THREE-DIMENSIONAL MODEL OF THE DEEP GEOTHERMAL RESOURCES IN PART OF THE TAUPO REPOROA BASIN

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ABSTRACT

A numerical model of the geothermal fields in part of the Taupo Reporoa Basin is discussed. The geothermal fields included in this model are: Atiamuri, Horohoro, Ngatamariki, Ohaaki, Ongarato, Orakeikorako, Reporoa - Golden Springs, Te Kopia and Waiotapu-Waikite. The model is made deep enough (6kms) so that the whole of the convective systems fit within the model. The aim of this study is to investigate the deep structure and fluid and heat flow in these fields and their inter-connectivity. The model correctly predicts the locations of geothermal plumes for the aforementioned fields, their shallow heat upflows and the temperatures in the upflow zones at approximately 3 km depth. The permeability structure and heat source distribution are the main parameters varied in the calibration of the model.

1. INTRODUCTION

Natural convective geothermal systems are formed through convection of water in the subsurface. Three fundamental factors are required for the formation of convective geothermal resources: 1) heat, 2) permeability, 3) fluid. Heating (above some critical level) of meteoric waters at mid-crustal to upper-crustal gives rise to large-scale convective flows. The driving mechanism is buoyancy resulting from the reduction of density caused by thermal expansion (Hanano, 2000, Rowland and Sibson, 2004). The reduction of viscosity of the fluid as the temperature increases also assists convection. Factors effecting fluid flow paths include the nature of the heat source, topography, and permeability distribution (Rowland and Sibson, 2004).

The Taupo- Reporoa basin (TRB) is located in the centre of the North Island of New Zealand. It is in the middle region of the TVZ (Taupo Volcanic Zone), and lies about 25 km north-east of Lake Taupo. As shown in Figure 1, the TRB is bounded by the Kaingaroa fault scarp to the east, the Paeroa fault block to the west and the two active calderas, Okataina and Taupo, to the north and south, respectively. Figure 1 shows the electrical resistivity map of the TVZ (nominal array spacing is 500m) and the location of the TRB within the TVZ. In Figure 1, low resistivity zones (approximately <30Ωm) generally correlate with active or extinct geothermal fields. The margins of most geothermal systems are characterized by a sharp resistivity contrast to depths of 1–2 km, indicating that hot geothermal fluid ascends from depth as a near-vertical plume (Rowland and Sibson, 2004).

In the TRB cold meteoric water slowly circulates downward over most of the system and as it become heated at depth, the heated water is concentrated into convectively driven, rising plumes. The upper portion of these convective plumes interact with the surface hydrology (Bibby *et al.*, 1995).

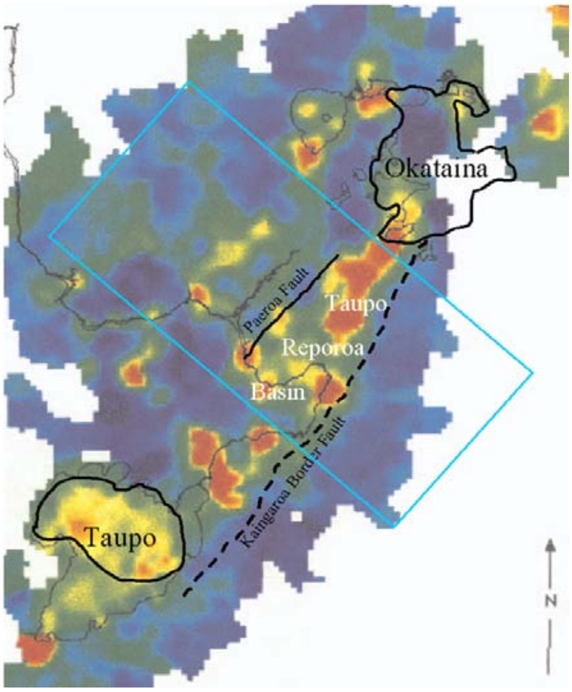


Figure 1 Location of the TRB on the TVZ and electrical resistivity of the TVZ (nominal array spacing = 500m) (Rowland and Sibson, 2004)

Observations show that almost all of the geothermal water is meteoric in origin for geothermal fields located in the TVZ. Outside the geothermal fields, evidence for down-flow of colder meteoric water is based on the interpretation of temperatures within wells. Low or negative temperature gradients are interpreted as being caused by the downward movement of cold waters from the surface. Such low temperature gradients occur consistently across most of the Taupo Volcanic Zone (TVZ). The total outflow of hot fluids from the geothermal systems could be provided by an average downflow of about 20 mm/yr over the whole area of the TVZ.

There are four mechanisms that can account for the heat transfer into base of the geothermal systems: magmatic fluids, heat conduction, magmatic intrusions and magmatic eruptions (Kissling, 2004). For this study conduction from the underlying ductile region into the convective zone is considered to be the main mechanism. From a reservoir modelling aspect; a large and deep enough model needs to be set up so that the whole convective system is contained within the model and the permeability has to be compatible with the observed flow paths and temperature distribution.

In the present study large-scale convection in part of the TRB system is of interest. The model area considered for this study is shown with blue boundaries in Figure 1. The thermal areas located in this area are Atiamuri, Horohoro, Ngatamariki, Ohaaki, Ongarato, Orakeikorako, Reporoa - Golden Springs, Te Kopia and Waiotapu-Waikite. The aim of this work is to investigate the source of the convection plumes that constitute the geothermal fields in the TRB region. The main interests of this study are: to identify what controls the location of these fields and whether the main control on the pattern of convection is the permeability structure or the nature of the heat source or a combination of both. Thus in this model the test parameters are the location and magnitude of the heat sources and the distribution of permeability.

The present study is similar in scope and objectives to that carried out on the whole TVZ by Kissling (Kissling, 2004, Kissling and Weir, 2005), however by focusing on a smaller area we are able to achieve a higher resolution model.

2. INFORMATION ON TAUPO REPOROA BASIN

The theme of this section is to improve understanding of the deep structure and dynamics of the TRB (Figure 1), one of the areas of most intense geothermal activity in New Zealand. The name "Reporoa" means "long swamp" in Maori, and attests to the poor drainage of the region.

The area investigated in this study is bounded with blue lines in Figure 2. The area of the geothermal fields shown in this figure (red shaded areas, labelled in smaller text) is measured at depths between 0.5 and 1 km. The Taupo Fault Belt (TFB) (grey lines) and known volcanic calderas (dashed black lines, names are in capitals) within the TRB are also shown. The numerals indicate the natural heat output of each geothermal field, in MW (Bibby *et al.*, 1995, Kissling and Weir, 2005).

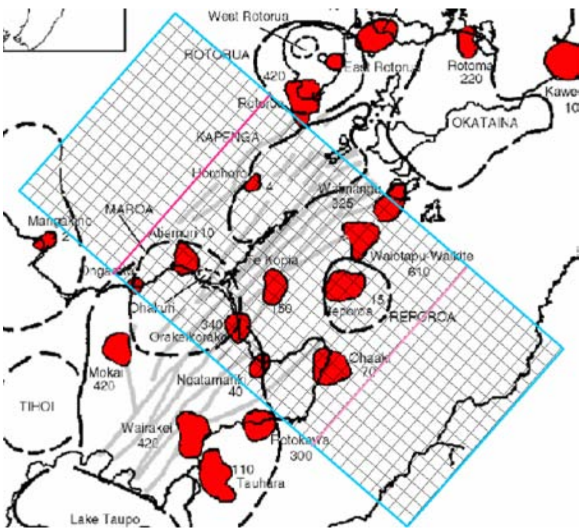


Figure 2. Model area (inside the blue lines), location of geothermal fields (red areas), TFB (grey lines) and known volcanic calderas (dashed black lines) within the TRB (Kissling and Weir, 2005).

On a very large scale, the TRB consists of an approximately 8 km deep convective zone overlying a 'ductile' region which extends to about 15 km depth (Figure 3). Kissling and Weir (2005) indicated that the temperature at the base of the convective zone at 8 km is likely to be 350°C. Extension of major faults in the TVZ occurs to depths of 6 to 10 km. At about 8-9 km the transition zone between brittle and ductile behaviour occurs (Kissling, 2004).

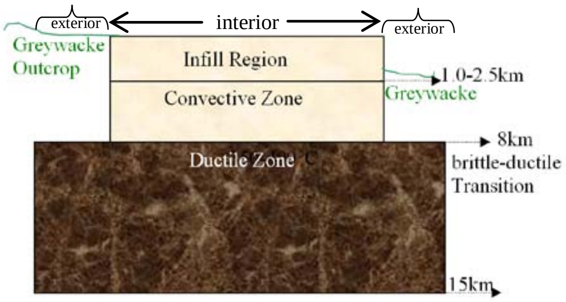


Figure 3 Schematic of the large scale structure in the TRB region.

Interior Region (within pink lines in Figure 2): Bibby et al. (1995) state that gravity anomalies in the TRB are associated with a broad region of low density pyroclastic infill, overlying denser basement material. The depth of this infill region is between 1 and 2.5 km (Kissling, 2004). The basement rock (greywacke) has been penetrated by drilling to depths of approximately 2 km at Ohaaki and Ngatamariki (Wood, 1996). The cross-sectional area of each of the convection plumes appears to increase at depths of 1-2 km, consistent with a decrease in permeability at the depth at which the greywacke basement begins (Bibby *et al.*, 1995).

Exterior region (outside pink lines in Figure 2): The region outside the TRB infill region consists of greywacke ranges. To the east, they extend to approximately 1000 masl and to the west, greywacke outcrops west of the Mangakino caldera.

Salient volcanic features in the TRB are Kapenga, Maroa, Reporoa and Whakamaru calderas (Figure 2). As can be seen in Figure 2, except for Te Kopia, all of the geothermal fields in the model area lie close to the margins of these calderas. According to Kissling, 2004 and Soengkono, 1995 the association of geothermal activity with caldera margins suggests that the boundaries between different geological units may play a role in the hydrology of these systems.

Location of the geothermal fields also depends on the positions of faults within the TFB. As can be seen from Figure 2, there is a negative correlation between regions of high heat flow and major faulting in the TVZ suggesting that the TFB is a region where major downflows of surface waters occur, and is the means by which much of the meteoric water in the geothermal plumes is transported to the base of the convective zone (Kissling and Weir, 2005).

The region around the TFB has higher permeability than the surrounding region due to fault movement and caldera collapse. TFB permeabilities may extend down to a depth of 8 km but for caldera regions this depth is less (Kissling and Weir, 2005).

Permeabilities have been estimated in the production areas of geothermal fields by means of interference tests and knowledge of vertical mass flows. Typically vertical permeabilities are of the order of 1-10mD, and horizontal permeabilities are at least an order of magnitude greater (Kissling, 2004).

Available heat output, mass flow rates and temperature information

A literature review was carried out on geothermal fields located in the model area, in order to find information about natural heat output, mass flow to the surface, and the temperature at a certain depth. Table 1 shows the estimates of the pre-exploitation natural heat output, mass flow rates to the surface and temperature data at 3 km depth for these geothermal fields. The heat output values given in the table are from Bibby *et al.*, 1995 except for data from Hochstein, 2007 for the Waiotapu field. The data marked with (*) shows the representative values of heat outputs compiled by Bibby *et al.*, 1995. Temperature data given by Leaver, 2006 are the inferred average temperature over 3 km depth range. They are adapted from Allis and Speden, 1991 and Cave *et al.*, 1993 which are compilations of the results of feasibility/prefeasibility studies and regional assessments.

Table 1. Natural heat outputs, mass flow rates to the surface and temperatures (at 3 km depth) for the geothermal fields within the model area.

	Heat output, MWe	Mass flow rates, l/s	Temperature at 3km, °C
Atiamuri	10[1]*	< 0.5 [3] 8.5 + steam [4]	165 [8]
Horohoro	4[1] *	0.5 [3] 7.5 [4]	220 [8]
Ngatamariki	40[1] * 38[1], 53[1]	10 + small mudpools [4]	260 [8] 280 [9]
Ohaaki	70[1] * 97[1], 80[1] 85-190[1]	up to 90 [6]	260 [8] 300 [10]
Ongarato	5[1] *	1? (dispersed) [3]	
Orakeikorako	340[1] * 660[1]	Up to 20 [3] 26+steam [4]	260 [8]
Reporoa+ golden springs	17.5[1] * 6.3[1] >15[1]	55 [3] 105 [4] 98 [5] 94.2[7]	230 [8]
Te Kopia	150[1] * 125[1]	3 [3] steam [4]	240 [8]
Waiotapu-Waikite	610[1] * Waiotapu: 475±125[2] Waikite:70[1]	25[3] 370 [4] >174 + Waikite [5] 145[7]	260-230 [8] Waiotapu >295 [11]

[1] Bibby *et al.*, 1995 [1]* Compiled by Bibby *et al.*, 1995
[2] Hochstein, 2007 [3] Cody, 2007
[4] Newson, 2010 [5] Newson, 1993
[6] Rowland and Simmons, 2005 [7] Giggenbach *et al.*, 1994
[8] Leaver, 2006 [9] Monsalve, 2008
[10] O'Sullivan and Clearwater, 2011 [11] Hedenquist and Browne, 1989

3. MODEL DESCRIPTION

In order to represent large-scale convection in part of the TRB system, a 3D numerical reservoir model was set up and calibrated by using the AUTOUGH2 and AUITOUGH2 software packages. The aims were to identify the permeability distribution and fluid and heat flow through the deep geothermal resources at depths of up to -5700 masl.

The boundary (blue line) and areal grid structure (chequered area) of the model is shown in Figure 2. Thus it includes the Atiamuri, Horohoro, Ngatamariki, Ohaaki, Ongarato, Orakeikorako, Reporoa - Golden Springs, Te Kopia and Waiotapu-Waikite geothermal fields.

Apart form the permeabilities the target data for calibration are the heat flows at the base of the model. In this study the top and bottom domains were subdivided into either 13 or 48 zones with the heat flow constant within each zone. The present modelling study is developed in two stages. First, an initial model (13-zones) was set up with a simple structure in order to get a general idea of the behaviour of the system and to see the effects of varying various parameters on the calibration of the model. Second, the 48-zone model was introduced to provide a more detailed representation of the various heat sources. The data used for calibration are the heat outflows to the surface and temperatures at 3km depth. Mass flows to the surface were also calculated for the model, however it is difficult to distinguish reservoir upflow from the natural groundwater movement. Therefore measured mass flows were not used directly for model calibration.

3.1 Model Grid

The model developed in this study covers an area 38 km by 82 km and extends to a total depth of -5700 masl. It contains 779 blocks per layer and each gridblock is 4km^2 in area (Figure 2). There are 13 layers, each 500m thick. The thickness of the blocks in the uppermost layers is varied to follow the water table and in some low elevation areas blocks are removed. Hence the model has 10060 blocks (including one for the atmosphere).

A SE-NW orientation for the grid structure was set up in order to represent the fault directions more accurately. The exterior region (outside of the pink lines in Figure 2) is included in the model in order to represent lateral inflow.

3.2 Rock Properties

The model domain is considered to be a porous medium where large scale permeabilities and other rock properties are uniform within individual geological units.

The main geological units in the model set up for this study are the shallow infill region (from the surface to a depth of 1.7 km), the deep infill region (from 1.7 km to 5.7 km), and an 'exterior' region (outside of the pink lines in Figure 2), as shown in Figure 3. Some of the rock properties assigned to these geological units, shown in Table 2, are based on the data used by Kissling, 2004.

Table 2. Rock properties used in the model. Units for density, thermal conductivity (TC) and specific heat (SH) are kg/m^3, W/(m K), J/(kg K), respectively.

Unit	Density	Porosity	TC	SH
Shallow infill	2200	0.1	3.0	1000
Deep infill	2650	0.01	3.0	1000
Exterior	2650	0.01	3.0	1000
Faults	2200	0.1	3.0	1000

The permeability of the various geological units differs for 13-zone model and 48-model model for the interior region. For the exterior region of both models the horizontal/vertical permeability were set to 0.3/0.1mD. This low permeability provides a permeability contrast between the interior and exterior regions and allows the temperature in the exterior region to remain close to a conductive distribution.

3.3 Boundary conditions

The upper boundary follows the water table of the region and is assumed to be fully saturated liquid water. The water table data are taken from Newson, 1993, O'Sullivan and Clearwater, 2011 and Jenkins, 2010. Water table levels vary from a minimum of +243masl to a maximum of +512masl. At the surface of the model, corresponding to the water table surface, the temperature and pressure are fixed at atmospheric values (a pressure of 1 bar and a temperature of 5°C)

It is assumed that the model is sufficiently large, that recharge outside the lateral boundaries of the model is negligible and they are treated as closed.

Because the model is deep enough, and it is assumed that it encompasses the whole convective system, the model does not require artificial deep recharge boundaries to represent deep inflows of meteoric water. Therefore there is no mass injection over the base boundary.

Kissling (2004) states that at sites distant from the TVZ, all of the data is consistent with a vertical temperature gradient of approximately 30°C/km. Therefore a heat flux of 0.09 W/m^2 is distributed uniformly over the exterior region of the base boundary.

At the base of the model various heat input values were tried over the interior part of the model. The total heat applied at the base of the models (based on the summation of heat outputs from all the geothermal fields) is given in Table 1.

3.4 The 13-zone model :

During the earlier stages of the model development, the base and top surface of the model domain were divided into 13 zones. Then a piecewise constant heat flux was applied across the base of the model. The heat flux applied at the base is proportional to the measured heat output from that region.

A simple permeability structure was used in the 13-zone model. Initially permeability values are taken from the 2D model of the TVZ developed by Croucher and O'Sullivan (2010), but these were modified in order to ensure the model ran to a steady state. The values of horizontal/vertical permeability used for 13-zone model are: 0.3/0.1mD for the exterior region, 8.0/3.0mD for the infill region and 4.0/2.0mD for the deep part of the interior region beginning at -1700masl (Figure 4).

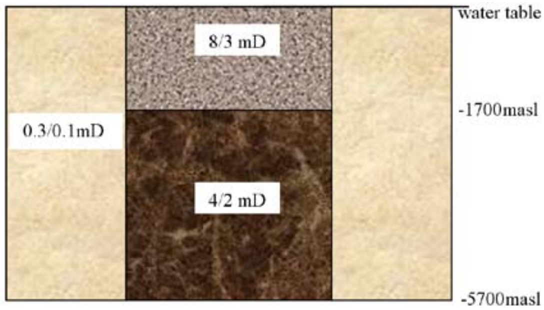
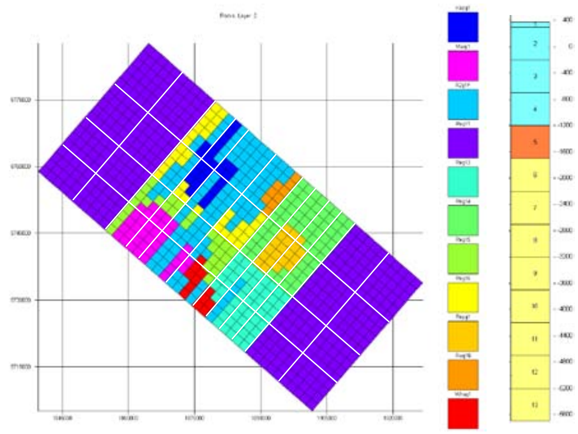


Figure 4 Simple permeability structure used in the 13-zone model.

Since some regions (e.g Waiotapu-Waikite) have a very high heat output from a small area, applying the equivalent of this high heat flux at the base of these regions caused the numerical model to run impractically slow. However distributing this high heat flux into the neighbouring regions allowed a steady state solution to be obtained. With this model it was possible to obtain several convective plumes but their locations were not correct. Therefore in order to obtain more accurate results, in the second stage of the study, a more detailed permeability structure and base boundary conditions were tried (48-zone model).

3.5 The 48-zone model:

To obtain a better representation of the base heat source the bottom and top surfaces of the model domain were divided into 48 regions and again a piecewise constant heat input was applied at the base. The model heat outputs at the surface from these regions were checked against the measured data as part of the calibration process. The white lines in the Figure 5 (a) show the partitioning of these 48-regions over the model area.



(a) **(b)**

Figure 5 (a) Areal and (b) vertical permeability distribution in the 48-zone model.

The permeability of the exterior region is unchanged from the 13-zone model, i.e. the horizontal/vertical permeabilities are 0.3/0.1mD for all layers in the model. For the interior region faults located in the TFB, and the Maroa, Kapenga, Reporoa, Whakamaru calderas were represented by individual rock-types (and therefore permeabilities), shown in Figure 5 (a) with blue, pink, dark blue, light

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orange and red areas, respectively. Additionally the rest of the interior region was divided into five regions (shown as three different shades of green, yellow and dark orange areas in Figure 5 (a)), each with a different set of permeabilities. During model calibration, additional refinement was made to the fault zones and caldera formations.

Allowance was also made for some variation with depth of permeability in the interior region. As shown in Figure 5 (b) the depth of these vertical permeability structures are: a) surface layers: from the water table to -1200m b) mid layers: from -1200masl to -1700masl c) deep layers: from -1700masl until -5700masl. Thus in total, including the exterior region, 35 different rock types were used in the model to represent the permeability distribution.

4. MODELLING RESULTS

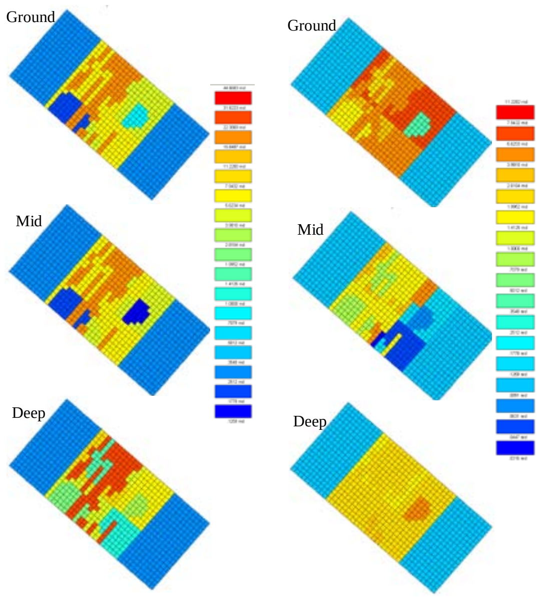
From experimentation with different permeabilities and heat flows in the 48-zone model, the best combinations of these parameters was selected, based on their effect on the positions of the plumes, heat outputs from the fields and temperatures at 3km.

Various forward and inverse model simulations were carried out to decide on the permeability distribution. The permeabilities that give the best results for the 48-zone model are summarized in Table 3. As there are 35 different rock types, representing the permeability distribution of the whole model, Table 3 groups these rock types as faults, calderas and the rest of the interior region. The range of permeabilities for surface, mid and deep layers (Figure 5 (b)), including maximum and minimum values, are shown in Table 3.

Table 3 Permeability ranges used in the 48-zone model for the interior region.

Level	Geological Unit	horizontal k, mD		vertical k, mD	
		min	max	min	max
surface	faults	17.5	17.5	5	5
	calderas	0.8	6.6	2	5.5
	rest of interior	4.2	7.2	4	7
mid	faults	5.3	17	0.04	2
	calderas	0.1	6.6	0.07	5.1
	rest of interior	4.3	7.1	0.05	3
deep	faults	27.6	27.6	2.7	2.7
	calderas	1.8	4.6	2	4.7
	rest of interior	1.4	8	2	2.3

Horizontal and vertical permeability distributions for surface, mid and deep layers are shown in Figure 6 (a) and (b) respectively.



(a) (b)

Figure 6 (a) Horizontal and (b) vertical permeability distributions for surface, mid and deep layers

Various heat input values and locations were tested at the base of the model in order to reproduce the source of the convection plumes that create the fields in the model area. The distribution of heat input over the bottom boundary shown in Figure 7 yields the best results in terms of plume location, heat flows and temperature values at 3 km.

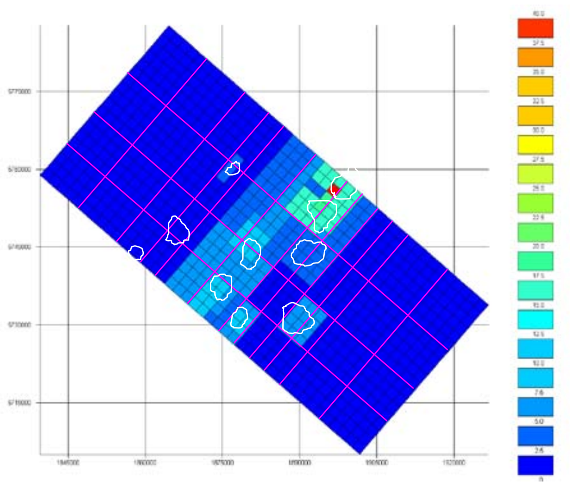


Figure 7 Areal heat flow (MW) distribution over the base boundary for the 48-zone model.

The total heat applied at the base of the model is 1485 MW (approximately 1300 MW, if we do not include the normal terrestrial heat flow ($0.09W/m^2$)). According to the values compiled by Bibby *et al.*, 1995, the total heat outflow estimate is approximately 1250 MW. However as shown in Table 1, these estimates have a large range (minimum 1030, maximum 1760 MW) and hence indicate a high level of uncertainty.

The results for the areal heat flow (MW) distribution at shallow depth (-700 masl) for the 48-zone model is shown in Figure 8. The reason for illustrating the heat flows at -700masl is to compare the locations of the plumes obtained with this model, to the measured field areas given in Bibby *et al.*, 1995. The white bounded areas in this figure corresponds to the areas of the geothermal fields, measured at depths between 0.5 km and 1 km in the TRB (Bibby *et al.*, 1995). As shown in Figure 8 the model correctly predicts the location of geothermal plumes for the fields located in the model area.

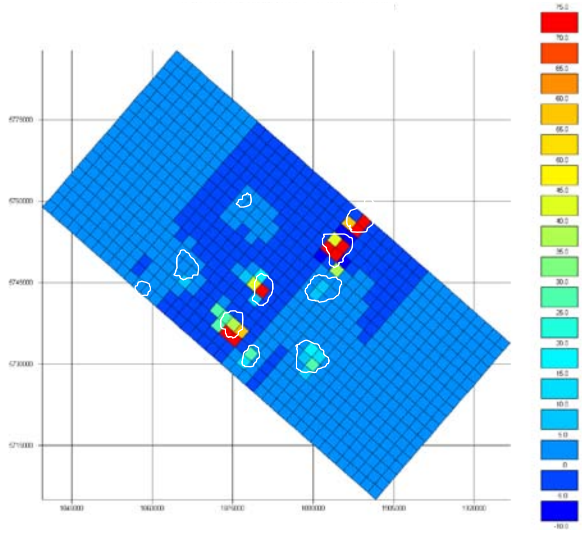


Figure 8 Areal heat flow (MW) distribution at a depth of -700masl for the 48-zone model

In order to be consistent with the model areas given in Figure 2, heat flows at a depth of -700masl were calculated. The heat flow was obtained by summing the positive heat flows from layer 4 to layer 3 at each of the grid-blocks located within the white bounded areas in Figure 8, for each geothermal field. Table 4 compares these calculated model results for heat flows to measurements of heat output for individual fields. In this comparison the heat output values compiled by Bibby *et al.*, 1995 have been used.

According to the heat flow comparisons in Table 4, except for the Waiotapu-Waikite region, there is good agreement between the measured data and model results. For the Waiotapu-Waikite region Bibby's 610 MW estimate is the summation of 540 MW heat loss from Waiotapu and 70 MW from Waikite. However for the Waiotapu field, Hochstein, 2007 states that, with a simplified mass balance calculation, based on chloride concentration, the 540MW heat loss is too high. Their estimate is 475 ± 125 MW, which gives a better agreement with the model result.

Table 4 also compares the measured/inferred temperature data at 3km in the particular TRB fields, to model results at -2950masl depth. According to this comparison, with the exception of he Horohoro field, the model results show a good agreement with the measured/inferred temperature data for TRB fields. However it should be noted that some of these data are inferred average temperatures based on regional assessments and their reliability depends on resource evaluation methods.

Table 4 Comparison of measured heat output (MW) and measured/inferred temperature (°C) data to model results.

	Measured heat output[1]	Model heat flow	Measured/ inferred T	T model
Atiamuri	10	11.1	165 [2]	168
Horohoro	4	2.8	220 [2]	163
Ngatamariki	40	40.3	260 [2] 280 [3]	271
Ohaaki	70	82.1	260 [2] 300 [4]	303
Ongarato	5	3.4		131
Orakeikorako	340	361.1	260 [2]	255
Reporoa+golden springs	17.5	20.4	230 [2]	228
Te Kopia	150	139.6	240 [2]	257
Waiotapu-Waikite	610	503.4	260-230 [2] Waiotapu >295 [5]	301

[1] Bibby *et al.*, 1995 [2] Leaver, 2006 [3] Monsalve, 2008
[4] O'Sullivan and Clearwater, 2011 [5] Hedenquist and Browne, 1989

The temperature distribution results for the model at a depth of -2950masl is shown in Figure 9. They show that, the highest temperatures at approximately 3km depths are seen at the Ohaaki and Waiotapu-Waikite geothermal areas. Atiamuri and Ongarato fields have the lowest temperatures.

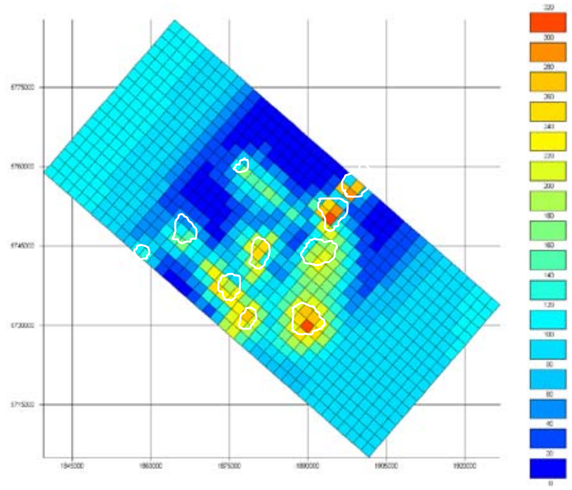


Figure 9 Areal temperature (°C) distribution at depth -2950 masl for the 48-zone model

Measured surface mass flow rates are compared to the calculated model mass upflows from deeper layers to +300masl in Table 5. However as shown in this table, the uncertainty of these data is large and for several fields steam discharge is unknown. Additionally, as the grid-blocks used in this study are large, it is difficult to separate geothermal manifestations from the natural ground water movement. Therefore the comparison shown in Table 5 was not used as part of the model calibration.

Table 5 Comparison of measured surface mass flow rates to the model mass flow to +300masl.

Field	Measured mass flow rates, l/s	Model mass flows, kg/s
Atiamuri	< 0.5 [1] 8.5 + steam [2]	17.9
Horohoro	0.5 [1] 7.5 [2]	5.3
Ngatamariki	10 + small mudpools [2]	56.3
Ohaaki	up to 90 [4]	99.4
Ongarato	1? (dispersed) [1]	7.8
Orakeikorako	Up to 20 [1] 26+steam [2]	398.5
Reporoa+golden springs	55 [1] 105 [2] 98 [3] 94.2[5]	30.1
Te Kopia	3 [1] steam [2]	122.6
Waiotapu-Waikite	25[1] 370 [2] >174 + Waikite [3] 145[5]	461.4

[1] Cody, 2007 [2] Newson, 2010 [3] Newson, 1993
[4] Rowland and Simmons, 2005 [5] Giggenbach *et al.*, 1994

5. CONCLUSIONS

In this paper a 3D numerical model of the complete convective zone of part of the TRB was described. It incorporates an exterior region and an interior region. The interior region includes the convective geothermal systems within the TRB, several caldera structures and the TFB.

The 13-zone model showed that with a very simple permeability structure, obtained by dividing the model area into three geological units (exterior, deep interior and shallow interior) it is possible to obtain a steady state model and some large plumes close to the real locations of the actual geothermal fields. For the model calibration, the locations of the plumes were required to be matched along with the heat flows and temperatures.

A more complex 48-zone model correctly predicts the position of the geothermal plumes for the fields located in part of the TRB, their shallow heat flows and the temperatures in the upflow zones at about 3 km depth. The match to the temperatures in particular is an advance on the results achieved by Kissling, 2004 for the whole TVZ. Most of his modelled geothermal systems were too cold although the heat flows were reasonable indicating that overall the permeabilities were too high.

Experimentation on the 48-zone model showed that in order to obtain the correct locations of discrete plumes, and to calibrate the heat flows and temperatures in the model, variable heat inputs over the base boundary are required. Additionally a relatively complex permeability distribution needs to be introduced including various geological units with several sub-units or rock-types.

The total surface heat output from the fields located in model area was estimated at approximately 1250 by Bibby *et al.*, 1995 (with a range of minimum 1030, maximum 1760 MW). This range includes the total of about 1300 MW heat (excluding the normal terrestrial heat flow (0.09W/m2) applied at the base of the model.

This model includes an exterior low permeability region and a higher permeability region inside the convective zone. In the interior region, permeability contrasts are required between the caldera, faults and the rest of the interior region in order for stable plumes to occur.

Further work in this project will include a refinement in grid size to facilitate more accurate calibration of model heat and mass outflows.

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REFERENCES

Allis, R. G.and Speden, I. G. (1991). *New Zealand's Energy Resources for the 21st century*. Paper presented at the Proceedings 4 th New Zealand Coal Conference.

Bibby, H. M.,Caldwell, T. G.,Davey, F. J., *et al.* (1995). Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation. *Journal of Volcanology and Geothermal Research, 68*(1-3), 29-58.

Cave, M. P.,Lumb, J. T.and Clelland, L. (1993). Geothermal Resources of New Zealand. Resource Information Report 8, Ministry of Commerce, New Zealand.

Cody, Ashley D. (2007). Geodiversity of geothermal fields in the Taupo Volcanic Zone, *DOC Research & Development Series 281*. Department of Conservation, Wellington.

Giggenbach, Wf,Sheppard, D. S.,Robinson, B. W., *et al.* (1994). Geochemical structure and position of the Waiotapu geothermal field, New Zealand. *Geothermics, 23*(5-6), 599-644.

Hanano, Mineyuki. (2000). *Two different roles of fractures in geothermal development*. Paper presented at the Proceedings World Geothermal Congress 2000, Kyushu - Tohoku, Japan, May 28 - June 10, 2000.

Hedenquist, Jeffrey W.and Browne, Patrick R. L. (1989). The evolution of the Waiotapu geothermal system, New Zealand, based on the chemical and isotopic composition of its fluids, minerals and rocks. *Geochimica et Cosmochimica Acta, 53*(9), 2235-2257.

Hochstein, M. P. (2007). Changes in geothermal manifestations and other surface features since the start of the thermal exploitation of the Mokai and Rotokawa geothermal fields, and an assessment of the Tokaanu-Waihi-Hipaua, Te Kopia and Reporoa Geothermal Fields and their regional plan classification, *Technical Report Series 27, New Zealand. Dept. of Conservation*.

Jenkins, Bevan. (2010). Personal Communication, Environment Waikato (Waikato Regional Council). Hamilton.

Kissling, W. M.and Weir, G. J. (2005). The spatial distribution of the geothermal fields in the Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research, 145*(1-2), 136-150.

Kissling, Warwick M. (2004). *Deep Hydrology of the Geothermal Systems in the Taupo Volcanic Zone, New Zealand, PhD thesis.* University of Auckland, Auckland, New Zealand.

Leaver, Jonathan David. (2006). *Identification and Interpretation of Characteristic Periodic Variations of Near Surface Fluids in the Te Aroha, Rotorua, and Orakeikorako Geothermal Fields of New Zealand using Wavelet and Fourier Analysis.* The University of Auckland, Auckland.

Monsalve, Luis Alejandro Urzúa. (2008). *Integration of a preliminary one-dimensional MT analysis with geology and geochemistry in a conceptual model of the Ngatamariki geothermal field.* The University of Auckland, Auckland.

Newson, Juliet. (2010). Geothermal Features Report, June 2010 s Annual Monitoring: Environment Waikato, Hamilton.

Newson, Juliet A. (1993). *Geothermal and Groundwater Hydrology of the Reporoa - Waiotapu Basin, MSc. Thesis.* University of Auckland, Auckland, New Zealand.

O'Sullivan, Michael J.and Clearwater, Emily. (2011). Ohaaki Modelling Report: Uniservices and Department of Engineering Science, University of Auckland.

Rowland, J.V.and Sibson, R.H. (2004). Structural controls on hydrothermal flow in a segmented rift system, Taupo Volcanic Zone, New Zealand. *Geofluids, 4,* 259–283.

Rowland, J.V.and Simmons, S.F. (2005). *Hydrological controls on mineralisation in the active epithermal environment, Taupo Volcanic Zone (TVZ), New Zealand*. Paper presented at the Proceedings of the 2005 New Zealand Minerals Conference.

Soengkono, S. (1995). A magnetic model for deep plutonic bodies beneath the central Taupo volcanic zone, North Island, New Zealand. . *Journal of Volcanology and Geothermal Research 68*, 193–207.

Wood, C.P. (1996). *Basement geology and structure of TVZ geothermal fields, New Zealand*. Paper presented at the Proc. 18th New Zealand Geothermal Workshop, pp. 157– 162.,