LATERAL TRANSPORT OF DEEP HOT FLUID AT OHAAKI

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ABSTRACT

Recent MT data suggest that the deep heat source which feeds the Ohaaki geothermal system in the Taupo Volcanic Zone (TVZ) in New Zealand is offset laterally by several kilometers from the shallow low resistivity area that marks Ohaaki geothermal field.

We use numerical modelling to demonstrate that lateral flows of several kilometres are possible with permeabilities which are typical of structural units found in TVZ geothermal fields.

1. INTRODUCTION

In a regional scale model of the TVZ-wide hydrothermal system (Kissling & Weir, 2005), the deep inflows of hot fluid into the TVZ geothermal systems were buoyancy-dominated and, because of the lack of deep geological control in the model, the fluids rise vertically from an underlying and widespread hot zone at depth (Bibby et al., 1995). While geological controls were known to exist in the shallow regions of many geothermal systems, for example the low permeability capping structures that occur at Rotokawa (McNamara et al., 2015), it was not practical to include these in regional scale numerical fluid flow models at the time.

Recent MT observations (Heise et al., 2016, Bertrand et al, 2015) suggest a closer (shallower) relationship between the geothermal systems and their underlying heat sources than was envisaged by Bibby et al. (1995). For example, conductive MT bodies, interpreted as crystallising magma are seen at depths > 3 km at Rotokawa, Ngatamariki, Rotorua, Waimangu and Ohaaki. A striking and distinctive feature of the body at Ohaaki is that it is offset by several kilometers from the shallow low resistivity anomaly of the geothermal field. In other systems (e.g. Rotokawa) the conductive body is vertically below the geothermal system or in some cases even appears to be entirely absent (e.g. Te Kopia, Orakei-Korako).

The question addressed in this paper is whether it is possible to displace a buoyancy driven flow far enough from a vertical path above its heat source to explain the MT resistivity model of Ohaaki, given our knowledge of the geological structure and reasonable estimates of the permeability in each of the significant geological units in the system.

2. OHAAKI GEOTHRMAL SYSTEM

Located near (~5 km) to the south-eastern rift margin of the TVZ, basement greywacke dips northwest beneath the Ohaaki Geothermal Field from depths of ~1 km in the southeast to more than 2 km in the northwest (Clotworthy et al., 1995) (Figure 1). Although the basement rocks directly beneath the field are high-temperature (300 °C) (Brockbank and Bixley, 2011), they have high electrical resistivity (Bertrand et al., 2013) and insufficient permeability to support fluid production. However, immediately above the basement is the Waikora Formation, an inclined layer of greywacke gravels that we postulate here acts as the permeable conduit for the deep upflow at Ohaaki (see Figure 4). Using broadband (0.01 – 1000 s) array MT data measured in the south-eastern TVZ at 2 km spacing, Bertrand et al. (2012) imaged a low-resistivity zone in the basement rocks that is offset to the northwest with respect to the shallow field boundary as defined by DC resistivity surveys (Risk et al., 1977) and surface features (Figure 2). This deep low-resistivity zone, located on the margins of the low-gravity Mihi volcanic depression (Soengkono, 2012), at the inferred southern margin of the Reporoa Caldera and near to the town of Golden Springs, is inferred to mark a zone of crystallising magma in the basement greywacke (Bertrand et al., 2015), representing the deep source of heat that supplies the Ohaaki Geothermal Field.

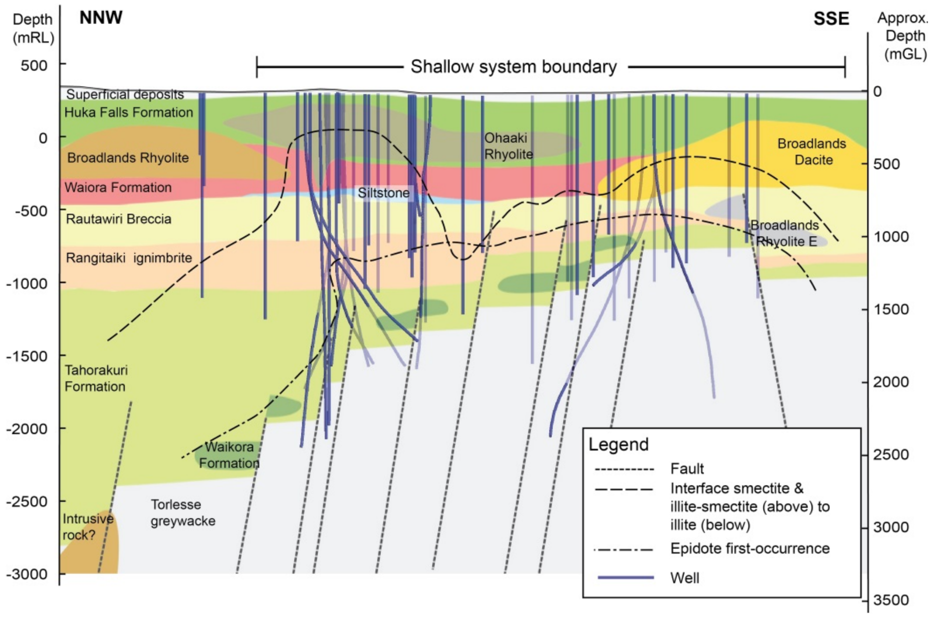

Figure 1: Geological cross section of the Ohaaki Geothermal Field, taken from Mroczek et al. (2016).

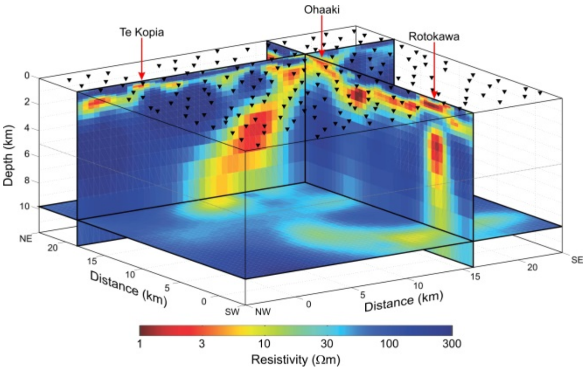

Figure 2: Fence-diagram of the 3-D resistivity model (from Bertrand et al., 2015) that shows a deep low-resistivity zone offset to the northwest from the Ohaaki Geothermal Field. MT site locations are shown by black triangles.

This 3-D MT resistivity model was combined with geophysical (resistivity and gravity) and with drilling results (geology and geochemistry) from more than 70 wells at Ohaaki to advance the conceptual reservoir model of the Ohaaki geothermal system (Mroczek et al., 2016). This refined conceptual model includes a major deep liquid upflow in the northwest marked by this basement low-resistivity zone (Figure 3). A low-resistivity connection to the shallow geothermal field approximately follows the interface between volcaniclastic rocks that overlie the greywacke basement (ie the Waikora formation) and requires ~4 km of lateral flow, which is the subject of this research.

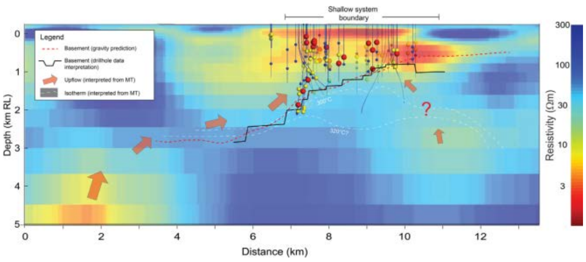

Figure 3: Cross-section through the 3-D resistivity model of Bertrand et al. (2015) along the profile line in Mroczek et al. (2016). Basement greywacke (black line), temperature contours (white dashed line) and well feedzones (red, yellow and blue dots) are shown. Arrows indicate inferred paths of fluid flow.

3. FLUID FLOW MODELLING

3.1 Modelling Code

For this study we have used a heat and water transport modelling code called TGNS (Kissling, 2014). TGNS is an implementation of a standard fully implicit finite-volume method for time-dependent multi-phase flow in porous media and shares many algorithmic features with the well-known code TOUGH2 (Pruess, 1991). To be more specific, TGNS solves the equations for mass (water) and energy (heat) conservation in a porous medium. Fluid transport is described by Darcy's law, where the fluid mass flux is proportional to the local pressure gradient, and the energy flux is given by the sum of advection and heat conduction terms.

3.2 Model description and assumptions

The simplified model of Ohaaki used in this paper is intended to test the idea that the permeability structure can displace a rising convection plume of geothermal fluid several kilometers laterally. The following simplifications have been made:

- The model domain (Figure 4) is 2-D, and aligned to cross the Western and Eastern banks of the Ohaaki geothermal system. The model domain corresponds to the cross-section used in Figure 1 of Mroczek et al. (2016).
- The fluid in the model is pure liquid water, with no CO_2.
- We represent the geology of the Ohaaki geothermal system with just five distinct geological units.

A schematic of the model domain is shown in Figure 4. This extends vertically from +250 mRL to -3250 mRL, and horizontally over 12,500 m so that it extends well beyond the shallow resistivity boundary of the geothermal system. It also encompasses the inferred location of the deep source of hot fluid in the north-north-west.

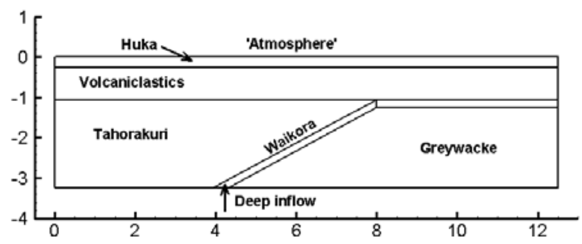

Figure 4: Model layout, showing simplified structure of the Ohaaki geothermal system with just five distinct geological units. As indicated, 300°C fluid is injected into the Waikora Formation at the lower boundary. The scales are labeled in kilometers.

To simplify the calculation, the upper boundary of the model is held at fixed conditions of 10 bar and 20°C. This over pressured 'atmospheric' boundary condition reduces the possibility of boiling at shallow depths, which slows the calculation significantly.

The lower boundary of the model is located largely within the low permeability greywacke and Tahorakuri Formation. No flow of fluid is permitted across this boundary, except at the location where the conduit formed by the permeable 200 m wide Waikora Formation intersects the boundary. This is at a position (X = 4 km in Figure 4) consistent with the centre of the resistivity anomaly at -3000 mRL derived from the MT inversion (at approximately X=9 km in Figure 3). Hot fluid is assumed to enter the system through the deeper Waikora Formation, and is accordingly injected into this formation at a rate and enthalpy consistent with data for the natural heat flow at Ohaaki summarised in Bibby et al. (1995). In the 2-D setting used here the fluid injection rate is 4 kg/s/100 m at a temperature of 300°C.

The lateral boundaries of the model are held at 'warm hydrostatic' conditions corresponding to a vertical temperature gradient of 50°C/km.

The model uses an unstructured computational mesh with polygonal-shaped elements. This allows the model definition to be increased in areas where extra detail is required or significant physical processes need to be resolved. In the present model the largest elements are approximately 250 m in extent, but the mesh is refined within the Waikora Formation so that the smallest elements are ~30 m across. There is a smooth gradation of element sizes between these limits to reduce numerical errors.

The absence of significant (caldera forming, ignimbrite depositing) volcanism in the Ohaaki region of the TVZ in the last 0.34 Ma (e.g. Wilson et al., 1995) means that it is reasonable to use a fixed geological structure in the model provided the simulation time is shorter than this. All models were run for a period of 100 kyr, and the resulting temperature distributions are close to steady state.

3.3 Model parameters

The model presented here contains five distinct rock types and permeabilities (Table 1) for these have been estimated using our experience of large scale modelling of the TVZ hydrothermal system (Kissling & Weir, 2004) and modelling of individual TVZ geothermal systems for engineering purposes.

Only two of the geological units in the model, the Waikora and Tahorakuri formations, have any real influence on the lateral upflow and for this reason the other units can be classified according to typical 'order of magnitude' permeabilities. Thus the basement Torlesse greywacke and Huka Falls Formation are known to be low-permeability units (e.g. Wood et al., 2001; Mielke et al., 2016, Grindley, 1965). The greywacke is assigned a permeability of 0.001 mD, consistent with the upper limit given in Meilke et al. (2016) and is intentionally kept low to suppress any flows in this formation. For the Huka Falls Formation a permeability of 0.1 mD is used so that some hydraulic connection to the surface is maintained. For the volcaniclastics, which constitute the production reservoir at Ohaaki, we use a permeability of 50 mD, which is inferred from early interference test data (described in Grant and Bixley, 2011) and is a typical permeability for convecting geothermal systems in the shallow crust (e.g. Manning, 1999).

Table 1: Permeabilities of the geological units used in the models.

Formation	Permeability (mD)
Huka Falls	0.1
Volcaniclastics	50
Waikora	100
Greywacke	0.001
Tahorakuri	0.1,1,2,3,4,5,10

Numerical experiments show that the permeabilities of the Waikora and Tahorakuri formations have by far the most influence on how the deep fluid is transported to the surface. For models presented here we have used 100 md for the Waikora Formation permeability, and a range from 0.1 to 10 md for the Tahorakuri Formation. The Tahorakuri Formation permeability (K_T) is the only model parameter which we vary.

4. RESULTS AND DISCUSSION

The models show that there are two distinct modes of behaviour, which depend on the value of the Tahorakuri Formation permeability (K_T). Representative examples of these modes, which we label 'confining mode' and 'buoyant mode', are shown in Figures 5 and 6. The vertical scale of these figures has been set so that the aspect ratio of the actual model domain (12.5 km × 3.5 km) is 1:1. The confining mode occurs for $K_T < 2$ mD, where the flow in the Waikora Formation is largely confined within that formation, although some upward leakage occurs as K_T increases. In this case, the permeability of the overlying Tahorakuri Formation is small enough to inhibit the vertical rise of hot fluid and so confines the flow to the highly permeable Waikora Formation. In the buoyant mode, for higher $K_T > 3$ mD, the buoyancy of the ascending hot fluid is sufficient to overcome the overlying permeability and the fluid rises vertically to the surface. The two modes are shown more clearly in Figure 7, which shows temperature profiles measured along the Waikora Formation, for the range of Tahorakuri Formation permeabilities.

The models presented in this paper represent a work in progress. They demonstrate that laterally displaced hot inflows from depth such as those observed at Ohaaki can occur with sufficient geological control and plausible permeabilities found in many TVZ geothermal fields. The models do not yet reproduce other features of the Ohaaki system. For example, temperatures >300°C at 2 km depth are much more widespread in the greywacke underlying the field than these models predict. The next generation of models will aim to generate a more accurate representation of the temperature distribution beneath the field. However, we do not expect these modifications to alter the fluid flow results presented in this paper, which are primarily dependent on the permeability distribution in the model.

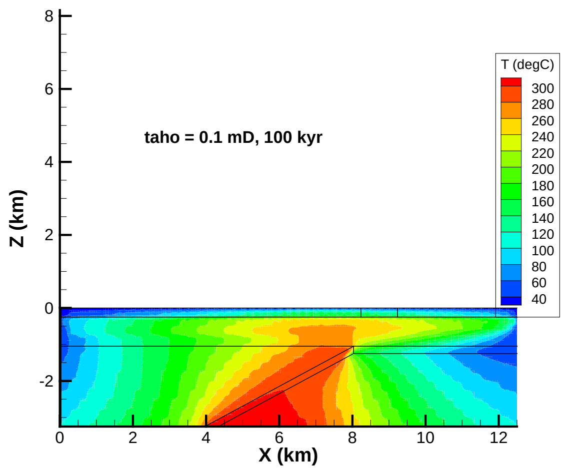

Figure 5: Temperature distribution in the 'confining mode' model with Tahorakuri Formation permeability equal to 0.1 mD. The hot upflow is largely confined within the inclined Waikora Formation and is transported 4 km horizontally from a depth of 3 km.

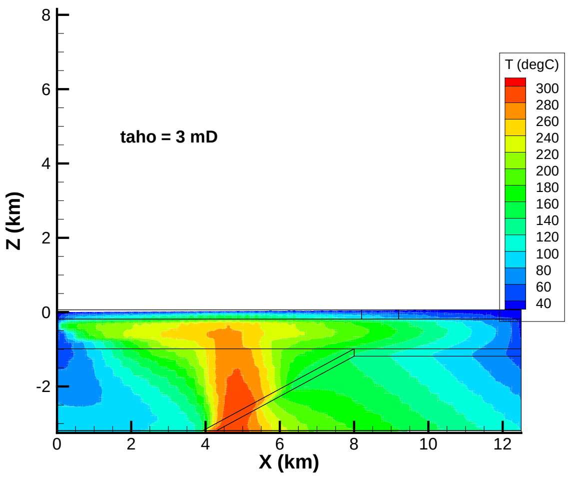

Figure 6: Temperature distribution in the 'buoyant mode' model with Tahorakuri Formation permeability equal to 3 mD. The Tahorakuri Formation permeability is sufficiently high that the hot fluid ascends essentially vertically to shallower depths because of its buoyancy.

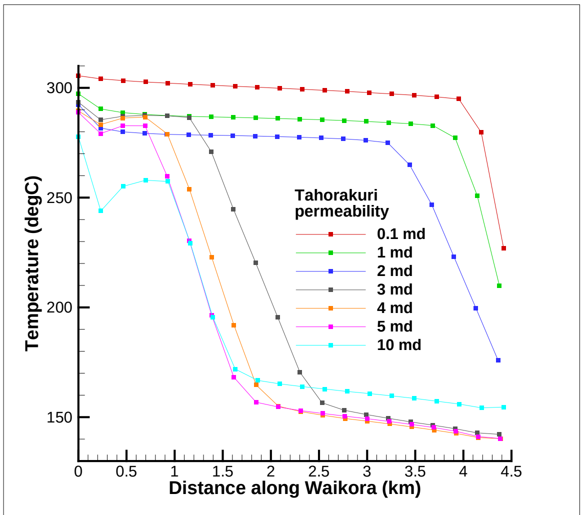

Figure 7: Temperature profiles along the Waikora Formation as a function of Tahorakuri Formation permeability. This shows that the transition between buoyant and confining modes for this model occurs between 2 mD and 3 mD. For Tahorakuri Formation permeabilities below this transition, hot fluid can be transported laterally over several kilometres and provides a hydrological model which is consistent with the MT model at Ohaaki.

5. CONCLUSIONS

We have presented simple models of the Ohaaki geothermal system using geological structures inferred from recent MT resistivity models. These models demonstrate that lateral transport of the high temperature deep upflow can occur over several kilometers with plausible permeabilities of the controlling geological units.

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