PROCEEDINGS, Twenty-Fourth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 25-27, 1999
SGP-TR-162

MODELING OF COOLING PLUTONS IN THE TAUPO VOLCANIC ZONE, NEW ZEALAND

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ABSTRACT

Modeling carried out using a super-critical version of TOUGH2 has been used to investigate different source models for the geothermal fields in the Taupo Volcanic Zone (TVZ), New Zealand. The models describe the cooling, by groundwater circulation, of magmatic intrusions into the upper 8 km of the crust. By comparing the calculated surface heat flux from these intrusions with actual thermal outputs in the TVZ, limits can be placed on the size of such magma bodies. Typically, many intrusions are required to provide the heat for a geothermal field like Wairakei. An ‘entrainment’ mechanism is identified that can explain the apparent stability of the TVZ geothermal fields over timescales many times longer than the cooling time for an individual intrusion.

INTRODUCTION

The Taupo Volcanic Zone (TVZ) in the North Island of New Zealand, contains 23 distinct geothermal fields (Bibby *et al.*, 1995), with thermal outputs ranging up to 400-600 MW. This heat is generally thought to come from magma intruded from depth into the shallow crust of the TVZ. There, it is cooled by the circulation of groundwater, resulting in plumes of hot fluid which rise buoyantly to the surface, forming the geothermal fields.

The basic properties of the intruded bodies (i.e. size, shape, depth, temperature etc.) are largely unknown, and this study is aimed at defining some of these quantities. By modeling the cooling of these intrusions and the consequent formation of geothermal fields, comparison can be made with real data from the TVZ. For example, the models must explain the physical size and spacing of the geothermal fields, their heat and fluid output, and their apparent longevity on time scales of several hundred thousand years. On a larger scale, the TVZ geothermal fields seem to be part of a single large scale convective system (Bibby *et al* 1995). This observation provided the motivation for the early work of Wooding (1978) on large scale convection in the TVZ and the ‘Hot Plate’ models of McNabb (1992). Part of this study is aimed at understanding the interaction of multiple magmatic intrusions, which might give rise to such large scale hydrological features.

Several authors have treated the problem of cooling intrusives 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 groundwater. 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.

The modeling 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 and heat source characteristics of the geothermal fields in the TVZ.

THE MODEL

Figure 1 shows the main features of the model presented in this paper. In order to include the complete convective system associated with a cooling pluton, and also to account for regional topographical flows, the model extends 80 kilometers horizontally, and 8 kilometers vertically. This region is divided into 3360 elements, each 0.5 × 0.4 kilometers. 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).

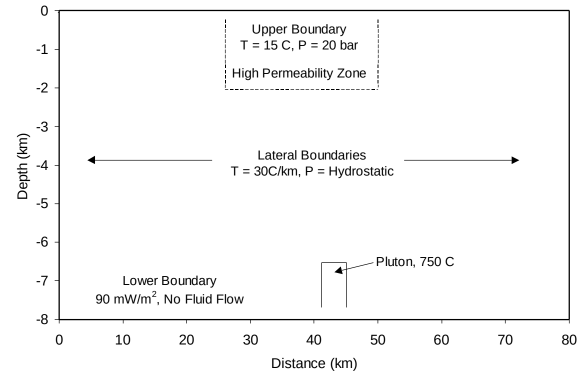

Figure 1. Schematic diagram showing main features of the model. The model represents a two dimensional west to east slice across the TVZ. The horizontal and vertical permeabilities in the high permeability zone are 50 mD and 5 mD. Elsewhere the permeability is isotropic and has a value of 1 mD. The vertical scale has been expanded for clarity.

The upper boundary of the model follows the regional topography (see next section for details), 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. It is assumed that no groundwater can circulate deeper than 8 kilometers, and therefore the lower boundary at this depth is impermeable to fluid flow. A heat flux of 90 mW/m^2 is applied however, to represent the average conductive heat flow through the earth. The vertical boundaries are held at hydrostatic pressure corresponding to a conductive temperature gradient of 30°C/km, consistent with this heat flux.

The permeability distribution used in the model reflects the general geological structure of the TVZ, as described by Wood (1997). The shallow regions (less than 2 kilometers depth) comprise (relatively) high permeability volcanic infill, and these have been assigned horizontal and vertical permeability of 50 and 5 mD respectively. These values are typical of those found in the developed regions of the geothermal fields. The infill region is 20 km wide. Underlying this is a greywacke basement, where permeabilities are much lower. This basement, and surrounding areas have been assigned an isotropic permeability of 1 mD.

TOPOGRAPHICAL FLOWS

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. This high ground defines the upper constant temperature and pressure (15°C, 20 bars) boundary of the model. The approximation to the topography used in the model is very simple. In coordinates measured east from the origin (see for example Figure 1) the ground surface between 10 and 20 kilometers, and between 60 and 70 kilometers, is 400 m higher and that between 70 and 80 kilometers is 600 m higher than the ground surface elsewhere in the model.

Steady state temperatures for this model are shown in Figure 2. This state is fundamentally different from that where the upper boundary is horizontal (in this case the temperature contours are horizontal and there is no fluid flow). Mass flows are generated from both regions of high terrain toward the central TVZ. These flows of cool fluid depress the temperature contours on either side of two low temperature plumes. These plumes contain most of the heat flux (90 mW/m^2) applied at the lower boundary of the model.

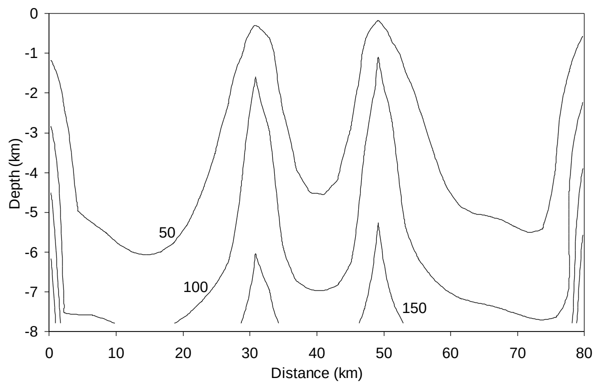

Figure 2 Steady state temperatures for a model incorporating crude topography of the TVZ. The contours are labeled in °C.

There is a substantial upward flow of low enthalpy fluid associated with these 'topographically driven' plumes. The magnitude of these flows is about one tenth the output of a Wairakei-like geothermal field, (400 MW, 400 kg/s) although the mean enthalpy of the flow is lower due to the low temperature of the plume. Similar topographically driven flows occur in other situations, for example in an isothermal model where the lateral boundaries are maintained at constant temperature and zero heat flux is applied at the lower boundary.

The particular solution shown in Figure 2 is not unique, and does depend on the value for the large scale permeability. For example, if this permeability is 2 mD (and isotropic) then only a single low temperature plume forms. The structure of the plume also depends on the exact topographical detail added to the model, and so will vary from place to place within the TVZ. The topography described here is typical of the southern TVZ region close to the Wairakei geothermal field. In the northern TVZ, the high terrain to the west is absent. However, low temperature plumes similar to those shown in Figure 2 occur quite generally provided a geophysical heat flux is applied at the lower boundary of the model.

PLUTON EMPLACEMENT AND COOLING

The process most fundamental to this study is the convective cooling of a magmatic intrusion by circulation of groundwater. In an important early paper Lister (1974), described the penetration of water into hot rock through fractures created by thermal stresses, and derived estimates of the permeability created in this process. In later work Fournier (1991) suggested that permeability will not be maintained at temperatures greater than 360°C, due to the brittle-ductile transition in the rock at this temperature.

There have been many experimental measurements of the permeability of heated rock, often with conflicting results. For example, Moore et al. (1994) found permeability reductions in granite in the range 300°C to 500°C. In contrast, Darot *et al*. (1992), found permeability to decrease at low temperature (20-125°C), but to increase above about 200°C. Whatever the permeability changes that occur in the high temperature region, the formation of the hydrothermal system will depend on the large scale permeability away from the pluton, as this is what controls the transport of heat and fluid to the surface. In the TVZ, the basement rock into which the magma is intruded is greywacke, which is a low permeability and porosity material, with the permeability being dominated by fractures. As a simplifying assumption in this work, taking into account uncertainties in the models and experimental results, a constant greywacke like permeability is adopted for the pluton.

A further uncertainty lies in the emplacement process by which the pluton, or magma chamber is formed. The rate of magma intrusion into the TVZ is about 0.2 m^3/s when averaged over time for a given location. The intrusion rate for a given pluton will be greater, as the TVZ does not fill uniformly with magma over time. Conservatively, if only one tenth of the TVZ is active at any time, the rate for a single pluton might then be 2 m^3/s. At this rate, a pluton will grow much faster than it can be cooled by conduction and groundwater circulation. For example, a 10 km^3 magma chamber will form in about 150 years, whereas the heat it contains could supply a geothermal field like Wairakei for about 1300 years (Grindley, 1965) and a smaller field for much longer. Because the cooling time scale is much longer than that for pluton growth, it will be assumed for the modeling carried out in this paper that plutons are emplaced instantaneously.

A final assumption must be made about the emplacement temperature of the magma. Magma at depth is expected to be close to 1200°C (Elder, 1976), but some cooling will occur during its rise through the crust. In the models here, an initial temperature of 750°C is assumed, with the heat capacity of the rock increased to account for latent heat effects.

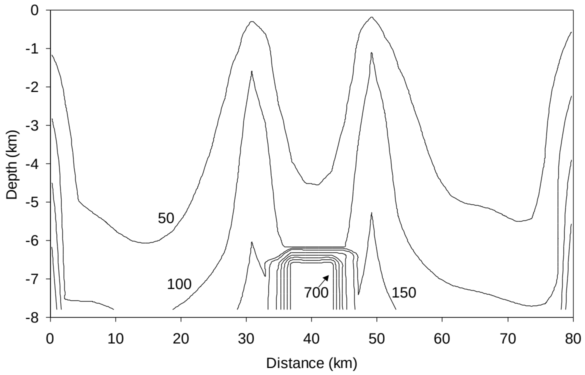

Figure 3. Initial temperature distribution with a 1.6 × 10 kilometer pluton emplaced centrally on the lower boundary of the model. Contours are at 50°C intervals below 200°C and 100°C intervals above 200°C.

With the assumptions outlined above, the cooling of magmatic plutons in the TVZ setting can now be modeled. To illustrate the nature of this cooling process, a 1.6 × 10 kilometer pluton is emplaced centrally in the model domain at a depth between 6.4 and 8 kilometers. The initial condition is illustrated in

Figure 3 - essentially the high temperature pluton is superimposed on the initial temperature distribution shown in Figure 2.

Figure 4 shows the temperature distribution after 6300 years. Significant cooling has now taken place, with the maximum temperature being 640°C, but the hot buoyant fluid has yet to reach the surface. The large scale convective system that forms in response to the pluton induces horizontal flows toward the pluton at depth. This fluid has its origin at the ground surface in the high terrain 20 to 30 kilometers from the center of the TVZ. The double-sided nature of the rising geothermal plume is a consequence of the rectangular geometry of the pluton and is absent for other geometries. For example only single plumes occur for semicircular or triangular shaped plutons.

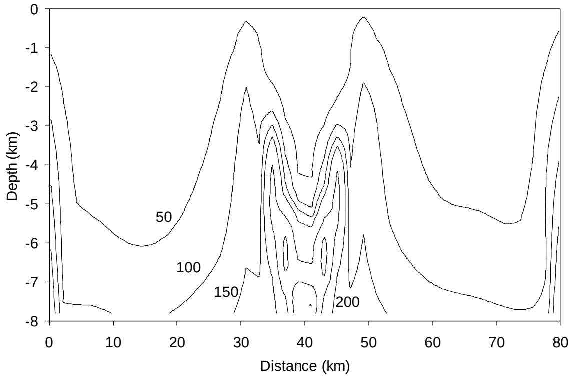

Figure 4 Temperature distribution 6300 years after pluton emplacement. The maximum temperature is now 640°C. The buoyant fluid has yet to reach the surface. Contours are labeled as described for Figure 3.

Significantly increased flow to the surface does not occur until about 10000 years after emplacement of the pluton. This is shown in Figure 5, which shows the temperatures at 12500 years. The maximum heat flow to the surface occurs at about 30000 years. This phase continues until about 70000 years, when the pluton has cooled sufficiently for there to be essentially no increase in surface flow above that in the initial state. However, temperatures are still over 200°C, and final cooling to near the initial state is not complete until after 200000 years.

Similar results are obtained with plutons of different sizes. However, with a smaller pluton, the maximum heat and mass flow to the surface is reduced and occurs later than in the example given here. The mean enthalpy of the induced flow is also smaller. For a larger plutons the peak fluid flow occurs sooner, is greater in magnitude and has higher enthalpy. Plutons between about 6 and 20 kilometers wide produce mean enthalpies of 1.0 to 1.4 MJ/kg, similar to the range observed in the TVZ.

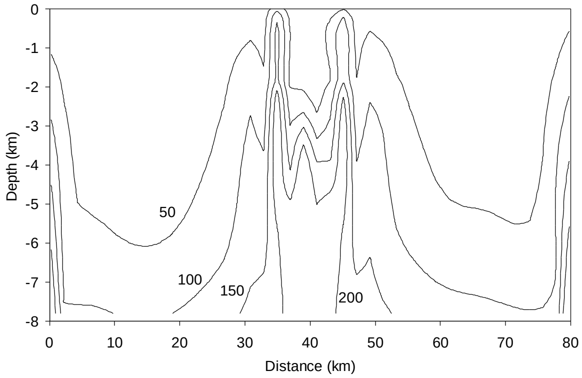

Figure 5 Temperature distribution 12500 years after pluton emplacement. The maximum temperature is now 350°C. The buoyant fluid has reached the surface, resulting in increased surface heat and mass flows. Contours are labeled as described for Figure 3.

It is instructive also to compare the total heat flow from the modeled plutons with that observed in the TVZ. Taking the TVZ to be 150 kilometers long, with a total heat flow of 4200 MW (Bibby *et al* 1995, Weir 1998), gives a heat output of 28 kW per meter (kW/m) (4200 MW/150 km) of the TVZ. The models give values of similar magnitude. For example, a 1.6 x 6 kilometer pluton has a peak output of 15 kW/m, and a 1.6 x 20 kilometer pluton has a peak output of 80 kW/m. The heat output depends on the geometry and location of the pluton (see next section), the permeability structure and the assumptions made concerning the emplacement and cooling of the pluton.

LOCATION OF PLUTON EMPLACEMENT

The TVZ geothermal fields are separated by up to 30 kilometers in the west to east direction across the TVZ (Bibby *et al*, 1995), and the source plutons might therefore be emplaced anywhere within a region this wide. Figure 2 shows that temperature variations in the initial state occur on a comparable length scale, so it is expected that individual plutons will be emplaced under quite different conditions. This has a surprisingly strong effect on how the plutons cool, and the subsequent formation of plumes of geothermal fluid.

In the model considered in the previous section the pluton is emplaced centrally in the model domain, and cools as shown in Figures 4 (6300 years) and 5

(12500 years). The heat output to the surface for this model is shown as curve A in Figure 8. This shows that it takes about 10000 years for heat from the pluton to reach the surface, followed by a relatively slow rise to a maximum at 12500 years and then a slow decline. Heat transport here is relatively slow - at 63000 years approximately 40% of the heat contained in the pluton has yet to reach the surface.

For comparison with the previous example, an identical 10 kilometer wide pluton is emplaced at the 50 kilometer point, beneath the right-hand low temperature plume present in the initial conditions. The temperature distributions for this model at 6300 and 12500 years are shown in Figures 6 and 7. Hot fluid rises to the surface more quickly in this case. This is due to the reduced viscosity of the overlying, higher temperature fluid. The rapid rise also means that less mixing takes place with the surrounding fluid, so the enthalpy of the fluid reaching the surface is higher.

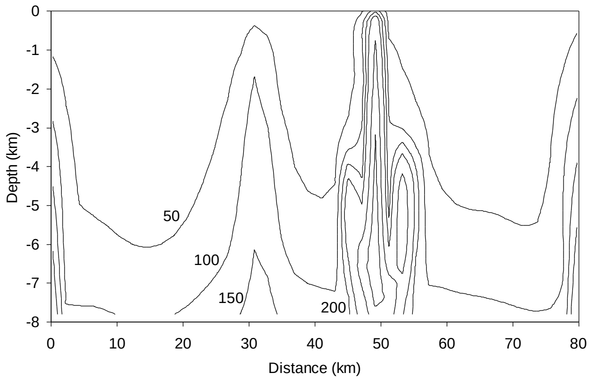

Figure 6 Temperature distribution 6,300 years after the pluton is emplaced below a warm region of the initial state. Contours are labeled as described for Figure 3.

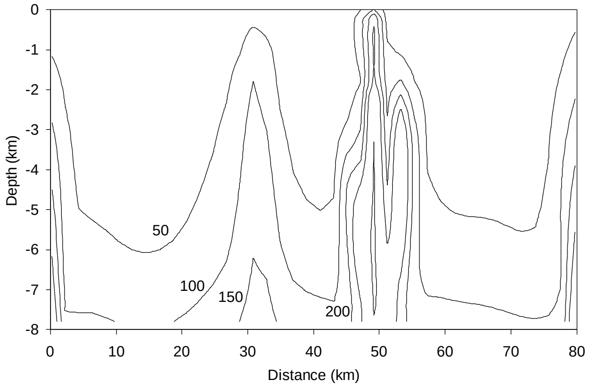

Figure 7 Temperature distribution 12,500 years after the pluton is emplaced below a warm region of the initial state. Contours are labeled as described for Figure 3.

The surface heat flow for this case is shown as curve B in Figure 8. In this case, the time for thermal breakthrough to the surface is 5000 years, and it takes only another 1000 years for the heat flow to reach a maximum. By 63000 years, over 98% of the heat contained in the pluton has been transported to the surface. When the pluton is emplaced into a warmer region of the domain, cooling is therefore both quicker and more efficient.

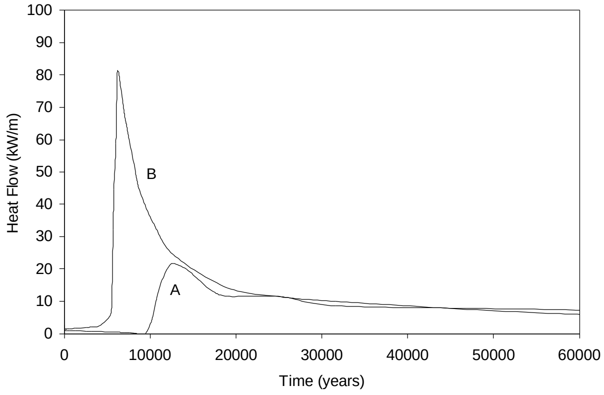

Figure 8 Comparison of surface heat flow for identical plutons emplaced below a cool region (curve A) and a warm region (curve B) of the initial state. At 60000 years cooling is essentially complete for curve B, but for curve A, approximately 40% of the heat contained in the pluton has yet to reach the surface.

MULTIPLE INTRUSIONS

Grindley (1965) presents evidence that geothermal activity may have existed at Wairakei for 500000 years, and Bibby *et al*. (1995) argue that the positions of the geothermal fields have not changed in the last 200000 years. These periods of time are much longer than the cooling time for even a large individual pluton (Figure 8), and this alone suggests that magma must be supplied continuously to the TVZ in order to maintain the required heat output. Grindley, in the same publication, shows that 3750 km^3 of magma are needed to supply the heat for Wairakei for 500000 years at the present rate.

The heat output for curve B in Figure 8 reaches a peak of 0.087 MW/m or 87 kW/m. This is about three times the average of 28 kW/m seen in the TVZ, and suggests that the pluton is about the maximum size possible. Another possibility is that the cooling of the pluton is too efficient. Cooling would be slower if the permeability was reduced above 350°C, (Fournier 1991) and this would allow similar heat flows from larger plutons. On the other hand, in curve A, where the pluton is emplaced in a less favorable position, the greatest heat output is only about one half of the TVZ average. It is possible that multiple intrusions of this type can provide an adequate heat source for the geothermal fields, and this idea will be explored in this section.

Figure 9 shows the temperature distribution 3000 years after the emplacement of a six kilometer wide pluton centered at x = 47 kilometers. The hot fluid has not yet reached the surface, but can be seen to rise more rapidly in the region overlain by warmer fluid i.e. the center of the low temperature plume.

At this time (3000 years) an identical pluton is emplaced six kilometers to the right (x = 53 kilometers) of the first. Figure 10 shows the temperatures 3000 years after this event. Again, it can be seen that hot fluid rising from the second pluton is transported to the surface more rapidly when overlaid by hot fluid – in this case the residual heat from the first pluton. Thus, even though the second pluton is displaced six kilometers from the first, the buoyant fluid reaches the surface in the same location.

This mechanism may explain how the geothermal fields can be heated from scattered, multiple intrusions of magma, and yet remain stationary for very long periods of time. In this example the peak heat output is enhanced by about 20% by the second pluton, and the period of increased surface flow is essentially doubled.

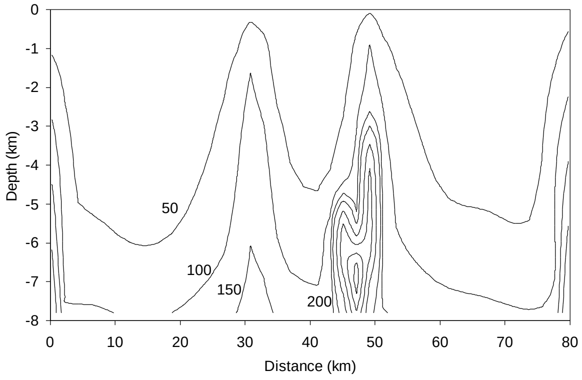

Figure 9 Temperatures 3000 years after emplacement of first 1.6 ´ 10 kilometer pluton, centered at x = 47 kilometers. Contours are labeled as described for Figure 3.

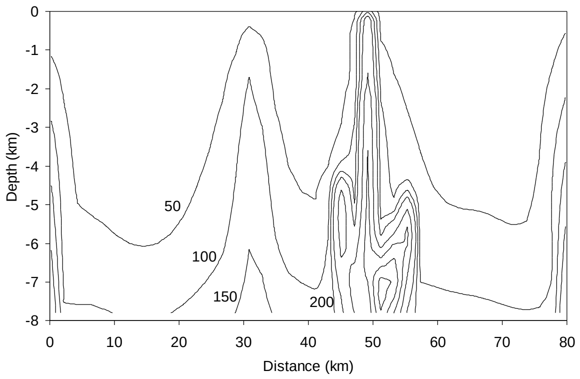

Figure 10 Temperatures 3000 years after emplacement of second 1.6 ´ 10 kilometer pluton, centered at x = 53 kilometers. Contours are labeled as described for Figure 3.

CONCLUSIONS

This paper has presented recent modeling aimed at understanding the large scale hydrology and heat source mechanisms of the TVZ geothermal fields. Models of cooling plutons show that the formation of geothermal fields is influenced strongly by the conditions at the location of emplacement.

If the pluton is emplaced into an area of initially warm (100°C to 150°C) rock and fluid, then the flow of hot fluid to the surface reaches TVZ-like values a few thousand years after emplacement. Warm regions which enhance the flow in this way may result from topographically driven flows, or from residual heat from previously emplaced and cooled plutons.

If the pluton is emplaced in a cooler region, flows to the surface are restricted by the viscosity of the overlying fluid. In this case, the pluton takes much longer to cool, and the fluid which reaches the surface has rather lower enthalpy than that seen in the TVZ.

The heat flux to the surface from a suitably emplaced pluton can attain TVZ-like values, but typically only for periods of a few thousand years. Evidence suggests that the geothermal fields are persistent features, with lifetimes of several hundred thousand years, and therefore many plutons are necessary to maintain the average heat output at the presently observed rate. Modeling of multiple intrusions suggests that this idea can also explain why the geothermal fields remain stationary on these timescales, regardless (to some extent) of the position of the emplaced pluton.

ACKNOWLEDGEMENTS

The author would like to thank Stephen White and Graham Weir for helpful comments on the manuscript. This work was funded by the Foundation for Research Science and Technology.

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