

The Distribution of the Geothermal Fields in the Taupo Volcanic Zone, New Zealand

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ABSTRACT

A numerical model of the large scale water and heat flows within the Taupo Volcanic Zone (TVZ), New Zealand is constructed. In the model the regions of high permeability and heat flow in the TVZ coincide, and lie within the TVZ envelope, defined to contain the Taupo Fault Belt and the most recent caldera collapse structures. The model correctly predicts the absence of geothermal fields in the central region of the TVZ, where cold surface groundwater descend to depths close to 8 kilometers before being heated and ascending in discrete plumes at the permeability barrier which occurs at the boundary of the TVZ envelope. The locations of these plumes can be identified with most of the major geothermal fields in the TVZ (Tokaanu, Lake Taupo, Wairakei and Tauhara, Rotokawa, Ohaaki, Waiotapu and Waikite, Tikitere, Rotoiti and Rotoma, Rotorua, Mokai). In addition, the model predicts two bands of convective upflow across the TVZ, both of which correspond roughly to the known geothermal features of Ngatamariki and Orakeikorako in the south, and Lakes Rotomahana and Tarawera in the north.

1. INTRODUCTION

The Taupo Volcanic Zone (TVZ) is a region of enhanced volcanic and geothermal activity stretching from Mount Ruapehu to Kawerau, in the North Island of New Zealand (Figure 1). The TVZ covers an area approximately 30 kilometers wide by 150 kilometers long and contains 23 known geothermal fields with an estimated total heat output of 4200 ± 500 MW (Bibby et al., 1995). Present day activity is largely restricted to the andesitic volcanoes Ruapehu, Ngauruhoe and Tongariro in the southern TVZ and Edgecumbe, Whale Island and White Island in the north. Volcanic activity is believed to have commenced in the TVZ about 2 Ma ago, but the major rhyolitic volcanism for which the TVZ is best known began approximately 1.6 Ma ago (Wilson et al., 1995).

The geothermal and volcanic activity in the TVZ is associated with the subduction of oceanic crust on the Pacific Plate beneath the Indian-Australian Plate. As the crustal rock descends it melts, and the molten material (magma) rises due to buoyancy forces toward the surface (e.g. Stevens, 1980). The TVZ is presently undergoing extension at a rate of approximately 8 mm/year (Darby et al., 2000). It is generally accepted that the volume created by this extension is being replaced by the ascending magma at a rate of about $1 \text{ m}^3/\text{s}$ (Stern, 1987). This magma supplies the heat for the geothermal and volcanic systems, although there is some debate (e.g. Hochstein, 1995) whether this volume of magma can in fact supply heat at the required rate.

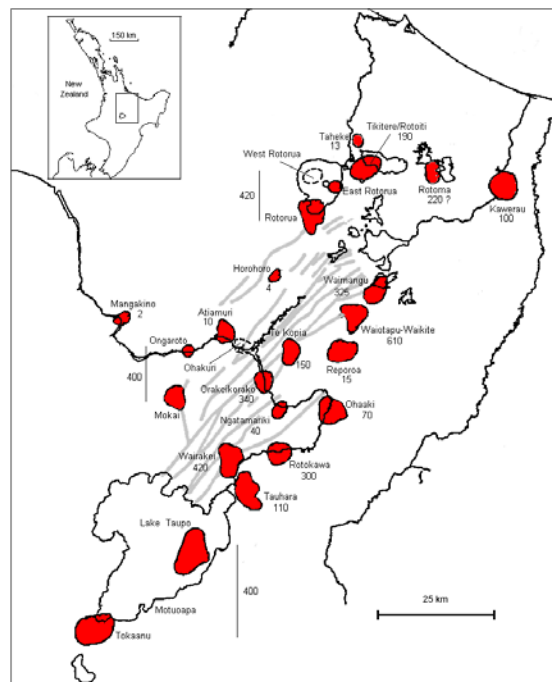


Figure 1. Location map for the Taupo Volcanic Zone in the North Island of New Zealand. The known geothermal fields are shown in red. The Taupo Fault Belt is indicated by the grey lines extending SW-NE in the western TVZ. The numerical values indicate the total heat flow from each geothermal field (MW).

Previous models of the TVZ hydrological system have been based on linear convection theory (Horton and Rogers, 1945; Lapwood, 1948; Wooding, 1978). These models predict that the geothermal fields are associated with upflows in regular convection cells, which in a homogeneous porous medium are separated by about twice the depth of the heat source. In the TVZ the typical spacing of the geothermal fields is about 15 kilometers, implying a heat source at about 8 kilometers depth. However, these models cannot explain the absence of geothermal activity in the central TVZ, or the west to east distribution of the geothermal heat output.

The purpose of this paper is to propose a mechanism which controls the spatial distribution of the TVZ geothermal fields. To do this, we create a numerical model of the TVZ hydrological system which includes the flows of heat and water, an idealised large-scale permeability distribution and a heat source at a depth of 8 kilometers. To carry out this study, a super-critical equation of state module has been developed for the geothermal simulator TOUGH2 (Pruess, 1991), which can describe the flow of water at the conditions expected deep in the TVZ. This code is more

fully described in Kissling (2004), and the references therein.

The first section of this paper summarises the key geophysical, geological and geochemical features of the TVZ which form the basis of the model described in this paper. The following sections describe the model itself and present a comparison between modelled results and the actual properties of the TVZ geothermal systems.

2. TWELVE KEY RESULTS FOR THE TVZ

1. The TVZ is a ~ 30 km wide region in the central North Island of New Zealand with a total heat flow (in the form of geothermal activity) of 4200 ± 500 MW (Bibby et al., 1995).
2. The TVZ is undergoing tectonic extension at a rate of 8 ± 2 mm/year (Darby et al., 2000). It is commonly believed that the volume created by this extension is filled by magma from depth at a rate of about $1 \text{ m}^3/\text{s}$ (Stern, 1987), and that this magma provides the heat source for the geothermal activity in the TVZ.
3. There are 23 geothermal fields in the TVZ, with heat flows in the range from 2 MW (Mangakino) to > 500 MW (Waiotapu). The geothermal fields lie in two bands in the western and eastern TVZ. Approximately 25% of the TVZ heat flow occurs from the western fields, and 75% from the eastern fields (Bibby et al., 1995).
4. The geothermal systems appear to be stable, long-lived features. For example, Grindley (1965) has suggested an age in excess of 500,000 years for Wairakei, and Browne (1979) has dated the Kawerau system to be at least 200,000 years old.
5. These geothermal fields lie on the perimeter of an envelope formed by the Taupo Fault Belt in the central TVZ, and the most recent volcanic calderas in the TVZ (Wilson et al., 1995).
6. Deep electrical resistivity and magnetotelluric surveys in the TVZ indicate that hydrothermal activity has never taken place in the central TVZ (Bibby et al., 1995; Bibby et al., 2000).
7. Analysis of earthquake swarms in the TVZ region shows that no swarm activity occurs below 8 km depth. This is interpreted (Bibby et al., 1995), as evidence for a brittle/ductile transition in the rocks at this depth. Consequently, it is believed that little or no permeability exists below this depth, and that groundwater therefore cannot circulate below this depth (e.g. Fournier, 1991).
8. The central TVZ comprises an extensive zone of faulting (Taupo Fault Belt). Due to lack of thermal activity and very low temperature gradients, (Studt and Thompson, 1969), this area appears to host the major regions of downflowing cool surface waters in the TVZ (Bibby et al., 1995). Outside the TVZ, temperature gradients are close to the geophysical gradient of $30^\circ\text{C}/\text{km}$, indicating that conduction is the dominant form of heat transport here (Thompson, 1977).
9. The chief geological units in the TVZ comprise a shallow (~2 km) thick layer of pyroclastic infill, approximately 30 km wide (Mordriniak & Studt,

1959), overlying perhaps 6 km of greywacke or igneous basement rocks (Wood, 1996). Exterior to the TVZ, there are axial greywacke ranges, rising to about 1000 metres above sea level on the Kaingaroa plateau in the east.

10. Isotope chemistry indicates that approximately 6% of the fluids in the western geothermal fields and 14% of fluids in the eastern fields of the TVZ is of magmatic origin (Giggenbach, 1995). Using these figures, a total of about 400 kg/s enters the TVZ at depth, or approximately 0.1 kg/s/MW of heat output from the TVZ.
11. The remaining ~ 90% of the geothermal fluid is of meteoric origin, and has a residence time in the TVZ of between 100 and 12000 years (Stewart, 1978). Approximately 2% of the annual rainfall of the region ($1.5 \text{ m}/\text{year}$) provides sufficient fluid for the geothermal systems of the TVZ (Kissling, 2004).
12. Temperature gradients within the upper 2 km of the TVZ geothermal fields indicate that groundwater convection is the dominant form heat transport in the TVZ (e.g. McNabb, 1992). Extrapolating the shallow temperature gradients to depth indicated a temperature of 350°C to 400°C at the brittle/ductile transition at 8 km depth.

3. THE TVZ MODEL

The model presented in this paper represents the complete onshore section of the TVZ and the surrounding region. The model domain covers an area of $150 \text{ km} \times 80 \text{ km}$ and is 8 km deep, consistent with the inferred depth of the brittle-ductile transition. The element size throughout the model is $1 \text{ km} \times 1 \text{ km} \times 0.5 \text{ km}$. Excluding boundary elements, the total number of elements is 192,000. The model domain is aligned SW-NE along the TVZ, as shown by the rectangle in Figure 2. The model described in this paper was run to simulate a period of 2 Ma, which is approximately the age of the TVZ.

The upper boundary of the model is held at 'atmospheric' conditions - fully saturated at $P = 1$ bar and $T = 20^\circ\text{C}$. The fully saturated upper boundary is used because the average infiltration rate of water into the TVZ is small compared to the total rainfall of the region. The lateral boundaries are held at hydrostatic pressure corresponding to the geophysical temperature gradient of 30°C per kilometer. These conditions also serve as the initial conditions in the interior of the model domain. On the lower boundary, there are two heat sources. The first has a strength of $0.09 \text{ W}/\text{m}^2$ and is distributed uniformly over the lower boundary. This is the conductive heat flow associated with the geophysical temperature gradient of $30^\circ\text{C}/\text{km}$ which is observed in regions adjacent to, but outside, the TVZ. The second 'geothermal' heat source will be described in the next section.

4. THE TVZ ENVELOPE

Figure 2 shows the locations of the geothermal fields in relation to the Taupo Fault Belt and the known caldera structures in the TVZ. There is a clear association between caldera and fault zone boundaries and the locations of geothermal fields. All of the 'major' geothermal fields in the eastern TVZ, from Wairakei/Tauhara to Waimangu are associated with the eastern margin of the Taupo Fault Belt. Similarly, the northern fields, Rotorua, Tikitere and Rotoma lie close to the boundaries of the Okataina, Rotorua and

Kapenga volcanic centres, as do the Taupo and Tokaanu fields to the Taupo caldera boundary. Mokai is located on the western margin of the Taupo Fault Belt (TFB). Of the small geothermal fields, Ongarato, Atiamuri and Horohoro are also associated with the western boundary of the TFB. The region defined by the TFB and the volcanic calderas will henceforth be referred to as the 'TVZ envelope', and will play a central role in the modelling in this paper. The TVZ envelope is shown in Figure 2 as the thick solid line.

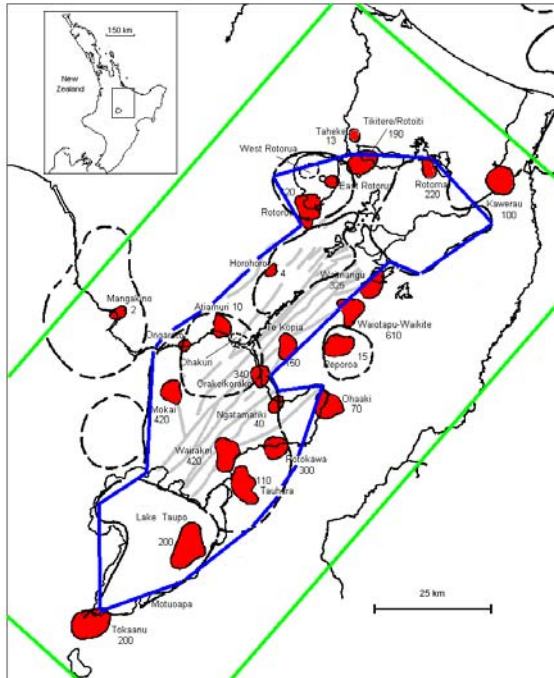


Figure 2. Location of geothermal fields, Taupo Fault Belt (grey) and known volcanic centres (dark/dashed lines) within the TVZ. The TVZ envelope is shown in blue. In the model presented in this paper, the features inside this envelope are associated with enhanced permeability. The model domain is aligned parallel to the Taupo Fault Belt, and covers a rectangular area 80 km × 150 km which extends beyond the boundaries of this figure (green).

The region within the TVZ envelope is assumed to be of high permeability relative to that outside the envelope because fault movements and caldera collapse will generate permeability. The depth of this enhanced permeability within the Taupo Fault Belt is assumed to extend down to 8 kilometers.

There are three geothermal fields which do not fit with this general picture, and the positions of these fields may be governed by entirely different processes. These fields are Kawerau, Reporoa and Mangakino. Of these Kawerau lies in the north-east of the TVZ, and is apparently outside the presumed boundary for the Okataina volcanic centre. Possible explanations for this are that the location of the field results from a shallow magmatic intrusion (Christenson, 1998), or that there is unmapped volcanic or faulting structure extending north-east from the Okataina volcanic centre (Wilson et al., 1995). Reporoa and Mangakino both have low heat flows, and their associated calderas are known to be very old structures (~2 Ma) within the TVZ (Bibby et al., 1995). In addition Reporoa is clearly linked by electrical resistivity surveys to the Waiotapu-

Waikite system (Stagpoole and Bibby, 1998), and may actually represent an 'outflow' from the Waiotapu system (Healy and Hochstein, 1973).

5. MODEL HEAT SOURCE

The TVZ heat source is highly variable in time and space, as evidenced by the sporadic nature of the TVZ volcanism (Wilson et al., 1995). Weir (1998) has modelled a spatially averaged heat source which links the rate of magmatic intrusions to the TVZ extension rate. In this paper, a simpler approach is taken, where contributions to the total TVZ heat flow from magmatic fluid, magmatic intrusions and conduction are lumped together and treated as a steady effective heat source at the base of the model. Kissling (2004) showed that discrete geothermal plumes occur at caldera boundaries when the heat source is coincident with the high permeability region which defines the caldera. In this paper the same assumption is made, and the TVZ geothermal heat source is defined to exist only in the region defined by the TVZ envelope.

The model has a spatially variable heat source with a total heat flow of about 4300 MW. The heat is applied piecewise in separate regions across the lower boundary of the model. To do this, the model domain was first divided into ten 15 kilometer wide strips in the SW-NE direction along the TVZ, and within each of these strips the TVZ envelope was further divided into two approximately equal areas, as shown in Figure 3. Heat flows were then assigned to each of these 16 regions. These flows were calculated by summing the observed geothermal heat flows (taken from Bibby et al., 1995) within each region. A summary of this calculation is given in Table 1.

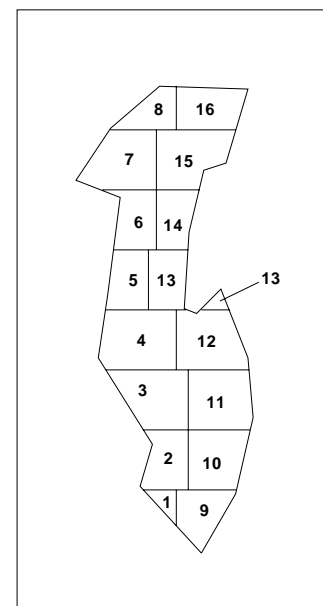


Figure 3. Assumed heat source region for the TVZ model. The TVZ envelope is defined by the locations of the volcanic calderas and the Taupo Fault Belt (see Figure 2). The envelope is divided into 16 regions, as indicated. The strength of the geothermal heat source within each region is proportional to the measured heat flux in that region. The permeable 'infill' region of the model is also defined by this envelope. The heat flows and permeabilities for each region are listed in Table 1.

Table 1. Summary of areas (km²), total heat flows (MW), heat fluxes (W/m²) and permeabilities adopted for the 16 heat source regions of the TVZ model (see Figure 2). The permeabilities are given in the form horizontal/vertical in units of 10⁻¹⁵ m². All regions outside the heat source region are assigned a permeability of 1/0.1 × 10⁻¹⁵ m²

Region	Area	Heat	Flux	Perm.
1	36	0	0	5/0.5
2	158	0	0	5/0.5
3	241	400	1.66	25/2.5
4	280	2	0.01	5/0.5
5	152	10	0.07	5/0.5
6	152	4	0.03	5/0.5
7	241	420	1.74	25/2.5
8	116	423	3.65	75/7.5
9	152	200	1.32	25/2.5
10	208	200	0.96	5/0.5
11	237	530	2.24	50/5
12	240	680	2.83	50/5
13	164	370	2.26	50/5
14	135	625	4.63	100/10
15	239	325	1.36	25/2.5
16	174	0	0	5/0.5

6. MODEL PERMEABILITY

Inside the TVZ envelope the permeability is defined piecewise in the same 16 regions as the heat source. Details are given in Table 1 and Figure 3. Permeabilities are related to the heat flux for each region - the higher the heat flux, the higher the permeability. The relatively high permeability used inside the TVZ envelope reduces the effect of high temperature conductive zones which form near the heat source when the heat flux is very high. These slow the computation very significantly and result from the reduced convective cooling in low permeability rocks. In particular this can occur in regions of the model near the Waimangu/Waiotapu areas where the heat flux is highest. The relationship between the heat flux and the assigned permeability is shown in Table 1.

For the region outside the TVZ envelope, the horizontal/vertical permeability has been set to 1/0.1 × 10⁻¹⁵ m². This exterior permeability provides an adequate permeability contrast between the interior and exterior regions for stable plumes to occur, and also ensures that the temperature in the exterior region remains close to its initial conductive distribution, thus avoiding the convective flows seen in this region when higher permeabilities are used (Kissling, 2004).

7. MODEL RESULTS

Figure 4 shows the temperature at a depth of 0.5 kilometers in the model at 2 Ma. In this case there are a number of stable high temperature plumes around the perimeter of the TVZ envelope. These have a maximum temperature of about 220 °C, and cold downflows appear in the eastern TVZ, in regions where the permeability is highest.

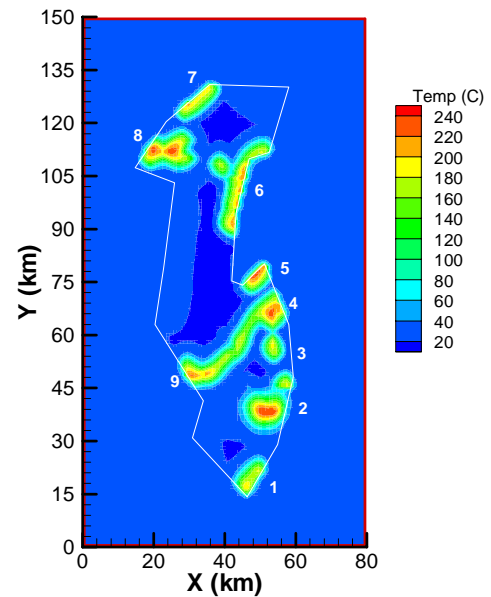


Figure 4. Plan view of the temperature distribution at a depth of 0.5 kilometers at 2 Ma for the TVZ model. The heat flows for each of the numbered plumes are listed in Table 2.

Figure 4 shows the temperatures at a depth of 7.5 kilometers in the model at 2 Ma. The regions of strongest downflow (dark blue) are apparent. The higher temperature regions inside the TVZ envelope and about its margin correspond mainly to upflows of hot fluid, and correlate well with the positions of the hot plumes at shallow depths in Figure 3. The relatively undisturbed temperatures at depth show that most of the fluid which comprises the TVZ geothermal systems originates from the surface within the high permeability TVZ envelope. From the surface it descends to a depth close to eight kilometres, is heated, and rises in discrete plumes around the envelope boundary to form the geothermal systems.

Figure 4 shows a good correspondence to the TVZ. The geothermal fields occur on the internal boundary of the TVZ envelope, and many of these can be identified with those in Figure 1. The plumes are listed by number, and these are referred to in Table 2. Comparing these figures and starting at the southern most point of the TVZ envelope, the first geothermal field appears at the apex of the envelope. This corresponds to the Tokaanu geothermal field (1). Moving anti-clockwise, the next large plume corresponds to Lake Taupo field (2). Two smaller plumes are at the location of the Wairakei/Tauhara system (3). The next plumes correspond to Rotokawa (4) and Ohaaki fields (5), with Ohaaki again appearing at the apex of two of the faces of the TVZ envelope. Moving northward a series of four or five small plumes correspond to the geothermal fields at Waiotapu, Waikite and Waimangu (6). The northern most modelled plume lies close to the fields at Tikitere, Rotoiti and Rotoma (7). Next, moving south, the double plume contains the heat of the Rotorua geothermal system (8). The last significant hot plume occurs close to the location of the Mokai geothermal field (9).

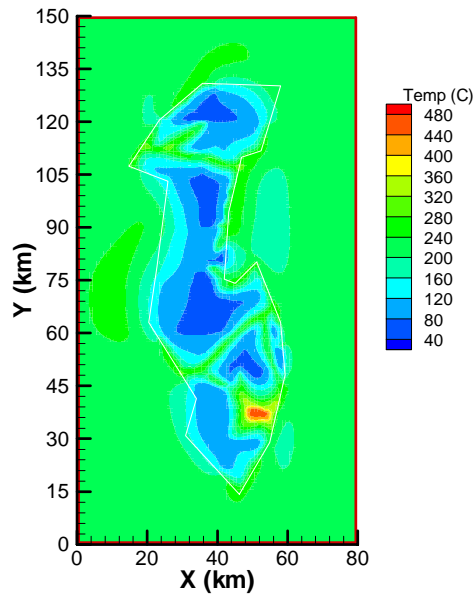


Figure 5. Plan view of the temperature distribution at a depth of 7.5 kilometers at 2 Ma for the TVZ model.

Table 2. Comparison of predicted and observed heat flows (MW) in the TVZ. The plume numbers are given on Figure 3.

Plume	Identification	Actual Heat	Model Heat
1	Tokaanu	200	211
2	Lake Taupo	200	244
3	Wairakei/Tauhara	530	191
4	Rotokawa	300	632
5	Ohaaki	70	446
6	Waiotapu/Waimangu/Waikite	935	1125
7	Tikitere/Rotoiti/Rotoma	410	406
8	Rotorua	420	725
9	Mokai	420	385

The heat flows for each of these geothermal plumes can be calculated. These are obtained by summing the heat flow to the surface for each plume, for all elements with a heat flow of more than 5 MW. These are listed in Table 2, together with the ‘identification’ of the plume with its actual TVZ counterpart(s). The Table shows that the heat flow from many of the modelled geothermal fields (Tokaanu, Lake Taupo, Mokai), or groups of fields (Waiotapu, Waimangu, Waikite and Tikitere, Rotoiti, Rotoma), are in good agreement with measurements. The calculated heat flow from the Wairakei/Tauhara system is too low, and the heat flows from Rotokawa, Ohaaki and Rotorua are too large. Except for Ohaaki, the heat flows agree with observation to within a factor of three, and the agreement is usually much better. The model does not reproduce the geothermal fields with low heat flow in the western TVZ such as Atiamuri or Horohoro. Thus, this model is quite successful in predicting the location of the large geothermal systems, and the calculated heat flows from these areas are in reasonable agreement with observation.

Inside the TVZ envelope, the model predicts a nearly continuous band of hot fluid at the surface which crosses

the TVZ between the modelled geothermal fields ‘Rotokawa’ and ‘Mokai’. In the actual TVZ this fluid appears in discrete plumes as the Ngatamariki, Orakeikorako and (possibly) Te Kopia geothermal fields. These fields are slightly to the north of the ‘band’, and have a total measured heat flow of 530 MW. The modelled heat flow is only 184 MW, although this figure depends on exactly how each of the Mokai and Rotokawa plumes are defined. In the northern part of the TVZ envelope, a similar but rather weaker band of hot fluid appears in the interior between the modelled ‘Waimangu’ and ‘Rotorua’ systems. This heat flow might be associated with the known heat flows in Lakes Rotomahana and Tarawera (e.g. Whiteford et al., 1996).

8. CONCLUSIONS

In this paper a model of the complete TVZ hydrological system has been constructed. This incorporates the idea of a ‘TVZ envelope’, which is defined as the region including the most recent caldera structures within the TVZ and the Taupo Fault Belt. The region within this envelope has moderate permeability and the exterior region has a lower permeability. A ‘heat sweep’ mechanism is proposed that leads to the formation of stable hydrothermal plumes. In this model, cool downflows from the surface in the interior of the TVZ are heated at depth, and the hot fluid is then swept outward to the permeability contrast where it ascends, rather than moves laterally, because of the low permeability barrier.

The model includes spatial variations in both the TVZ heat source and the permeability within the TVZ envelope as a means of explaining the highly variable heat output across the TVZ. Relatively high permeabilities within the TVZ envelope have been used in the model. We believe these to be representative of the permeabilities on kilometer length scales within the TVZ.

The model predicts that geothermal systems lie around the boundary of the TVZ envelope, and exist as stable, discrete plumes a few kilometres across, persisting for periods of the same order as the age of the TVZ. The positions of the larger groups of geothermal fields are well predicted. The heat flows from the major geothermal fields are usually predicted to within a factor of two to three (Table 2), but the small geothermal fields (~ 10 MW) such as Horohoro and Atiamuri are entirely absent. The model predicts large downflows of surface waters in the western and central TVZ which supply most of the water for the geothermal systems. This is in accord with the observation (Bibby et al., 1995) that there is a ‘negative correlation’ between regions of high heat flow and major faulting in the TVZ.

In the model there is a weakly defined large scale system of three convection cells superimposed on the TVZ. Downflows of cool surface fluid occur in the middle of these cells, and the cell boundaries are formed by linear ‘bands’ of hot fluid. These bands appear to be controlled by the geometry of the TVZ envelope, as they occur also in models with uniform permeability and/or heat source distribution. For the TVZ model described in this paper, these bands correspond approximately to actual geothermal areas in the TVZ (Ngatamariki and Orakeikorako in the southern band, and the thermal areas in Lakes Tarawera and Rotomahana in the northern band), although the predicted heat output from these fields is not very accurate.

Some geothermal areas, such as that at Kawerau, do not fit with the model presented in this paper. This may be because of unmapped faults within the TVZ extending

north from the Okataina volcanic centre, or possibly because Kawerau is controlled by a heat source related to the nearby active volcano Putauaki (Mt Edgecumbe). Mangakino and Reporoa geothermal fields are also 'problems', although they are small fields which cannot influence the overall TVZ hydrology significantly.

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