from the production at DPF.

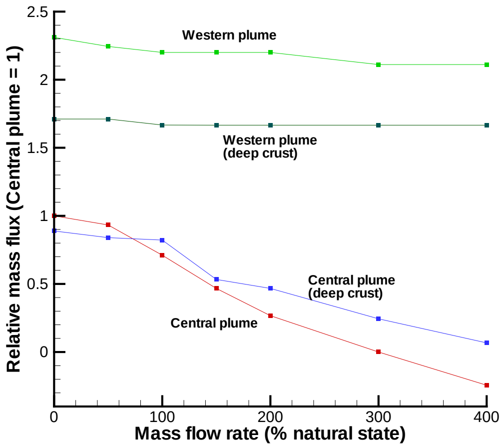

Figure 7. Surface mass flows for central and western plumes, after 150 years, as a function of production rate. Points on the graph are obtained by integrating the upward flows of heat and mass at the rock/atmosphere interface across the top of the plume (DPF).

3.4 Field Recovery

We now consider the recovery of the geothermal field DPF following the cessation of production after 150 years. In figure 8, the pressures and temperatures for wells A and B are shown as a function of time since the end of production. Data is shown for production rates of Q=100% and Q=400%. Due to difficulties with the 'atmospheric' boundary elements in the TOUGH2 model, it has not been possible to run this simulation beyond 43 years of recovery, but nevertheless some key features of the recovery can be seen. Firstly, we note that while figure 4 shows that only a small temperature change (~20°C) occurs during the production period, 43 years is insufficient time to show any significant temperature recovery. Indeed, we expect, for a thermal diffusion coefficient of (typically) ~10^{-5} ms^{-2}, a timescale for full temperature recovery by conduction alone might be of the order of hundreds to thousands of years.

For the pressures the situation is somewhat better. Here the pressure curve for Q=100% reaches a plateau after about 10 years, while that for Q=400%, though still rising at 43 years, is projected to level off somewhere between 50 and 100 years. Note that the pressures do not reach the initial pressure again, but the shortfall is consistent with the density changes resulting from the (yet to recover) temperature deficit in the DPF plume. In both cases the pressure recovery period is rather shorter than the production period, although the plots are otherwise consistent with a suggestion by O'Sullivan *et al.*, (2010) that the recovery period depends on the 'production ratio', the ratio of produced energy to the natural energy flow (or in this paper, the almost equivalent ratio Q, of mass production to natural mass flow). One possible reason for the much shorter timescales seen here is the additional pressure support resulting from the fluid column which spans ~6km vertically from the surface to the brittle-ductile transition. This is the source of deep recharge to the geothermal system, and will be discussed in more detail in the next section of this paper.

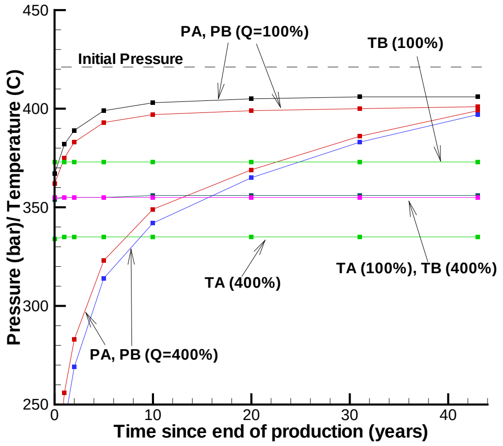

Figure 8. Pressure and temperature recovery (at feeds for wells A and B) following 150 years of production at Q=100% and Q=400%. .

3.5 Deep Recharge

A further numerical experiment has been carried out to evaluate changes in the deep hot recharge to the DPF system due to shallow production. Changes in deep recharge have been implemented in models of individual geothermal systems (e.g. at Wairakei by Mannington *et al.*, 2004), but do not seem to have ever been calculated from first principals. The present TOUGH2 model is well suited to this because it contains, at least in principal, all of the pressure sources affecting DPF, and unlike previous models, there is no prescribed mass and heat flow into the base of the model. Here, the recharge is driven only by pressure differences created by the fluid production from the field.

To do this, the production depth is reduced compared to previous models to 3 km, and production rates of Q=200% and Q=400% are simulated. The vertical mass and heat flows are calculated near the base of the plume of DPF just above the brittle-ductile transition. These are then normalised with respect to the initial mass flow (i.e. so that natural mass flow = 1) and are shown plotted against time in Figure 9. The normalised heat flows, which are calculated in exactly the same way, lie very close to the mass flow curves and are not shown in the figure.

There are four distinct regimes apparent in Figure 9. First, for times less than ~0.1 years, the recharge is small and (roughly) independent of the production rate. This behaviour is exactly that expected if the induced recharge depends on the difference between the well pressure and some deep pressure, say at the base of the ductile crust. It then follows (second regime), that as the well pressures start to drop, some dependence on production rate will appear – here the induced recharge becomes larger for Q=400% up to about ~5 years. In the third regime, the recharge reaches a maximum at ~5 years and then drops to a minimum after 20 years of production. The temporary drop in deep mass recharge appears to occur because of the formation of a two-phase zone which forms above well A, but further work is needed to fully understand this. The fourth and final regime starts at ~20-30 years. Here the produced fluid is now largely steam and the well pressures begin to drop more rapidly, resulting in the induced recharge continuing to increase.

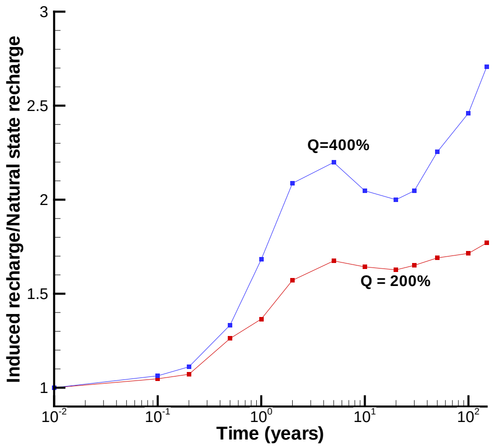

Figure 9. Deep mass recharge to DPF induced by shallow production expressed in terms of the natural state recharge, for Q = 200% and Q = 400%. The recharge of energy to DPF follows essentially the same curves. Note the logarithmic time scale, which has been used to highlight the maximum in the recharge which occurs after 5 years of production

4. DISCUSSION AND CONCLUSIONS

In this paper we have looked at the effects of producing high temperature fluid from >5 km depth in a geothermal system, just above the brittle-ductile transition. Our model is based on regional scale permeabilities calculated by the rock mechanics code SULEC, with flows of water and heat calculated using a high temperature and pressure version of TOUGH2. We simulate production from a geothermal system for a period of 150 years, with no reinjection.

We find that production rates up to 400% of the natural state flow are sustainable for the 150 year period, and result in significant pressure drawdowns, but mostly only small temperature changes. This suggests that, if our model assumptions are correct, with appropriate management a great deal more heat could be mined from the base of the geothermal system.

Deep production of fluid produces significant effects on surface flows of heat and mass above the geothermal system. In particular, there is an initial decline in surface activity, and in ‘worst case’ scenarios the mass flow then ceases while heat flow becomes essentially conductive. In more favourable cases, the mass flow can recover to ~60% of it’s initial (natural state) value, while heat flow can exceed that of the natural state because of the increased steam flow resulting from deep boiling.

There are significant effects on neighbouring geothermal fields, where heat and mass flows to the surface are found to decrease with time as a result of deep production in our ‘production’ field. In this paper we assume that the crustal permeability is uniform (at 1 mD), so this conclusion might be modified if, for example, the permeability is much lower in the cooler regions outside the geothermal plumes.

It has not been possible to simulate field recovery from long term production for more than a few decades. However, on these timescales the recovery of field pressures is largely complete, while temperature recovery is not yet significant.

Production-induced deep recharge to the geothermal system has been calculated from 'first principals' and shows complex behaviour depending on both pressure and temperature changes in the system. Typically, induced recharge can exceed the natural recharge by a factor of 1.5-3 after 150 years of production at rates 2-4 times the natural recharge.

The relatively low spatial resolution of the present model (1 km grid blocks), is not ideal for investigating the field responses to deep production in any detail, but nevertheless we feel it is sufficient to capture some important aspects of this. Future work will focus on developing more detailed models of these important systems.

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