SOURCE MODELS FOR THE TVZ GEOTHERMAL FIELDS

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SUMMARY - This paper presents results from large scale two and three dimensional hydrological models of the TVZ geothermal fields. Two heat source concepts for the geothermal fields are presented - the 'hot plate' model, where the heat source is constant both spatially and in time, and the 'cooling intrusive' model, where a body of hot rock is cooled by circulating ground water. The influence of large scale topography on the hydrology of the TVZ is explored. Topographically driven heat flows strongly influence the development of the hydrothermal systems. Where multiple intrusions occur, heat and mass flows from new plutons are channelled preferentially into regions where remnant heat from old plutons remains. This mechanism can account for the stable positions of the geothermal fields over periods much longer than the cooling time for an individual pluton.

1 INTRODUCTION

This paper presents some recent large scale hydrological modelling of the Taupo Volcanic Zone (TVZ), New Zealand. This region contains 23 distinct geothermal fields (Bibby *et al.*, 1995), and the large scale hydrology influences both the nature and position of these fields within the TVZ. The modelling described here extends previous work by Kissling (1996, 1997) by including topographical effects and by explicitly treating the heat source as a high temperature intrusion which is cooled by circulating groundwater. The work described here draws on studies by Cathles (1977), Norton and Knight (1977) and Hayba and Ingebritsen (1997), but is specifically aimed at understanding the hydrology of the geothermal fields in the TVZ.

It is natural to think that the heat produced by the geothermal fields comes from the cooling of some magmatic body at depth, and several authors have treated this problem in some detail. Cathles (1977) and Norton and Knight (1977) used finite difference techniques to model the cooling of hot intrusive magma bodies by circulation of ground water. These studies examined a variety of conditions pertinent to the problem but were necessarily restricted by the computing resources of the day. This meant, for example, that only crude approximations to the thermodynamic and transport properties of water could be used. More recently, Hayba and Ingebritsen (1997), have published an extensive study of the cooling of plutons by ground water using the code HYDROTHERM. Their paper addresses many of the shortcomings of the earlier work of Cathles and Norton and Knight, in particular by including both two-phase and super-critical fluid transport. All of this previous modelling has been carried out in a two dimensional setting.

This paper begins with a brief review of the main features of the hot plate models. This provides a basis for comparison with the more realistic models presented in the next sections. These include topographical detail and a mechanism for supplying the heat, namely the cooling of an intrusion of hot rock. The pluton model is then used to investigate questions of the initiation and persistence of geothermal fields in the TVZ. In the last section some preliminary three dimensional modelling is presented. This allows the validation of results against geophysical data which is inherently three dimensional, such as the gravity and magnetic anomalies associated with the TVZ.

2 HOT PLATE MODELS

McNabb (1992), proposed the idea of a widespread hot plate beneath the TVZ, which arises because of the phase properties of water-brine mixtures at high temperatures and pressures. The hot plate consists of a 'heavy brine' phase, and would be expected to occur at depths of between 5 and 10 kilometres. The hot plate is about 30 kilometres wide, with a thickness of a few hundred metres and a temperature between 400°C and 500°C. The idea of an extensive, relatively low temperature heat source (compared to magma) is attractive in that it provides just the type of source needed to drive large scale convective flows in the TVZ, as suggested by Wooding (1978).

A numerical study by McNabb *et al.* (1993) showed that heavy brine layers can indeed form in the depth range 5 to 10 kilometres, although this paper was concerned with mid-ocean ridges rather than the TVZ geothermal fields. Using models involving only pure water, Kissling (1996, 1997), has shown that sources with hot plate-like geometry can reproduce many of the observed properties of the TVZ geothermal fields with large scale permeabilities on the order of 1 milliDarcy (mD).

Figure 1 shows the main features of a simple two dimensional hot plate model. The domain of the model extends 80 kilometres horizontally, and 8 kilometres vertically. This is divided into 1680 1.0 x 0.4 kilometre numerical elements. This discretisation is rather more coarse than desirable but was chosen to allow quick turn around when running models, while preserving reasonable accuracy. The models are run using a super-critical version (Kissling, 1995) of the TOUGH2 code (Pruess, 1991).

The upper boundary of the model is horizontal, and is maintained at a constant temperature and pressure (15°C and 20 bars respectively). These conditions correspond roughly to those at the base of the shallow ground water aquifers, which have not been included in the models to reduce computational costs, and to avoid having to model the unsaturated zone near the surface. At the lower boundary, a heat flux of 90 mW/m^2 is applied. This maintains a conductive temperature gradient of 30°C /km throughout the domain before the hot plate is 'turned on'. The vertical boundaries are held at hydrostatic pressure corresponding to this temperature profile. The hot plate is represented by a constant flux heat source forty kilometres wide, centred on the lower boundary. The heat flux of 1 W/m^2 is the average heat flux over the TVZ. Finally, no fluid flow is permitted across the lower boundary of the domain.

The hot plate models exhibit a range of behaviour as the ratio of vertical permeability (k_v) to horizontal permeability (k_h) changes. For large values of k_v/k_h the fluid motion is erratic and unsteady, but periodic solutions with discrete convective cells appear as this ratio is decreased. These periodic solutions are thought (McNabb, 1992) to explain the apparent separation of the geothermal fields within the TVZ. In the west to east section of the TVZ modelled here, the geothermal fields have a bimodal distribution, with a mean separation of about 20 kilometres (Bibby *et al.*, 1995).

Two examples of hydrothermal systems resulting from hot plate models are given here. In the first, shown in Figure 2, $k_v/k_h = 2$ ($k_v = 2$ mD, $k_h = 1$ mD). In this case, the resulting hydrothermal system comprises three separate, unsteady plumes. As the ratio k_v/k_h decreases, the solutions become more stable in time and the separation between the plumes is greater. Where $k_v/k_h = 1.5$ (Figure 3) a pair of plumes occurs. These plumes are not steady in time, but do have properties similar to those of the TVZ geothermal fields. The region containing fluid hotter than 200°C is just a few kilometres across and the shallow temperatures (< two kilometres) are in the range 250 to 300°C. The plumes are separated by 8 kilometres, equivalent to the distance between the Wairakei and Tauhara geothermal fields. In this example the hot plate temperature is close to 400°C, as proposed by McNabb (1992).

It is puzzling that none of the hot plate models seem to give truly stable multiple plume solutions. The instabilities in the present examples appear to be related to the constant pressure condition at the upper boundary, as hot plate models with no flux conditions at this boundary do produce stable hydrothermal systems. A detailed analysis of this problem, such as that given by Straus (1973) would be of interest in defining regions where the solutions are stable.

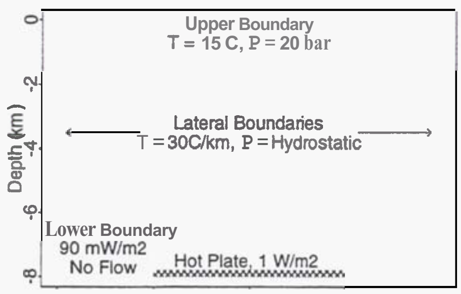

Figure 1: Diagram showing the boundary conditions for the hot plate model. The permeability and other rock properties are constant. The vertical scale has been exaggerated for clarity.

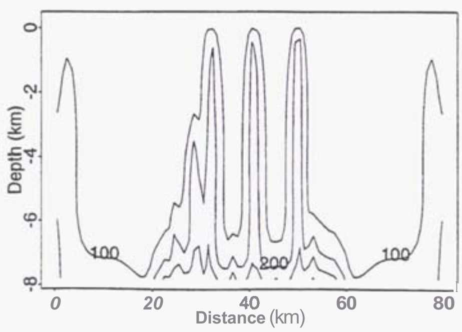

Figure 2: Example of a hot plate model where three distinct hydrothermal plumes form. Systems of this type are not steady in time. In this example, $k_v = 2$ mD and $k_h = 1$ mD. The interval between the contours is 100 °C.

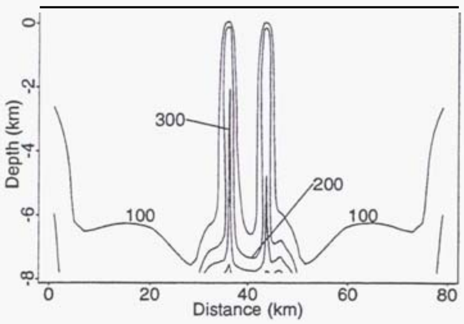

Figure 3: Example of a hot plate model where two hydrothermal plumes form. The plumes are separated by 8 kilometres, and have similar properties to the TVZ geothermal systems. In this example, $k_v = 1.5$ mD and $k_h = 1$ mD. The interval between the contours is 100 °C.

3 TOPOGRAPHY

An important factor not considered in the previous models is topography, and how this influences the large scale hydrology. This was considered by Hayba and Ingebritsen (1997), but these authors examined only the very simple case of terrain with a constant slope. The TVZ lies in a broad basin, and is bounded on both sides by high ground. By assuming that this high ground defines a surface of constant temperature and pressure (15°C and 20 bars), an initial state including the normal geophysical heat flux of 90 mW/m^2 has been calculated. The TOUGH2 grid in this case is similar to that used for the hot plate models, except that the upper, constant temperature and pressure boundary now takes into account the variation in surface height. The approximation to the topography is very simple. In coordinates measured east from the origin (see for example Figure 1) the ground surface between 10 and 20 kilometres, and between 60 and 70 kilometres, is 400 m higher and that between 70 and 80 kilometres is 600 m higher than the ground surface elsewhere in the model.

The permeability has also been modified by including a high permeability region forty kilometres wide and two kilometres deep. This corresponds to the region of volcanic infill in the shallow region of the TVZ. The horizontal and vertical permeabilities in this region are 50 and 5 mD respectively, typical of those found in the productive regions of geothermal fields. The remainder of the domain has horizontal and vertical permeabilities of $k_h = 4$ mD and $k_v = 1$ mD, respectively.

Steady state temperatures for this model are shown in Figure 4. This state is fundamentally different from that in the flat topography case. Mass flows are generated from both regions of high terrain toward the central TVZ. These flows depress the temperature contours on either side of a central low temperature plume. This plume results from focussing of the heat flux (90 mW/m^2) applied at the lower boundary of the model into a region 10 to 20 kilometres wide. It is a robust feature, which also occurs if the lateral boundaries are held at cold (15°C) hydrostatic pressure.

There is a substantial upward mass flow associated with this low temperature plume. The magnitude of this flow is about one third of the peak 'geothermal' flow in model A given below, where a cooling pluton is located beneath the warm upflow (see Figure 5). Topographically driven upflows of similar magnitude occur in other situations, for example when the lateral boundaries of the model are maintained at cold (15°C) hydrostatic conditions, and even when zero heat flux is applied at the lower boundary of the model.

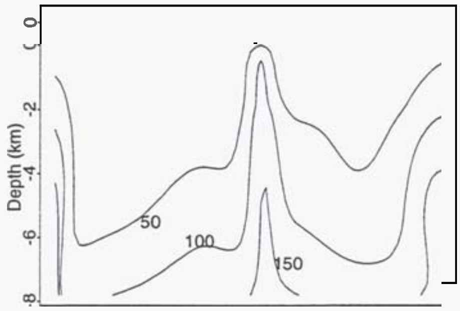

Figure 4: Steady state temperatures for a model incorporating crude topography of the TVZ. The interval between the contours is 50 °C.

4 COOLING PLUTONS

In the hot plate models discussed in the previous section the rate of heat transfer to the groundwater system is prescribed. A more realistic model involves the cooling of a hot magma body or pluton. Cooling occurs by convection in the surrounding ground water, and a geothermal field is created when heat and mass from the pluton are transported to the surface. Although it is expected that the actual emplacement temperature is close to 1200°C (Elder, 1976) in this paper the pluton is assumed to have cooled sufficiently to be below its freezing point, with an initial temperature of 750°C. In common with other authors referred to in this paper, it is assumed that the emplacement of a pluton occurs instantaneously, and that it is treated as a permeable medium with constant permeability equal to that of the surrounding host rock.

This cooling process can be modelled with TOUGH2. The model presented here is used to investigate the conditions which affect the initiation of a geothermal field, and how these geothermal fields are maintained in the same location for periods much longer than the cooling timescale of an individual pluton.

4.1 Initiation of Geothermal Fields

The initial state of the model is taken to be that shown in Figure **4,** with the addition of a **4** x 6 kilometre pluton on the lower boundary. Figure 5 shows the temperature 6,300 years after the pluton was placed beneath the low temperature plume in the initial state (Model **A).** In contrast, Figure 6 shows the temperature contours at the same time for a pluton placed in a cool part of the domain (Model B). Figure 5 shows that the initial low temperature plume acts to channel the heat and mass flow from the pluton to the surface, whereas in Figure 6, the hot fluid has yet to reach the surface. This channelling does not occur in isothermal models, despite mass upflows occuring in these as well. The lower viscosity of the fluid above the pluton in Model **A** plays an important role in the formation of the hydrothermal plume. Other models (not presented here) show that this channelling occurs if the pluton is placed within about five kilometres of the low temperature plume shown in Figure **4.**

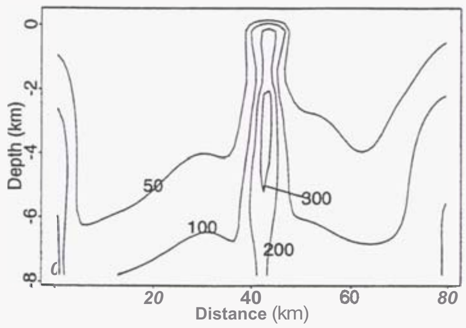

Figure 5: Model **A.** Temperature distribution 6,300 years after the pluton is emplaced below a **warm** region of the initial state. The contours are labelled in degrees C.

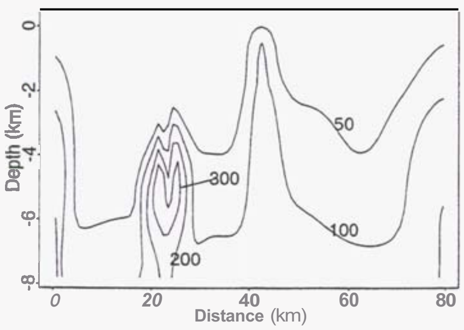

Figure 6: Model B. Temperature distribution 6,300 years after the pluton is emplaced below a cool region of the initial state. The contours are labelled in degrees C.

The heat flow to the surface for these two models is shown in Figure 7. The heat flows have been scaled so that they represent a geothermal field five kilometres wide. Thus the upper curve (Model **A),** which peaks at 280 MW, is similar in magnitude to many of the TVZ geothermal fields. The highest temperature in the upper two kilometres of the plume is close to 300°C, again similar to TVZ values. The contribution to the heat flow from the initial state is **35** MW, and **this** has been subtracted from the curves. The bottom curve (Model B) has a lower peak (about 50 MW), and a much slower rise and decay. The point where the hot fluid reaches the surface occurs at about 15,000 years. The maximum temperature reached in the upper two kilometres in Model B is 110°C - too cool for the TVZ.

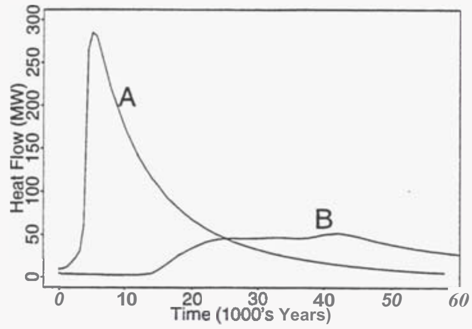

Figure **7:** Comparison of surface heat flow for plutons emplaced in different conditions. The peak heat flow of the upper curve corresponds to a geothermal field with a thermal output of **280** MW.

4.2 Persistence of Geothermal Fields

The upper curve (Model **A)** shown in Figure 7 remains above 200 MW for less than 5000 years. Grindley (1965) presents evidence that geothermal activity may have existed at Wairakei for **500,000** years, and Bibby *et al.* (1995) argue that the positions of the geothermal fields have not changed in the last 200,000 years. With a typical lifetime of (say) 100,000 years, the geothermal fields clearly need a much larger heat source. Grindley, in the same publication, shows that **3750 km^3** of magma are needed to supply heat to Wairakei for 500,000 years at the present rate. Either a continuous supply **of** magma **from** a much larger and deeper source (this is proposed by Grindley), or multiple, smaller intrusions are required.

Larger plutons than those shown in the previous examples will produce surface heat flows higher than those observed in the **TVZ**. For example, a 5 x 10 kilometre pluton produces a peak thermal output of about 600 MW, which is close **to** the maximum seen in the TVZ (Bibby *et al.*, 1995). Thus, individual plutons cannot be much larger than this because the resulting heat flows would be too high. This means that any larger magma body, if it exists, cannot be wholly in contact with the groundwater system, and therefore does not cool 'all at once' as in the models presented here.

The previous examples showed that the development of a hydrothermal system can be strongly affected by even a weak thermal perturbation. Much stronger temperature variations occur following the emplacement and cooling of a pluton. The upper curve (Model A) in Figure 7 shows that it takes over 60,000 years for the system to cool back to near the initial steady state. During much of this time conditions would be favourable for the convective flow from any new pluton to be channelled into the previously existing plume. To test this idea, a model is now presented where two plutons, separated by 8 kilometres, are emplaced 3000 years apart.

Consider again a model with initial conditions as in Figure 4, and a 750°C, 4 x 6 kilometre pluton centred on the lower boundary of the model. Figure 8 shows the temperature distribution 3000 years after the emplacement of the pluton. There is a tendency for the plume to develop sideways into the region that was initially warm. The horizontal displacement between the centre of the plume and the centre of the pluton is 3 kilometres. At this time another pluton of the same size is introduced 8 kilometres to the east (right) of the first. The temperature 3000 years after this event is shown in Figure **9.** The flow from the second pluton is channelled into the higher temperature region which remains from the first pluton. In this case the centre of the plume is displaced horizontally to the west (left) **4** to 5 kilometres from the centre of the pluton. Throughout this process the position of the surface outflow remains the same.

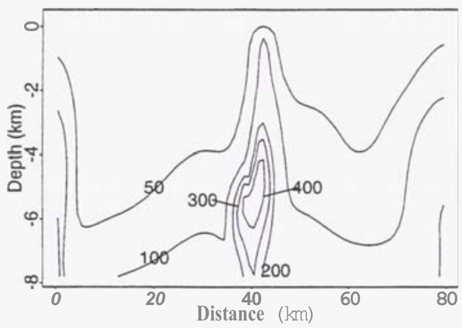

Figure 8: Temperatures 3000 years after emplacement of first pluton, centred at 40 kilometres. The contours are labelled in degrees C.

These results show that recurring pluton emplacements can lead to stationary geothermal plumes, even if the later plutons are emplaced several kilometres horizontally from the position of the geothennal plume. Cooling timescales of perhaps 50,000 years mean that the frequency of emplacement of new plutons can be quite low. A mechanism of this type can explain the apparent persistence of the TVZ geothermal fields in the same location for periods much longer than the cooling times of individual plutons.

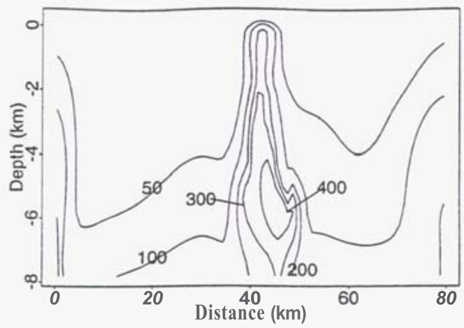

Figure **9:** Temperatures 3000 years after emplacement of second pluton, centred at 48 kilometres. The contours are labelled in degrees C.

5 THREE DIMENSIONAL MODELS

Much of the geophysical data available for the TVZ geothermal fields is three dimensional in nature. The magnetic, gravity and electrical resistivity anomalies associated with the TVZ fall into this category. While two dimensional 'slices' of these data can be used to validate models of the type already presented in this paper, three dimensional models are preferable.

The three dimensional model is similar to those previously described, with the initial and boundary conditions being identical. The permeability is uniform at 1 mD. The model covers an area of **20** kilometres square x 8 kilometres deep. The dimensions of the **TOUGH2** elements are 1.0 x 1.0 x 0.8 kilometres. **A** 21 km^3 pluton at 750 "C is emplaced at the lower boundary and allowed to cool. An example of a geophysical signature calculated from the model, the total field magnetic anomaly (due to demagnetisation of rock at high temperature) at 1000 m altitude, is shown in Figure 10. Eventually, calculations of this type will be used to validate more detailed three dimensional models.

The main difficulty with three dimensional models is obtaining adequate spatial resolution with current computers. The present model covers 20 x 20 kilometres and has 4400 elements, each approximately one kilometre across. To model a region of the TVZ 80 x 80 kilometres would require 70000 elements at the same resolution. The practical limit at present is about 20000 elements. The most appropriate element sizes vary across the region modelled. In the vicinity of the pluton (and the region above it) 100 metre elements are probably desirable, whereas two to five kilometre elements might suffice near the lateral boundaries. **A** fixed grid of this type containing less than 20000 elements could be constructed for a region of the TVZ 80 x 10 kilometres and 8 kilometres deep.

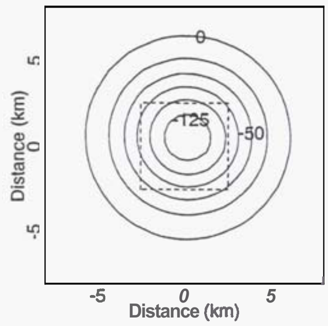

Figure 10: Total field magnetic anomaly due to a 21 km^3 pluton at 8 kilometres depth, 3200 years after emplacement of the pluton. The outline of the pluton is shown by the dashed line. The interval between the contours is 25 nT.

6 CONCLUSIONS

This paper has presented recent two and three dimensional modelling aimed at understanding the large scale hydrology and heat source mechanisms of the TVZ geothermal fields. Hot plate models can produce hydrothermal systems similar to those in the TVZ, and naturally explain the observed spacing of these features. Cooling pluton models which include topographically driven flows suggest that geothermal fields will only form if the pluton is emplaced into a region that contains warm water. This warm fluid can result from either topographical effects or from the emplacement and cooling of an earlier pluton. The longevity of geothermal fields and their persistence in a single location can be explained by heat and mass flows from multiple intrusions being channelled into these warm regions.

7 ACKNOWLEDGEMENTS

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