FACTORS CONTROLLING LARGE-SCALE CONVECTIVE GEOTHERMAL SYSTEM IN THE TAUPO VOLCANIC ZONE (TVZ), NEW ZEALAND

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ABSTRACT

A review of Taupo Volcanic Zone (TVZ) geothermal fields' settings shows that most systems share the same general characteristics, some of which include: low topographical terrain, river/lake systems proximity, a capping structure and a highly fractured zone. In a number of cases, the presence of surface water seems to be associated with the separation of the plume into two entities on either side of the body of water.

This paper aims to model typical TVZ-like geothermal systems to natural state using a single large-scale model to explore the impact of the system's internal (e.g. caprock permeability, faults) and external (e.g. cold surface water, topography) features on the geometry and location of the heat plume.

2D models developed include the total extent of the hydrological system (from the surface down to the ductile impermeable crust) and key internal and external features to evaluate if a large-scale, self-contained 2D model can account for heat patterns observed in TVZ geothermal fields. Numerous simulations were conducted using Super Critical-AUTOUGH2 to assess the qualitative impact of each parameter on the convective model of heat distribution.

1. INTRODUCTION

1.1 Background

The TVZ, located in New Zealand's central North Island, is an onshore extensional basin with active volcanism and a high heat output that induces large convective cells of hot geothermal fluids. Rising high-enthalpy fluid flows through formations of variable permeabilities before being discharged at the surface. Provided certain conditions are satisfied (e.g. impermeable formation overlying a porous and permeable formation), a geothermal reservoir will develop from which high-enthalpy fluid can be produced to the surface at sufficient flow rate to extract energy economically.

In recent years, geothermal fluids have been exploited down to a depth of approximately 3-4 km and a maximum temperature of around 350-370 ºC. As a result, many models describe the first few kilometres of the subsurface (down to 3-4 km) which encompass only a portion of the convective regime. Several high-enthalpy mass sources are therefore required and applied to bottom boundary to artificially feed the model, failing to describe the overall convective flow.

Furthermore the development of new technologies will lead to deeper and hotter resources being targeted to increase the yield of the heat extraction process. Deeper models describing the natural heat and mass flow at depth will be required. These may encompass the whole convective system from the ground surface down to the impermeable ductile crust.

The present work focuses on the controlling factors of such large-scale flow. Features commonly found in geothermal systems within the TVZ such as topography, presence of a river/lake system, fractured zone, capping structure are investigated using the super-critical TOUGH2 simulator. This allows us to assess these feature's qualitative effects on the heat distribution in the shallow and deep parts of the model.

1.2 Simulator

At the high pressures (> 225 bar) and temperatures (>370 ºC) found in deep geothermal systems, supercritical conditions may occur. To simulate these systems a reliable computer code that can handle these high temperatures and pressures is required. A modified version of TOUGH2, (a numerical simulator widely used in the geothermal industry), has been developed (Croucher and O'Sullivan 2008) that can handle supercritical fluids, and is used in this work. This simulator uses IAPWS-97 thermodynamic formulation operating at up to 800^0C and 100MPa. Its operating range is made up of four distinct regions, corresponding nominally to liquid, vapour, supercritical and two-phase pure water.

2. TAUPO VOLCANIC ZONE GEOTHERMAL SYSTEMS

The TVZ is region of active continental extension with enhanced volcanic and geothermal activity, located in the North Island, New Zealand. It occupies a narrow band 350 km long and 50 km wide oriented SW-NE, stretching from Mount Ruapehu on the central plateau to beyond the Bay of Plenty (Figure 1).

2.1 Geothermal fields

Accompanying the high frequency of volcanic activity is an extremely high natural heat flow, which induces large convective cells of hot rising fluid; the surface manifestation of these cells are the geothermal fields. All the high enthalpy fields of central New Zealand lie within the TVZ.

Surface features occurrences and resistivity surveys have uncovered more than 20 fields (Figure 1).

Location of the geothermal fields (in red) and associated heat flow (MW) relative to the major hydrological (rivers/lakes) and structural (calderas) features are shown in Figure 1. Location of the geothermal fields in regards to the topography is presented in Figure 2.

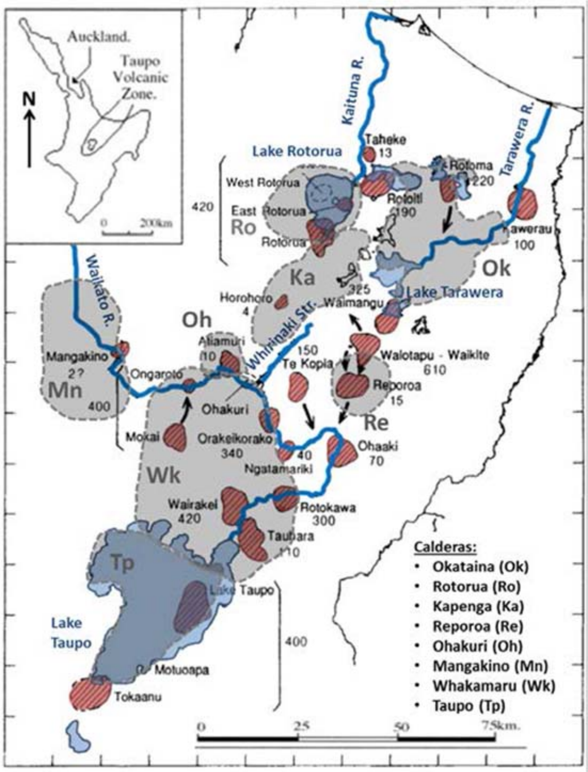

Figure 1: Locations of geothermal fields, surface hydrology and volcanic centres in the Taupo Volcanic Zone (from Bibby et al., 1995).

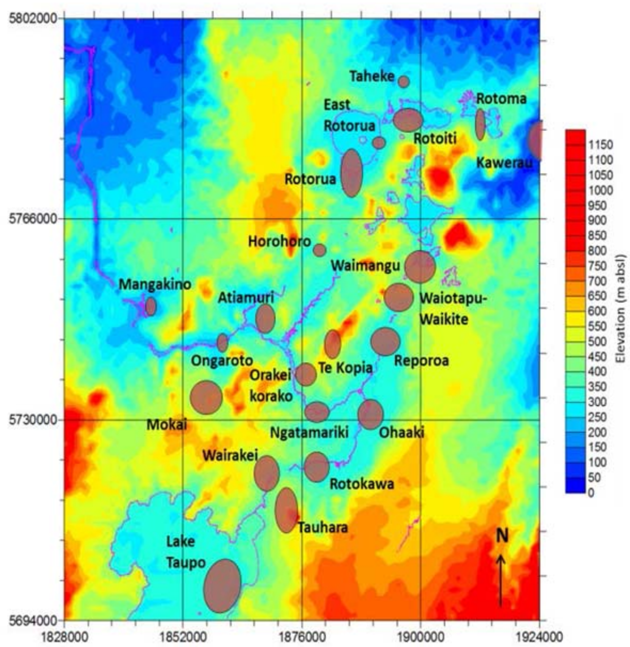

Figure 2: Surface elevation (masl) and location of the geothermal fields (from LINZ Topographic Maps)

Heat output, extent, maximum temperature recorded - which are themselves a function of the maximum drilled depth (e.g., temperatures at Atiamuri may be hotter than 165°C below 600 m depth) – proximity to surface hydrology and topography for each field are summarized in Table 1. These will be used to build and calibrate a TVZ-like geothermal system.

The criteria to describe the topography are as follows:

- Low: <350 masl
- Intermediate 350-450 masl
- High >450 masl

Table 1: Characteristics of geothermal fields in the TVZ (from Bibby et. al., 1995 and NZGA, 2013)

Field Name	Calibration variables			Features	
	Heat Output (MW)	Area (km^2)	Maximum T^oC // Depth (m)	Topo-graphy	Hydrological feature
Lake Taupo	425±175	58±11	169 // 107	Low	Lake Taupo
Tauhara	110	25±8	279 // 2400	Low	Waikato River
Wairakei	420	25±4	271 // 2200	Low	Waikato River
Rotokawa	300	18±4	320 // 2500	Low	Waikato River
Ohaaki	95±5	14±2	310 // 2400	Low	Waikato River
Ngatama- riki	40-50	7-11	290 // 3373	Low	Waikato River
Orakei korako	340-660	9-14	265 // 1140	Low	Waikato River
Atiamuri	10	8±2	165 // 600	Low	Lake Atia-muri
Mokai / Ongaroto	400±160	14±4	326 // 2000	High	-
Mangakino	4	8±4	254 // 3192	Low	Waikato River
Te Kopia	125-250	11-15	240 // -	High	-
Reporoa	15	12-15	230 // 1500	Low	-
Waiotapu	610	18-24	>295 // -	Low	-
Horohoro Springs	4	4±3	160 // 500	Low	Waikato River
Waimungu	325±80	20-26	250-290 // -	Interme diate	Lake Roto-mahana
Rotorua	470±50	30±5	200 // 200	Low	Lake Rotorua
Taheke	13	2-4	-	Low	Okere Inlet
Tikitere-Rotoiti	15±5	190	140-190 // -	Low	Lake Rotoiti
Rotoma	220±60	20±5	250 // 1500	Low	Lake Rotoma
Kawerau	84-210	18-36	310 // 2100	Low	Tarawera River

Figure 1 and Figure 2 and Table 1 highlight that geothermal fields are primarily located next to a surface water systems (Waikato River, Lake Taupo, Lake Rotorua, and Tarawera River), in low elevation terrain and in highly fractured areas (calderas' verge). The importance of such parameters will be discussed in the following section for further model testing.

2.2 Key Parameters influencing the shape of the geothermal plume

Fields in the South-West of the TVZ are located in low elevation terrain on either side of the Waikato River (e.g. Wairakei-Tauhara, Rotokawa, Ohaaki and others). Other fields such as Mokai are located in high terrain and have little surface manifestation above the upflow zone. These observations led to the study of the causal relationship between topography/surface hydrography and surface manifestations /upflow zone.

Examples of TVZ fields will be used to discuss key features shared by most fields. As we show later, these features have a direct impact on the mass and heat distribution.

2.2.1 Surface hydrology and temperature

The Ohaaki geothermal field is located to the northeast of the Taupo Township. It extends on both sides of the Waikato River. Drillhole temperature at a depth of 500m shows a drop from 250°C to 200°C on each side of the river (Figure 3). Resistivity and magnetotelluric (MT) surveys and wellbore temperature data suggest that the plume parting originates at depth (Christenson et al. 2002). This phenomenon may have two possible explanations:

1. A structural origin: faults provide pathways for the fluid from depth to both sides of the Waikato River (Ohaaki and Broadlands faults) resulting in two distinct upflow zones.
2. A hydrological origin: density difference between the Waikato River, cold surface water (≈10°C) and the hot rising fluid (>100°C) may cause the cold surface water to percolate down into the reservoir leading to the temperature discrepancy.

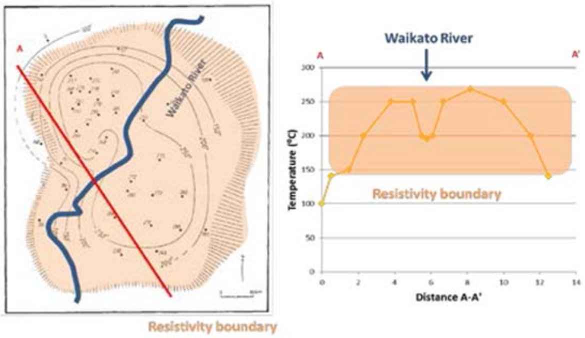

Figure 3: Resistivity boundary and drillhole temperature distribution at a depth of 500m at Ohaaki (from Bibby et al., 1995).

The effect of faults on geothermal mass and heat flow has been widely examined. However the effect of such cold surface body of water has not been studied thoroughly. The importance of this effect will be examined to assess if it can effectively separate the plume into two parts at the observed depth (i.e., whether the surface hydrology drives the system or there are two individual up-flows).

2.2.2 Topography

The Mokai geothermal field is located about 25 km northwest of the Taupo Township, at an elevation of ≈500 masl and has only minor thermal surface manifestations. The largest spring is located 5 km north on the banks of the Waikato River (Ongaroto) at an elevation of approximately 250 masl (Figure 4).

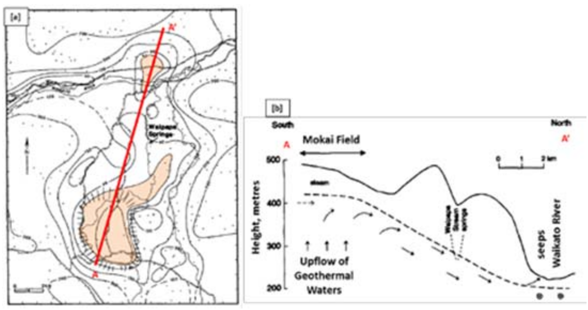

Figure 4: Subsurface drainage of geothermal fluids from the upflow zone, towards the Waikato River. [a] Resistivity map. [b] Cross section of the conceptualised fluid flow (from Bibby et al., 1995).

Resistivity measurements show a low resistivity extending from the Mokai settlement towards the Waikato River, linking the inferred upflow zone to the spring (Bibby et al., 1995). The height of the water column and thus the hydrostatic pressure is higher in elevated terrain (Mokai) which "directs" the geothermal fluid toward low topographical terrain (Ongaroto).

2.2.3 Faulting

Most fields are known to be highly faulted (e.g. verge of calderas or within the Taupo Fault Belt). These faults may act as the preferential pathway for the fluid from the deeper part of the TVZ to the surface and their importance will be tested in this work.

2.2.4 Caprock

The production zone at the Wairakei field is capped by the low permeability Huka Falls formation. It is characterised by liquid surface discharges (geysers and hot springs) in the Geyser and Waiora Valleys. Outside the production zone, in the southern part of the field (Karapiti area) such a capping structure is absent and steam discharge features are found (Clearwater, 2010). The presence of a caprock affects the nature of surface manifestations and is linked to the establishment of a geothermal reservoir. The capping structure above each geothermal reservoir traps hot rising fluid at depth and acts as a barrier from cold groundwater.

2.3 Heat and Mass Flow in the Taupo Volcanic Zone

2.3.1 Heat source

Geothermal systems draw on the heat from a wide area extending beneath much of the TVZ and rise as plumes of hot geothermal fluid (Bibby et al. 2009). The heat is believed to originate from conductive cooling of high temperature rocks at lower levels in the crust. There is however no widespread agreement as to the origin of the heat supply (Rowland et al. 2010). Magnetotelluric and seismic surveys both identified at about 15 km deep reductions in resistivity respectively increases in the velocity models indicating that a portion of melt exists within the rock matrix (Bibby et al. 2009 and Rowland et al. 2010). These are interpreted as heavily intruded lower crust or anomalous mantle which would account for the heat source (Bibby et al. 2009 and Rowland et al. 2010). However these depths are beyond what is being modelled in this work. Instead a simple overall representation of the heat anomaly is used.

2.3.2 Fluid circulation and origin

Bibby et al. (1995) demonstrated that almost all the geothermal fluid is discharged at the surface. This observation leads to the conclusion that an external fluid recharge is necessary to feed the system. Isotopic studies (mainly δD and $\delta^{18}O$) conducted for numerous fields have concluded that the deep geothermal water has primarily a meteoric origin (of small magmatic input) (Dempsey, 2012). This implies a convective circulation of meteoric water that percolates from the surface to the deeper part of the TVZ where it is then heated and rises to the surface.

The depth in the crust to which groundwater can circulate within the crust is determined by temperature gradient, lithology, water content and strain rate. These factors control the depth of the transition zone between a brittle state which can support fracturing (and therefore permeability) to a ductile state where pore pressures are lithostatic which reduces its ability to support fluid flow. The brittle-ductile transition coincides with the base of the seismogenic zone which can be estimated by the cut-off depth in seismicity of around 8.0 km (Bibby et al. 1995).This depth is considered to be the lower limit for hydrothermal fluid circulation within the TVZ. The lower boundary of all the models presented in this work is therefore set at 8.0 km depth.

The total volume of water discharged at the surface from all the TVZ geothermal fields – corresponding to the recharge required from meteoric water –comprises about 2% of the total rainfall in the region (Kissling, 2004). It is assumed then that sufficient water is available at the surface to supply the geothermal systems. This has an implication for the choice of boundary condition on the upper boundary of the model. The upper boundary can be assumed to consist of fully saturated liquid water, because the precipitation rate is much greater than the infiltration rate into the deep TVZ.

3. MODEL DESCRIPTION

3.1 Conceptual model

A conceptual 2D model was built which reflects the structure and physical processes of the system. Meteoric waters percolate down on each side of the model from the surface to the brittle ductile transition depth (Figure 5). Fluid is then heated by a heat source located in the centre of the model. This reduces fluid density and induces buoyancy driven upflow through a fracture network to the surface where it is discharged. It was assumed that the following parameters are most likely to have a major influence on the heat and mass flow of a TVZ-like geothermal system:

1. Cold surface body of water
2. Topography
3. Faults
4. Caprock permeability

The importance of these parameters is investigated in the numerical modelling undertaken in this work.

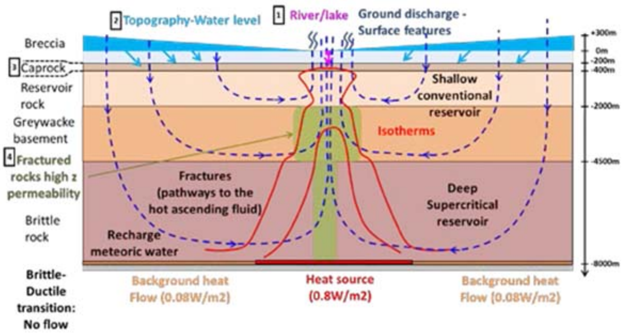

Figure 5: Conceptual model of an idealised TVZ geothermal system.

3.2 Geological settings

Geophysical studies using gravity, seismic or MT, have contributed in determining the structure and geology of the TVZ. A broad region of low density volcanic infill, up to 2.0 km deep, overlying a denser greywacke basement has been identified. From the data available, a simplified overall stratigraphy for the first 8km of crust is assumed and implemented in the model (Table 2).

A ratio between horizontal and vertical permeability of 1:5 was chosen as it has shown a stability increase in the model simulations. For the fault rock types this anisotropy is not implemented as enhanced vertical permeability seems appropriate for faults.

Table 2: Rock properties

Rock type		Depth [km]	(x, y) Permeability [10-15m2]	(z) Permeability [10-15m2]	Porosity
Volcanic infill	Breccia	Atm 0.20	50	10	0.15
	Caprock	0.20 0.40	0.1	0.2	0.10
	Reservoir Rock	0.40 2.0	7.5	1.5	0.15
Basement	Greywacke	2.0 4.5	2.5	0.5	0.10
	Upper Fault		1.2	1.2	0.15
	Brittle Rock	4.5 8.0	0.5	0.1	0.05
	Lower Fault		0.2	0.4	0.15

The following properties were applied to each formation, conductivity of 1.5 W/m°C, specific heat of 1100 J/kg °C and density: 2650 kg/m^3.

3.3 Model Domain

In choosing the model dimensions, several criteria were considered:

- A large horizontal dimension in order to account for the cold recharge from outside the resistivity boundary into the reservoir. This also allows us to explore a range of topographic settings and surface features.
- The convective circulation depth is known to be approximately 8.0 km. Therefore the model was required to match this depth.

The primary difference between this study and many other models of geothermal systems is the lateral and vertical extent of the simulated region. The model encompasses the whole convective regime; no artificial injection of mass is required at the bottom boundary. The model is therefore mass-conservative and should be able to produce the correct overall convective flow. This enables better understanding of the controls on the large-scale circulation. It also allows investigation of the deep high-enthalpy reservoir (> 3.0 km deep), which might be targeted in the future.

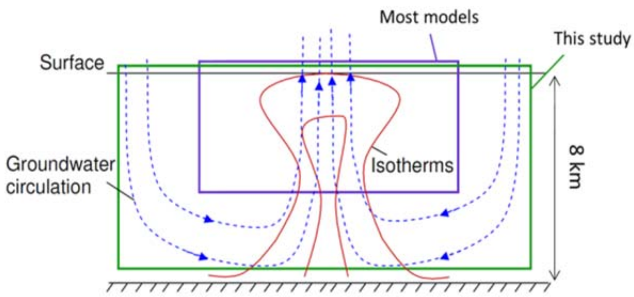

Figure 6: Model domain.

The 2D model developed for this study has a regular grid (200m × 100m) consisting of 100 columns and 80-85 layers (topography dependent). The total horizontal extent is 20 km and the depth is 8 km. The total number of blocks is between 8000-8500. The topography can vary from +300m on the side of the model to 0m in its centre.

4. BOUNDARY CONDITIONS

As discussed in Section 1.2.2, a fully saturated model is implemented (Figure 7). The top surface of the model is set at the groundwater level and fixed to atmospheric pressure. Therefore fluid may leave or enter in response to any pressure changes within the model.

The vertical sides of the model are closed (impermeable) boundaries. This is based on the assumption that the whole large-scale convective system has been captured within the boundaries of the model.

Heat fluxes are applied to the bottom boundary of the model, which represents the general background heat flux as well as the central heat flow anomaly accounting for the deeper TVZ heat source.

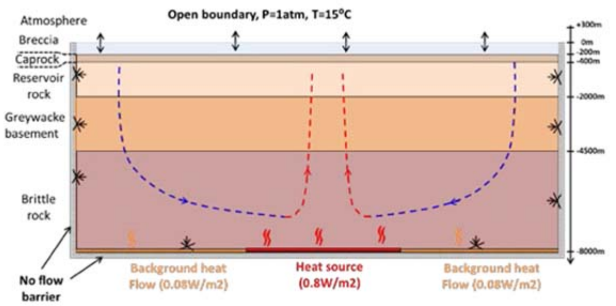

Figure 7: Boundary conditions.

5. NATURAL STATE MODELING RESULTS

The focus of this work is to develop undisturbed, natural-state geothermal circulation models. This is the preliminary stage of geothermal reservoir modelling, prior to history matching and forward modelling – the exploitation stage. To reach a steady state, the simulation is run until primary variables (pressure, temperature, and density) are no longer changing. The natural-state model will be used qualitatively to match a wide range of observations. In doing so, it will provide insight into factors that control subsurface mass and heat flow in geothermal settings.

5.1 Base Model

As an initial condition, we applied a uniform heat flux of 0.08W/m² to the base of the model. This resulted in a vertical temperature gradient of 30°C/km and a conductive heat transfer regime.

For the base case model, a heat anomaly is implemented at the lower boundary to represent a magmatic heat source. Heat flux, permeability structures and fault structures were adjusted until temperatures approximated TVZ geothermal fields. The best matches to temperatures were found with a heat source of 0.8 W/m^2, a permeability structure presented in Table 2 and a single vertical fault (Figure 8) and will be used as the base model. It is worth noting that the heat flux of 0.8 W/m^2 corresponds closely to the transfer rate estimated by Hochstein for the TVZ (Hochstein, 1995).

A convective regime was observed with the formation of a plume of hot geothermal fluid rising to the surface in the center of the model (Figure 8). The system exhibits general characteristics of a TVZ-like system at shallow depth as described in the literature:

- Temperature ranging from 180°C to 300°C in the geothermal reservoir (400m-2.5km).
- Low temperature gradient inside the plume 10-15°C/km (280°C at 800m 300°C at 2.5km).
- Surface discharge of a fluid at 100°C upright of the geothermal plume.
- The width of the plume increases with depth as the permeability reduces.
- Sharp temperature boundary between the plume and the surrounding groundwater maintained by the dynamics of the convective regime (advection of cold fluid into the column).

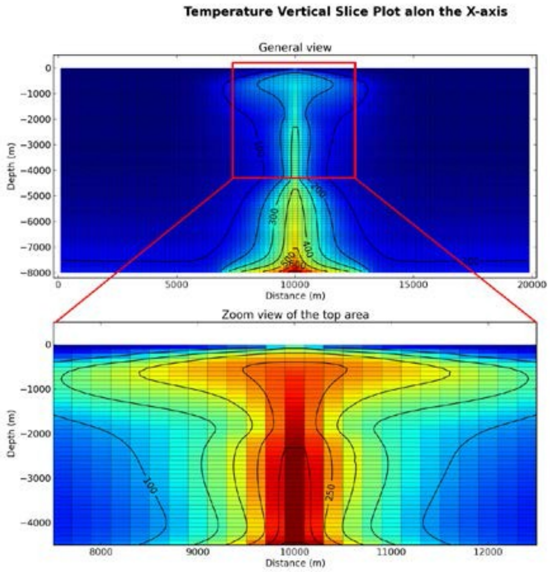

Figure 8: Base model. Temperature distribution.

Three fault structures were implemented to assess its importance as conduits for the rising geothermal fluid.

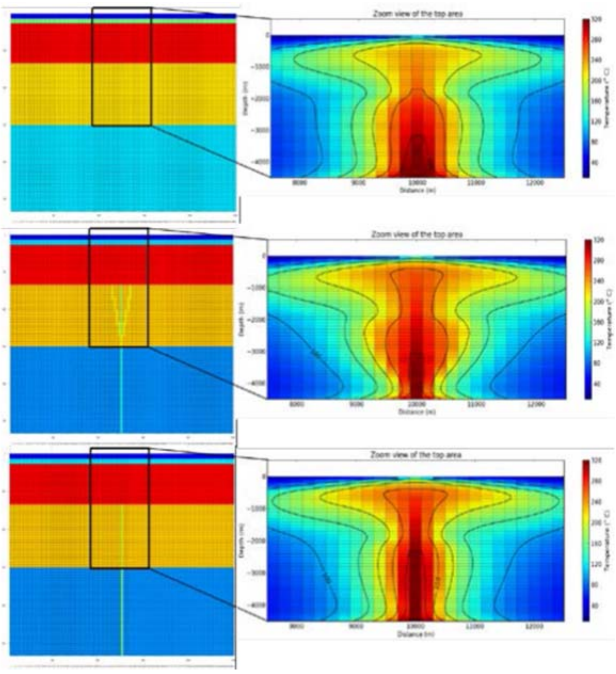

Figure 9: Base model. Faults impact on the temperature distribution

Figure 8 shows that when faults are implemented the temperatures inside the geothermal reservoir at a depth of 800m increases from 240°C (no fault) to 268°C (Tri-fault) or 280°C (Single fault). Furthermore the horizontal extent of plume in the shallow reservoir (T>180°C) increases significantly. Therefore, having a deep fault connecting the deep to the shallow reservoirs is paramount to model appropriate reservoir temperature and extent.

5.2 Other simulations

Specific features, such as a surface body of water, topography settings and various cap rock permeability were added to the base model and compared to the base-case scenario to explore the effects on plume temperature and geometry. These scenarios are presented in Table 3-5.

Table 3: Symmetrical model scenarios (Models 1-2)

Surface water (depth)	0m	20m	50m	80m	120m
Flat	**Model 1.a**	**Model 1.b**	**Model 1.c**	**Model 1.d**	**Model 1.e.**
Topography	**Model 1.f**				
Features	Caprock k_z =0.2mD	Caprock k_z =0.6mD	Caprock k_z =1.5mD		
Flat	Model 2.a	Model 2.b	Model 2.c		

5.2.1 Effect of a cold surface body of water

The surface body of water is implemented by excavating the appropriate depth (h) from the top layer and applying the hydrostatic pressure corresponding to the depth of the surface water. That is:

$$P = P_0 + \rho \, g \, h,$$

where P_0 is the atmospheric pressure, ρ is the water density at 10°C, g is the gravity acceleration equal to 9.81 m/s^2, and h is the body of water depth.

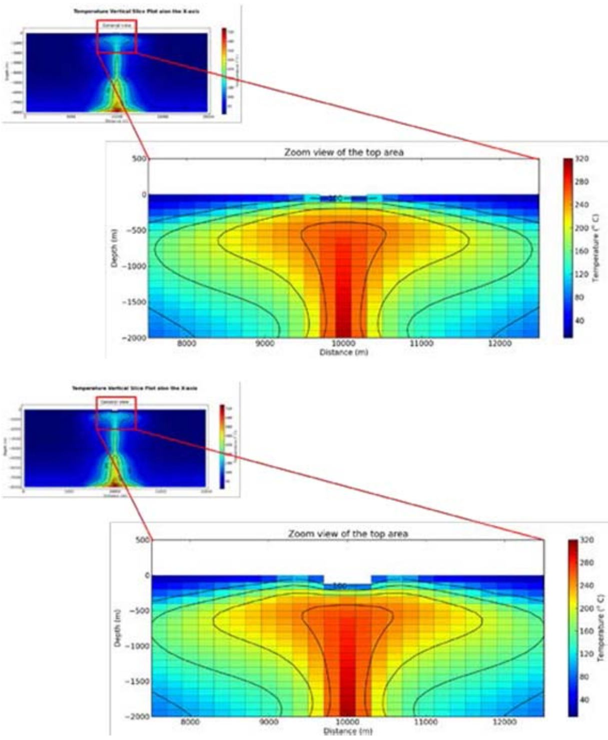

Figure 10: Effect of cold surface body of water [a] Model 1 b. [b] Model 1.e

The effect of the surface cold water body increases with its depth. However its impact is limited to the first few hundred metres (500 m maximum). Below this depth the presence of surface water has no significance (Figure 10).

The Waikato River does not seem to have a role in the creation of two upflows, as observed at Ohaaki. Faulting, local topography or some combination of the two may play a dominant role in this regard (Rissmann et al. 2011).

An alternative hypothesis is that the vertical permeability of the caprock implemented in this model may be too low and prevent the downflow of cold water into the reservoir. Various vertical permeabilities will be tested in Model 2 (2.2.4).

5.2.2 Effect of centered topography

A centered topography ranging from 300 m to 0 m is set as described in Figure 11.

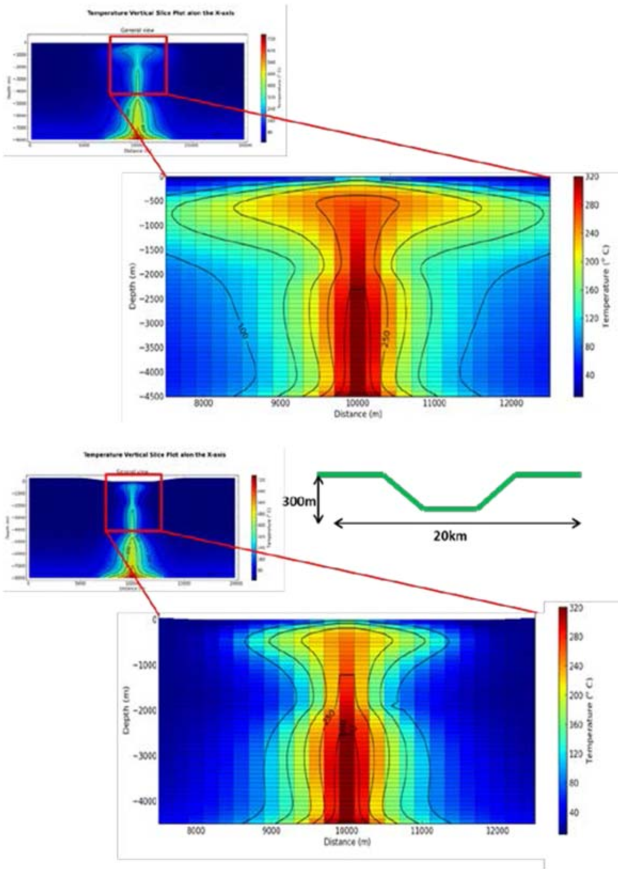

Figure 11: Effect of a symmetric topography [a] Model 1.a. [b] Model 1.f.

Topography impacts the horizontal extent of the geothermal reservoir. An increase of pressure on each side of the model caused by a higher water table induces a cold side flow of water into the reservoir (Figure 11). This results in a narrower surface expression of the geothermal field.

5.2.3 Effect of the cap rock

Three different values of vertical permeability (Table 3) are tested to assess the impact of the caprock on the geothermal reservoir and the infiltration of the cold surface water.

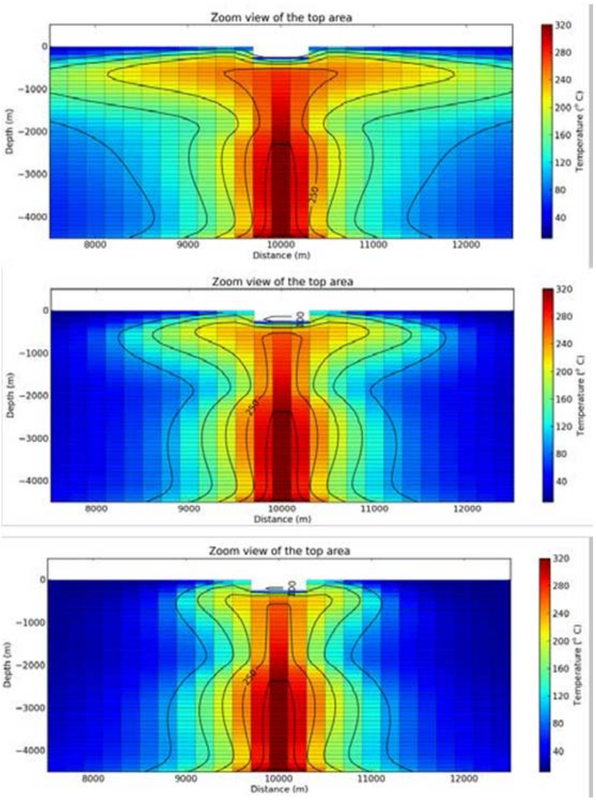

Figure 12: Model 2 a-c. Caprock permeability impact.

The vertical permeability of the capping structure controls the extent of the shallow reservoir. The higher the permeability within the cap rock, the smaller the reservoir (Figure 12).

In Figure 12, we show that the lack of a caprock structure does not increase the depth to which the cold water percolates. The density difference between the cold surface water and the geothermal fluid is not sufficient to overcome the pressure of the rising fluid. Therefore regardless of the capping structure the presence of a surface body of water only affects the near subsurface and does not influence the plume geometry at a greater depth.

5.3 Asymmetric simulations

5.3.1 Effect of an asymmetrical surface water

The effect of the location of a cold surface body of water was investigated by shifting horizontally its location (Table 4). Two sets of simulations were conducted using a body of water of respectively 20m and 120m deep.

Table 4: Asymmetrical surface water scenarios (Models 3-4)

Surface water location from model centre		+400m	+1000m	+2000m
Depth	20m	**Model 3.a**	Model 3.b	Model 3.c
	120m	**Model 4.a**	Model 4.b	Model 4.c

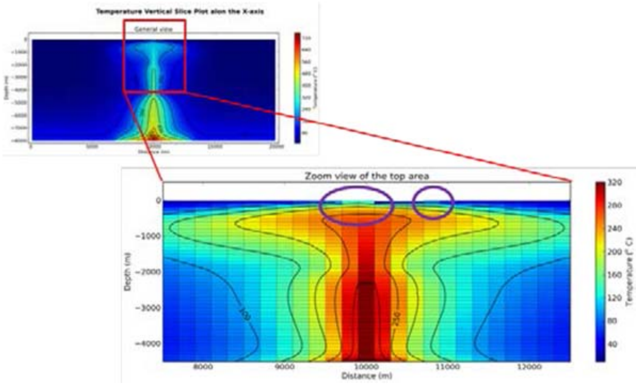

Figure 13: Model 3.a. Effect of a shallow body of surface water on the location of surface features. The surface features (purple circle).

- Very slight shift of the main surface features location to the left (100-200m).
- A main zone of surface discharge is located on the left hand side of the model (closest to the upflow) and a minor zone on the right hand side.
- The heat distribution of the upflow is not affected by the surface water.

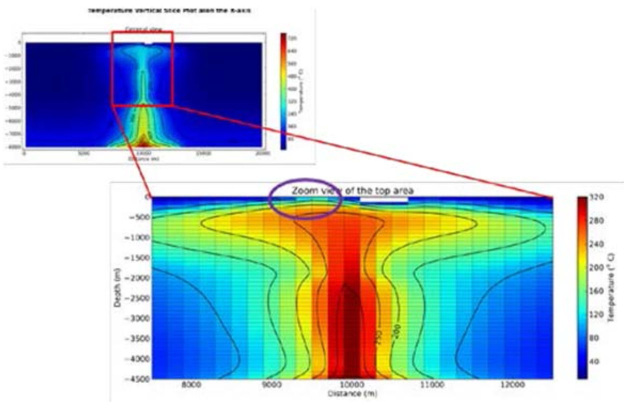

Figure 14: Model 4.a. Effect of a deep body of surface water on the location of surface features (purple circle).

- Shift of the main surface features location to the left (400-600m).
- A single zone of surface discharge is located on the left hand side of the model (closest to the upflow).
- The geometry of the upflow is slightly affected by the surface water (down to a depth of ≈2000m).

The presence of a surface body of water has an effect on the near surface temperature distribution and surface features location. There is a strong correlation between depth of the surface body of water and lateral displacements of surface features and shallow plume geometry. An effect is observed only if the surface cold water is located within 2000m upright of the vertical plume. Therefore both the depth and the location of the surface water control shallow heat distribution.

5.3.2 Effect of an asymmetrical surface water

The impact of an asymmetrical topography with 20m deep river is then investigated (Table 5).

Table 5: Asymmetrical topography scenarios (Models 5)

Centre (x axis)	10000	10400	11000	12000	16000
Topography	Model 5.a	Model 5.b	Model 5.c	Model 5.d	Model 5.e

Topography has a significant influence on the heat distribution and plume location in the shallow and intermediate part of the system that is 500 – 4000m deep (Figure 15).

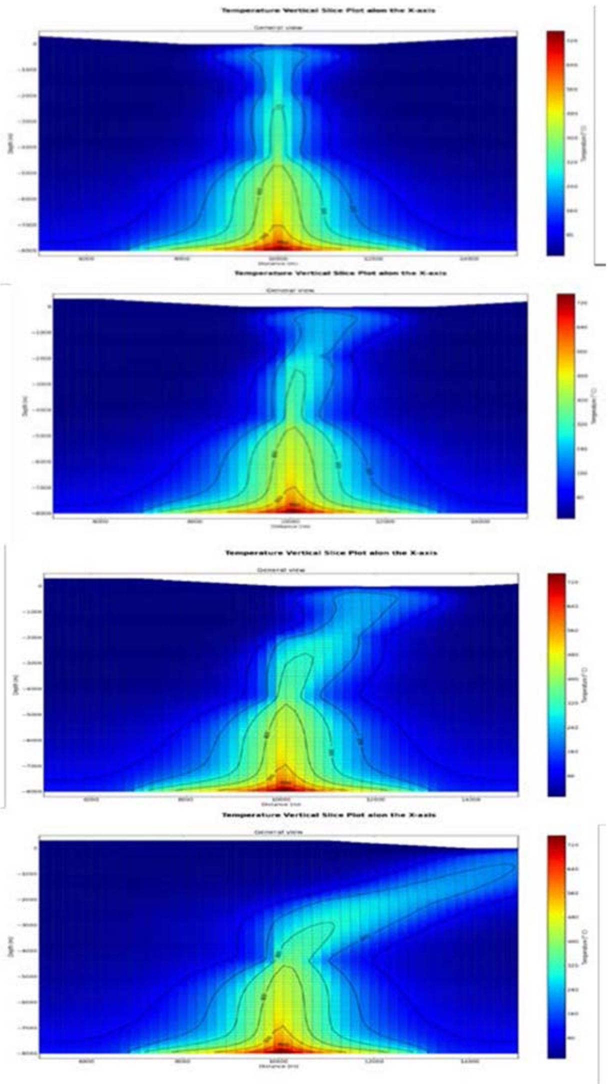

Figure 15: Model 5 b-e. Effect of the topography on the plume geometry

If the heat source is not upright of the low topographical terrain, the rising plume will be progressively displaced toward the low terrain. The geothermal fluid will breach the surface a few kilometres from the up-flow much like what is observed at Mokai. The topography will control the depth and the distance of the displacement.

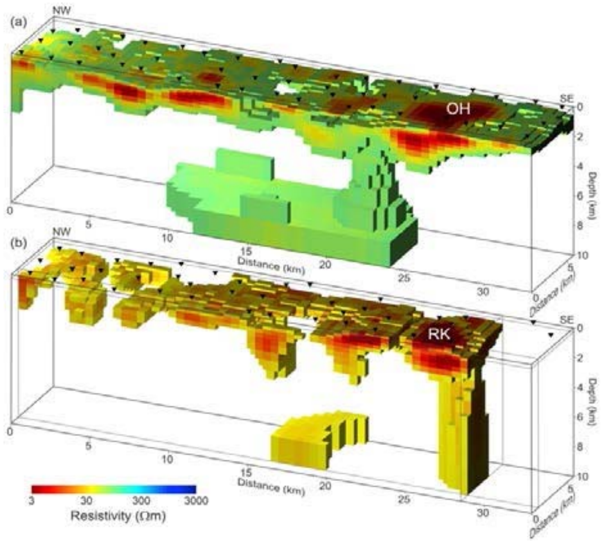

Figure 16: 3-D models of the full MT impedance tensor data (Rotokawa, Ohaaki) (from Bertrand et al. 2012).

3-D inversion models of Broadband magnetotelluric data published in 2012 show vertical low-resistivity zones. They connect surface geothermal fields to inferred heat sources that lie below the brittle-ductile transition (Bertrand et al. 2012). Figure 16 shows 3-D models of the full MT impedance tensor data through Ohaaki and Rotokawa. Resistivity cut-off is used to permit a 3-D view of the vertical Rotokawa and offset to the northwest Ohaaki low-resistivity plumes that connect to the surface geothermal fields.

Similarities between these 3D inversions of MT data and the simulations results are observed (Figures 15-16).

First, increases of the width of the plume with depth are observed in both MT models (Ohaaki and Rotokawa) and in our models.

Second, two configurations appear in the resistivity structure:

- The Rotokawa field (RK) which is analogue to Model 5.b
- The Ohaaki field (OH) which has a similar profile than Model 5.c-e

Although Rotokawa and Ohaaki are both located in low elevation terrain and astride the Waikato River, they have a different resistivity patterns. The heat distribution at Ohaaki could be caused by the lateral offset of the heat source relative to the low topographical terrain which would induce a displacement of the plume toward the low elevation terrain. Phenomenon not observed at Rotokawa if the deep geothermal plume is directly upright of the low elevation terrain.

6. CONCLUSION AND FUTURE WORK

This study explored simulations of large-scale convective hydrothermal circulation for a typical TVZ geothermal field. The entire flow system was encompassed, from the deep supercritical area to the shallower zone. The simulations are consistent with what is described in the literature.

The simulations conducted provide the following conclusions:

- Vertical faults through the (Greywacke) basement and the underlying "brittle" formation are essential to obtain temperatures encountered in geothermal reservoirs.
- Low permeability in the caprock overlying the reservoir formation is an essential prerequisite to the formation of a geothermal reservoir, but is not required to prevent ingress of cold-water from surface hydrological features (e.g., lakes, rivers) into the reservoir.
- Topography controls the large-scale flow of geothermal fluids and offers a relatively close match to observation. For instance, Model 5 b. and
- d. match respectively MT 3D inversion models at Ohaaki and Rotokawa.
- Surface hydrology does not show a significant effect on the plume geometry. However, it does influence to some extent the location of surface manifestations.

Future work will involve implementing more complex fault structures. These could provide the geothermal fluids with different pathways to the surface and result in two upflows within the geothermal reservoir. Furthermore different heat source configurations could be tested to assess their influence on the circulation system.

Ultimately, we wish to apply the model to real field data for validation. Such a model will incorporate site-specific permeability distribution, caprock location and thickness, fault network. It will also contain information on surface features, e.g., topography, hydrology, as well as downhole temperatures necessary to calibrate the model.

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