NUMERICAL MODEL OF THE DEEP HYDROTHERMAL CONVECTION IN THE TAUPO VOLCANIC ZONE, NEW ZEALAND

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ABSTRACT

The Taupo Volcanic Zone (TVZ) is a NNE-trending rifting arc, characterized by extensive volcanism. Associated with this volcanism high-temperature (>250°C) geothermal fields occur with convective circulation to depths of 7–8 km. The purpose of this study is to create a representative model of the deep hydrothermal convection of the TVZ. Study investigates the variables that are affecting the major features controlling the geothermal fields distributed throughout the area. Model encompasses 21 geothermal fields, namely Kawerau, Rotoma, Tikitere/Rotoiti, Taheke, Rotorua, Horohoro, Waimangu, Waiotapu-Waikite, Reporoa, Te Kopia, Ohaaki, Orakeikorako, Ngatamariki, Atiamuri, Rotokawa, Ongarato, Mangakino, Mokai, Wairakei, Tauhara, and Lake Taupo.

The model was divided into two main regions, the interior region and exterior region. Interior region is bounded by the Kaingaroa Fault to the East, with the Taupo Fault Belt (TFB) presented in the centre of the TVZ. The heat flow at the base of the exterior region is set to the normal terrestrial flow of 0.09 W/m^2, while the heat distribution at the base of the interior region is varied to achieve the measured heat output at the surface. Dominating geological structures such as caldera boundaries, distribution of greywacke basement and faults that provide the permeability needed to facilitate the movement of fluids in the system were inferred from recent geological and geophysical studies. The distribution of heat at the base of the model (approximately 6.7 km) and the permeabilities of geological structures were the parameters to be estimated. The model was calibrated to predict the location of discrete plumes, magnitude of heat discharge from each field and reservoir temperature.

1. INTRODUCTION

New Zealand is located at the subduction zone, where the oceanic Pacific Plate (Hikurangi Plateau) is subducting beneath the continental Australian Plate (Kermadec Arc) with a NE – SW direction. This activity is creating an active continental volcanic arc/back-arc basin where the Taupo Volcanic Zone (TVZ) is formed. With an approximate area of 30 kilometers wide and 150 kilometers long (Kissling & Weir, 2005), it spreads between Whakaari Volcano (White Island) in the Northeast and Mount Ruapehu in the Southwest.

The appearance of tectono-magmatic faulting, diking, uplift, and subsidence across the arc are signs that rifting and magmatism are still actively occurring in the TVZ (Rowland et al., 2010). The main source of heat for the TVZ is due to its volcanic arc settings that are formed from subduction activity, causing magma to intrude into the shallow crust as well as rhyolite eruption with an average of 0.28 m^3/s for the last 0.34 Ma (Wilson, 1996). The heat flow, estimated to be produced about 2600 MW/100 km (Hochstein, 1995), is considered high compared to other volcanic arc settings.

In this paper we present a numerical model which represents a generalized overview of the tectonic and magmatic settings of the geothermal systems in the central TVZ, in order to investigate the fascinating questions such as: Why they occur in their particular locations? Why there is a spatial separation of these systems? How stable are the hydrothermal systems and their positions? Do topographical features influence the location of the geothermal fields?

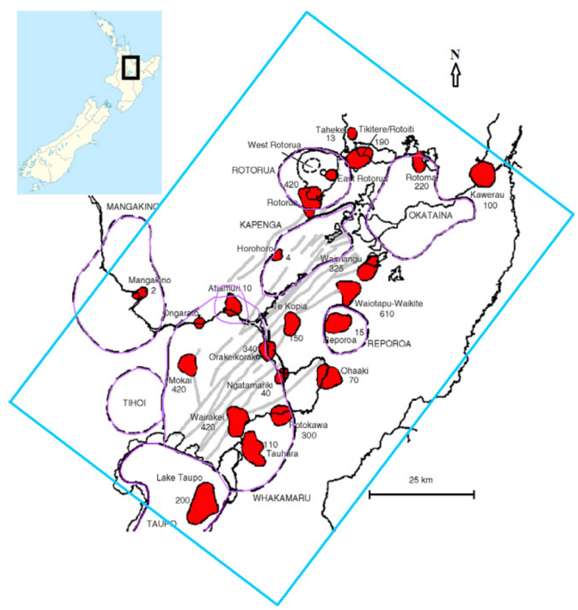

Figure 1 TVZ geothermal fields (red shaded areas), TFB (Grey lines), volcanic centers (bounded with purple lines) (modified from Kissling and Weir (2005))

Studies on the TVZ geothermal systems (e.g. geologic features, geophysical explorations and hydrothermal alteration patterns) have contributed greatly to get insights into many important aspects. However volcanic and tectonic settings of the geothermal systems in the central TVZ are still poorly understood and many concepts are controversial. Our aim is to set up a numerical model by using the former studies available in the literature. A large scale convective model that encompass entire TVZ hydrological system can improve the understanding of these concepts.

In New Zealand, there is a total of over 1000 MWe of installed geothermal electricity generation capacity from the conventional geothermal resources, covering 16 % of the national electricity generation (Carey et al., 2015). This amount is extracted from a depth less than 3 km where the temperature reaches up to ~340°C. Possible deep geothermal resources (3.5–7 km) beneath the convective system can increase the energy production significantly. On a more practical level, creating a model overarching entire TVZ and simulating deep linkages between each system can be useful for the assessment of the potential deep utilization of these geothermal resources as well as a better management of the fields currently being exploited.

A previous numerical modelling study was undertaken by Kissling and Weir (2005) to represent large scale flows of water and heat which give rise to the geothermal fields in the TVZ. This model investigated large diameter permeability contrasts (e.g. 15 cm and 30 cm) but not include the details of individual geological structures. It was able to represent the approximate locations of high heat discharging geothermal fields also absence of geothermal fields in the central part of the TVZ. Kaya et al. (2014) developed a model with a similar scope and objectives, however by focusing on a smaller area, Taupo Reporoa Basin (TRB). This model included the calderas and fault structures within the TFB and was able to predict the position of the geothermal plumes distributed within the TRB, their surface heat flows, and temperatures in the upflow zones at approximately 3 km depth.

For this study we set up a model of the complex convective geothermal systems within entire TVZ, including their deep hydrothermal convection occurrence by using the dominating geological structures (i.e. calderas, basement structures and faults). The model aims to replicate the steady state behaviour by matching the natural spacing of convective plumes, their heat discharge observed at the surface and reservoir temperatures. The modelling process is conducted by using AUTOUGH2 (Yeh et al., 2011; Yeh et al., 2012), the University of Auckland's version of TOUGH2 (Pruess et al., 1999). MULgraph (O'Sullivan and Bullivant, 1995), TIM (Yeh et al., 2013) and The PyTOUGH software (Croucher, 2013; Wellmann et al., 2012; Yeh et al., 2012) were the main visualisation tools used in this study.

2. CONCEPTUAL MODEL

On a very large scale, the TVZ consists of an approximately 6–8 km deep convective zone overlying a 'ductile' region which extends to a depth of about 15 km (Kissling, 2004). The current structure of the TVZ results from the brittle response to NW-SE directed rifting of an average of 8 mm/year (Darby et al., 2000). This extension allows a ductile mantle and partially melted structures enter at the deeper parts of the system (Kissling and Ellis, 2012). As a result, these magmatic intrusions and conduction in the ductile layer provide an effective heat source at the base of the convective zone. Wilson and Rowland (2015) indicates that about four times as much magma is trapped at depth below the central TVZ than is erupted, feeding heat, volatiles and chemicals into geothermal systems.

The mesozoic greywacke acts as the basement throughout the whole TVZ. The depth of the basement varies approximately 1-3 km between the geothermal fields located in the TVZ. Its depth is approximately 1 km around the Kawerau area; in the northern part of the TVZ, while it crops out to the east and west of the TVZ. The basement becomes deeper underneath the caldera regions and shallower outside the calderas (Soengkono, 2011). The area encompassed for this study is shown with blue lines in Figure 1, together with the Taupo Fault Belt (TFB) (grey lines) and known volcanic centres bounded with purple lines. Because of its high permeability, the TFB is considered to be the main path for the meteoric water infiltration from the surface providing the fluid for hydrothermal convection to occur (Bibby et al., 1995).

Salient volcanic features in the TVZ are Rotorua, Okataina, Kapenga, Maroa/Ohakuri, Reporoa and Whakamaru, Taupo, Tihoi and Mangakino. The association of geothermal activity with volcanic centre margins suggests that the calderas provides deep-rooted fracture systems which allow circulation of both cold and hot water into heat-source regions (Kissling and Weir, 2005; Soengkono, 2011). The calderas are believed to provide deep-rooted fracture systems which allow circulation of both cold and hot water into heat-source regions which may not be directly beneath the shallow parts of the fields (Wood, 1996).

A conceptual model of the TVZ region has been proposed by Hiess et al. (2007), indicating the role of crustal processes which is associated with faulting in the TVZ and also areas where faults are intersecting with caldera margins (Figure 2). The very low temperature gradients, compared to the gradient outside the TVZ supports the reason for the TFB being considered to be the primary path for downflows of cool surface waters, which is the main supplier of fluid for the hydrothermal convection in the TVZ (Bibby et al., 1995). Supported by the low gravity anomalies and drilling data, the shallow infill regions consist of weak low-density pyroclastic deposits fills the caldera collapse structures (Soengkono, 2011).

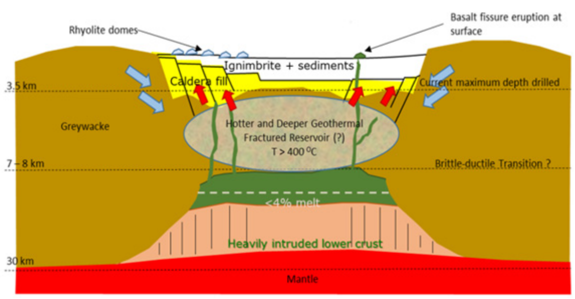

Figure 2 Schematic of the large scale structure in the TVZ (modified from Hiess, (2007))

2.1. Available heat output and temperature information

Based on information from various studies, the measured pre-exploitation natural heat discharge at the surface and inferred average temperature over 3 km depth range of geothermal fields used to compare with the modelling results are shown in Table 1. Since some of heat flow measurements have large uncertainties, the red highlighted ones were chosen for the calibration of this study. 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. Measured natural heat outputs and inferred temperatures (at 3 km depth) for the geothermal fields within the model area.

Field	Heat Output (MW)	Temperature at 3km (°C)[e]
Kawerau	84[a], 210[a], 100[b]	250
Rotoma	220 ± 60[a]	200
Tikitere-Rotoiti	140[a], 190[a]	230-130
Taheke	13[a,b]	230
Rotorua	470 ± 50[a], 470[b]	220
Horohoro	4[a], 5[b]	150
Waimangu	325±80[a], 250[b]	260
Waiotapu-Waikite	610[a], 475±125[d]	260-230
Reporoa	40[d], 45[a]	230
Te Kopia	125[a], 150[a,b], 250[a]	240
Ohaaki	70[a], 97[a], 85-190[a], 95[c]	260, 300[f]
Orakeikorako	340[a], 660[a]	260
Ngatamariki	40[a], 38[a], 53[a]	260
Atiamuri	10[a], 5[b]	165
Rotokawa	219[a], 300[a], 600[a]	280
Ongarato	5[a]	-
Mangakino	4[a]	220
Mokai	400±160[a], 100[b]	280
Wairakei	420[a], 530[b]	230, 270[g]
Tauhara	110[a], 250[b]	240, 300[g]
Lake Taupo	120[a], 425±175[a]	-

(a) Other sources but referenced by Bibby et al., 1995
(b) Cody, 2007 (c) Rissman et. al., 2012
(d) Hochstein, 2007 (e) Leaver, 2006
(f) O'Sullivan and Clearwater (2011) (g) Yeh, 2015

3. NUMERICAL MODELLING

In the TVZ major meteoric water is transported to the base of the convective zone located between 6-8 km where the transition between brittle and ductile behavior occurs. As it becomes heated at depth, it is concentrated into convectively driven rising plumes. The nature of the heat source, permeability distribution and topography are the major factors effecting fluid paths.

3.1 Model grid and rock properties

To represent whole convective system of the TVZ, a large and deep enough model needs to be set up. The model set up for this study covers an area of 82 km x 120 km and thickness of approximately 6.7 km. 21 geothermal systems included in this study are Kawerau, Rotoma, Tikitere/Rotoiti, Taheke, Rotorua, Horohoro, Waimangu, Waiotapu-Waikite, Reporoa, Te Kopia, Ohaaki, Orakeikorako, Ngatamariki, Atiamuri, Rotokawa, Ongarato, Mangakino, Mokai, Wairakei, Tauhara, and Lake Taupo. The permeability has to be compatible with the observed mass and heat flow paths, therefore the model needs to be calibrated by defining the locations of the geothermal plumes, surface heat and mass discharge, and reservoir temperature within the TVZ.

The areal grid structure of the model is shown in Figure 3, contains 2,460 gridblocks per layer with a uniform area of 4 km^2 as shown in Figure 3. It is oriented in the NE-SW direction parallel to the TFB which is believed to be a major permeability that controls the TVZ. The model is divided into 13 layers (Figure 4) with each layer set at 500 m thickness, except for the uppermost layer which varied to follow the water level.

Figure 3 The areal grid structure of the model and initial rock type distributions at -700 masl (Layer 3) with faults representing the TFB (grey)

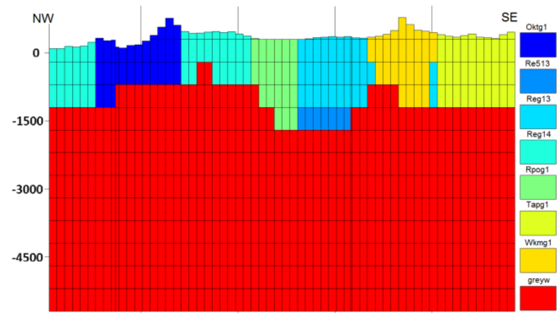

Figure 4 NW-SE cross-section showing vertical grid structure, surface elevations and rock type distribution

The initial model follows a very simple geological structure. The deep convective region was represented with greywacke basement, shown with red colour in Figure 4. The surface of this basement rock was implemented based on a 3D gravity model developed by Soengkono (2011). The shallow volcanic infill region represented with major volcanic centers surrounded with ignimbrite and sediments (Figure 3). Faults occurring in the central part of the TVZ such as the TFB, are introduced into the model by assigning different rock type (shown with grey in Figure 3) corresponding to those areas.

Initially rock properties are uniform within individual geological units. The rock properties assigned to these geological units are based on the values used in Kaya et al. (2014). Specific heat capacity and thermal conductivity of the rock are 1000 J/(kg K) and 3 W/(m K) everywhere. While the density of greywacke basement was taken as 2650 kg/m^3, the rest of the model was assumed as 2200 kg/m^3. Rock porosity ranges between 0.01 and 0.1.

Initial permeabilities have been estimated in the production areas of geothermal fields by means of interference and tracer tests (e.g. Wairakei (Hunt and Kissling, 1994), Ohaaki (Grant and Bixley, 2011) and Ngatamariki (Boseley et al., 2010)), as well as modelling studies of individual fields or regional models within the TVZ. Distribution of permeability varied during the calibration process in order to obtain compatible pathways with the observed mass and heat flows.

3.2 Boundary conditions

Initially the depth of the uppermost layer was set to follow the water table (Figure 4). Assuming that the atmosphere is saturated with water (so that liquid water could flow down into the model and liquid and vapour could flow up into the atmosphere), the EOS1 module of TOUGH2 was used for simulating flow of pure water. 1 bar and 15 °C conditions were implemented for the constant atmospheric pressure and temperature, respectively.

Because the model is large and deep enough, and it is assumed that it encompasses the whole convective system, it does not require artificial recharge from base or side boundaries to represent deep or lateral inflows of meteoric water.

For the heat flux distribution, the base of the model was simplified into two main regions, interior and exterior region. A heat flux of 0.09 W/m^2 is distributed uniformly over the exterior region of the base boundary based on the data presented by (Thompson, 1977) which are consistent with a vertical temperature gradient of approximately 30 °C/km. At the base of the interior part of the model heat input values were tried progressively modified during model calibration.

4. CALIBRATION RESULTS AND DISCUSSION

4.1 Modelling process

The model was developed in three stages

Model 1

The uppermost layer is set at the water table and simulated using EOS1 (pure water) module of TOUGH2. The geological distribution is set to follow the calderas and volcanic centres distributed throughout the TVZ as shown Figure 3. The greywacke zone was represented with a single uniform rock type. This initial model had a simple base heat flow distribution.

Some regions (e.g Rotorua, Mokai, Waiotapu-Waikite, Wairakei) have a very high heat output from a small area. Therefore applying high heat flux at the base or neighbouring region was necessary to obtain separate convective plumes. Modifications on the heat flux distribution over the basement boundary allowed obtaining localized plumes near the geothermal field boundaries. Initially the model runs impractically slow.

After many gradual modifications on the heat inputs and rock permeability, we obtain a model running up to large times required for a natural state simulation. Figure 5 shows surface heat discharge distribution for at the early stages of Model 1. Later on this model was calibrated for better representation of heat outflow distribution (Figure 6).

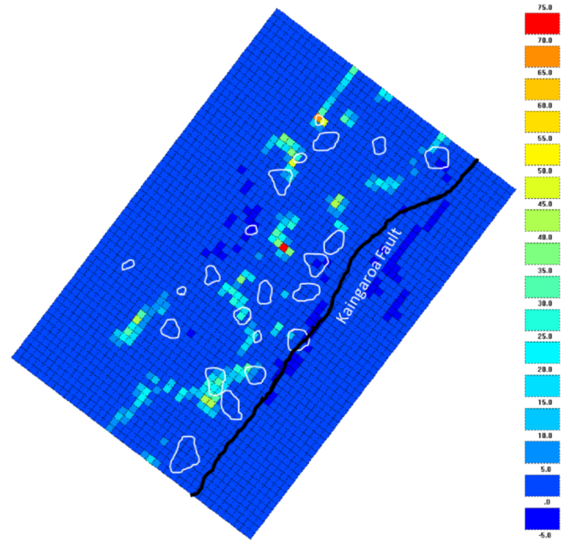

Figure 5 Areal heat flow (MW) distribution at the surface for initial version of Model 1

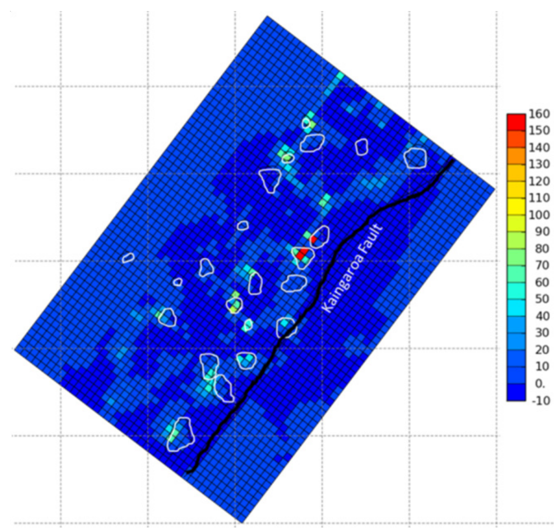

Figure 6 Areal heat flow (MW) distribution at the surface for final version of Model 1

Model 2

Model I was used as the base model. The uppermost surface (Layer 1) is set to follow the topography of the region (ground surface) and air water interface at the ground surface was included by using EOS4 module. Cold groundwater recharge from surface was provided by injecting a proportion of the average rainfall into the surface blocks. The rate of infiltration assumes 10% of the rainwater is absorbed into the ground (Yeh et al., 2014). The average rainfall was assumed as 1000 mm/year. Considering the computational time, only one large atmospheric block was implemented at the topmost boundary. This does not allow us to include the effect of additional surface recharge from the lakes and rivers.

Model 3

Model I was used as the base model.

In the later stages of the modelling, to represent up to date information on geological structure, the most recent interpretation of the fault structure was implemented into the model. According to the interpretations of Villamor and Berryman (2001), the major faults controlling the activities in the TVZ are continuously present down to the deeper region of 6 to 10 km depth. Based on a 3D interpretation of the TVZ faults by Alcaraz (2015), the greywacke basement was differentiated into greywacke and greywacke faults (Figure 7).

Calibration is continuously carried out to achieve better results for the comparison of the locations of the plumes obtained with this model, to the measured field areas given Figure 1, their heat outflows at the surface and reservoir temperatures by readjusting the rock properties together with the heat inputs at base of the model.

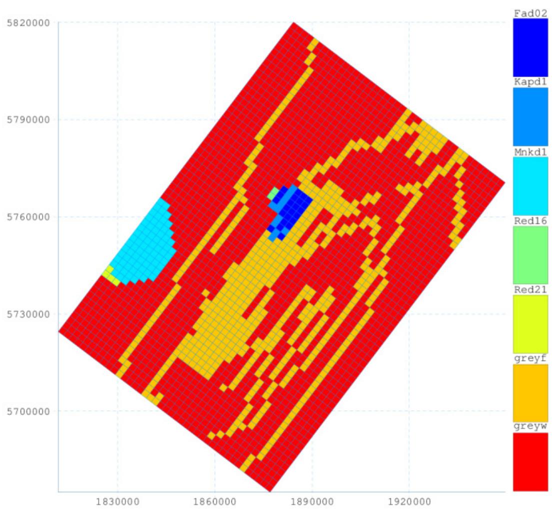

Figure 7 Layer 7 (-2450 masl) rock type distribution indicating faults implemented based on geological interpretation by Alcaraz (2015)

4.2. Simulation results

As a result of many forward modelling runs, a combination of permeability distribution and heat influx parameters that gave a good fit to the positions of the plumes and heat outputs from the fields was selected.

In order to represent the heterogeneity of the system and achieve a better calibration, the large geological units were subdivided and various combinations of these parameters were tried. An illustration of the permeabilities of shallow zone (layer 2, +50 masl) that give the best results for the Model 3 is shown in Figure 8. There are 56 different rock types, representing the permeability distribution of the whole model, including faults, each caldera system, the greywacke basement and the rest of the model domain.

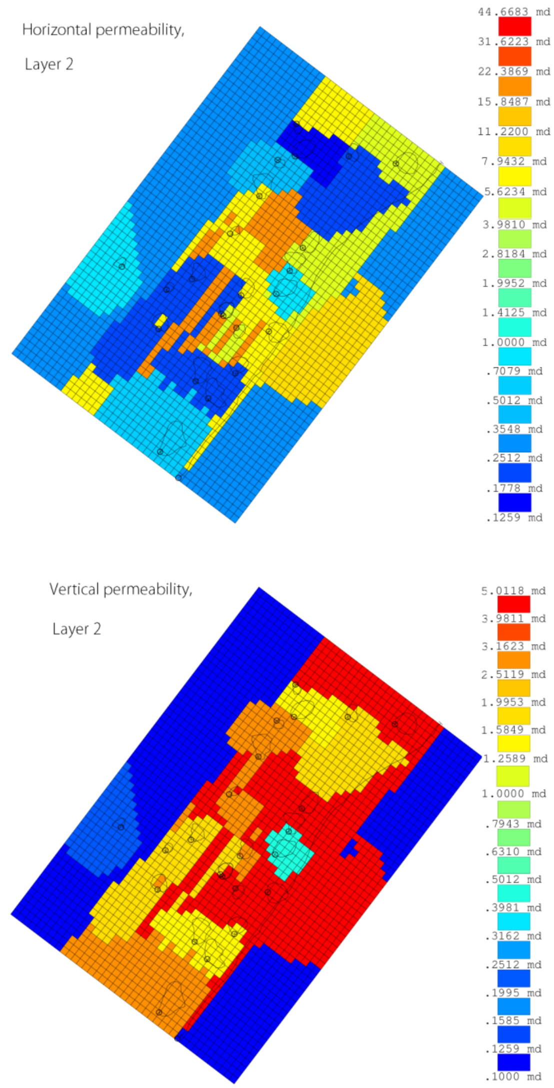

Figure 8 Horizontal and vertical permeabilities of shallow zone (layer 2, +50 masl)

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 9 yields the best results in terms of plume location and magnitude of heat flows.

The results for the areal heat flow (MW) distribution at surface for the best model are shown in Figure 10. The locations of the geothermal fields predicted by this model agree reasonably well with the measured field areas given in Figure 1. The white bounded areas in this figure correspond to location of the geothermal fields. Since the model grid-block sizes are very large, the fit to the area of the geothermal fields is approximate.

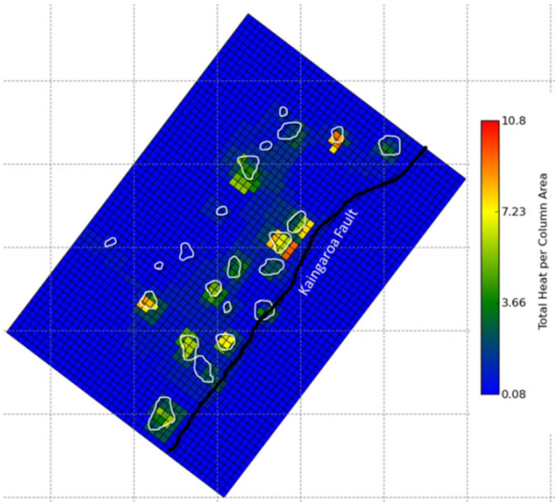

Figure 9 Heat distributions (MW) at base (Layer 13) for Model 3

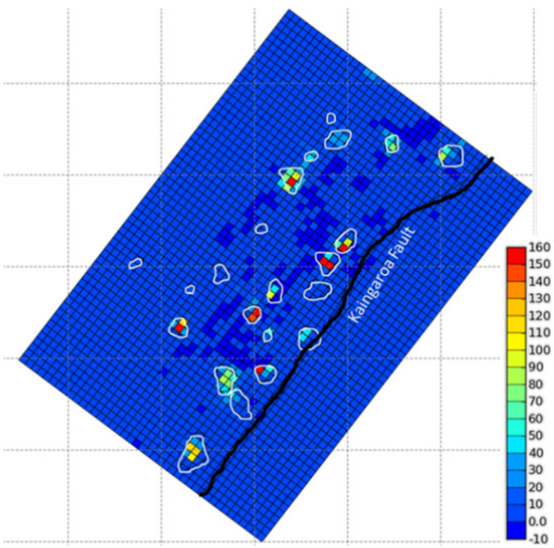

Figure 10 Areal heat flow (MW) at surface

The total heat flux applied at the base of the model is 5,380 MW, approximately 4,980 MW if the normal terrestrial heat flow (0.09 W/m^2) was eliminated from the summation. This value is slightly higher than the measured heat flow (4,410 MW) from 21 geothermal fields obtained from presented in Table 1.

As shown in Table 2, the comparison between the magnitude of measured and model heat flows shows a reasonably good match. However, the comparison of inferred reservoir temperature at 3 km depth with the model result does not agree well. It should be noted that the inferred temperature values given in this table are based on regional assessments which indicate a high level of uncertainty. Additionally the model results for temperature values represent an average temperature of very large gridblocks (2 km x 2 km x 0.5 km). For a more reasonable approximation, it is necessary to refine the gridblock size of the model. Low temperature values between convective plumes at very deep layers are indication of large downflows of surface waters which supply most of the water for the TVZ geothermal systems.

Table 2 Comparison of measured heat output (MW) and measured/inferred temperature (°C) at 3 km to model results.

Field	Measured Heat Output	Model heat Output	Measured /inferred T	Model T, °C[e]
Kawerau	84[a], 210[a], 100[b]	216	250	193
Rotoma	220 ± 60[a]	217	200	243
Tikitere-Rotoiti	140[a], 190[a]	184	230-130	219
Taheke	13[a,b]	14	230	126
Rotorua	470 ± 50[a], 470[b]	447	220	268
Horohoro	4[a], 5[b]	9	150	160
Waimangu	325±80[a], 250[b]	320	260	255
Waiotapu-Waikite	610[a], 475±125[d]	594	260-230	289
Reporoa	40[d], 45[a]	38	230	211
Te Kopia	125[a], 150[a,b], 250[a]	144	240	239
Ohaaki	70[a], 97[a], 85-190[a], 95[c]	93	260, 300[f]	170
Orakeikorako	340[a], 660[a]	345	260	247
Ngatamariki	40 [a], 38 [a], 53[a]	53	260	180
Atiamuri	10[a], 5[b]	6	165	115
Rotokawa	219[a], 300[a], 600[a]	300	280	208
Ongarato	5[a]	10	-	145
Mangakino	4[a]	2	220	182
Mokai	400±160[a], 100[b]	403	280	299
Wairakei	420[a], 530[b]	406	230, 270[g]	269
Tauhara	110[a], 250[b]	113	240, 300[g]	213
Lake Taupo	120[a], 425±175[a]	427	250	238

(a) Other sources but referenced by Bibby et al., 1995
(b) Cody, 2007
(c) Rissmann et. al., 2012
(d) Hochstein, 2007
(e) Leaver, 2006
(f) O'Sullivan and Clearwater (2011)

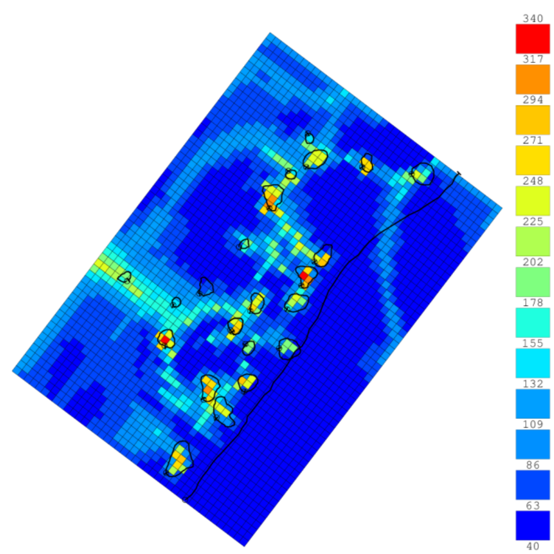

Figure 11 Areal temperature (°C) distribution at Layer 12 (depth -4950 masl)

5. CONCLUSION AND FUTURE WORK

A numerical model for the natural state conditions of the TVZ has been developed. The model represents a deep and large scale hydrothermal convection underlies entire TVZ and investigates its inferred geological structure and hydrological settings.

Experimentation on the various model set up showed that the main parameters influencing the formation of discrete heat plumes are the distribution of deep heat source and permeable flow channels. The heat flows are varied across the base of the model in order to obtain pathways consistent with observed features of the TVZ. Spatial variations in the distribution of permeability were necessary to provide a better calibration on the highly variable surface heat discharge across the TVZ. Since the geological structures have a major control on the flow paths of heat being able to flow to the surface, the model was divided into large volume of geological units, such as calderas, faults and basement rock. However, more refinement in the rock type distributions and heterogeneity required for a better match between model results and measured data.

The final model was able to replicate the correct natural spacing of the convective heat plumes. Measured and calculated surface heat outflow values within each geothermal field showed a good match.

Temperature distribution at the deeper layers shows that between the geothermal plumes a relatively low temperature zones occur, indicating downward flows of cold recharge water. The reservoir temperatures at 3 km depth show high temperature regions for each field even though the temperature values for some of the field lower than the inferred values. For a more reasonable comparison, it is necessary to refine the gridblock size of the model, as current model only able to predict the average temperature of a very large volume.

The final model includes an air/water interface at the groundwater surface and the top of the model follows the topography of the TVZ. The surface recharge was implemented by injecting a proportion of the average rainfall into the surface blocks to represent infiltration of rainwater. However the surface recharge via rivers and lakes were not represented. This can be implemented in future development of the model.

The difference between the models constructed in this study compared to a reservoir scale natural state model is that it is a fully convective model, thus no mass injection is required over the base boundary. However Giggenbach (1995) estimated 6 – 10% fraction of magmatic water was present in the fluid circulating in the reservoir. This magmatic fluid entrance can also be represented in the model by using EWASG module of TOUGH2 to include the effect of deep saline water intrusions.

This model is only calibrated to delineate heat plume locations, inferred reservoir temperature at 3 km, and the magnitude of surface heat discharge. Surface mass discharge can also be included in the future to produce a more representative model.

A grid refinement and further calibration is required to obtain a better representation of temperature distribution including representative temperature profiles from drillhole data throughout the TVZ. Model could also be extended to deeper levels (8 – 10 km) to investigate supercritical conditions, permeability/depth/temperature relationship, and homogeneous heat distribution conditions.

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