MEASURING HEAT FLUX DYNAMICS THROUGH THE CLAY CAP IN THE WAIRAKEI-TAUHARA GEOTHERMAL FIELD

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ABSTRACT

This paper develops a multidisciplinary analysis of the extent, stratigraphic context, and thermal structure of the hydrothermally altered clay cap in the Wairakei-Tauhara geothermal field of New Zealand. We recovered unprecedented information on the clay cap geometry and heat transfer dynamics that helps in the understanding of these complex hydrothermal systems.

First, using a joint inversion of magnetotelluric (MT) and methylene-blue (MeB) data, we imaged a ~300 m thick conductive clay cap that tracks the primary aquiclude overlying a distinct reservoir unit. Then, by mapping wells temperature and lithology into this structure, we differentiated contemporary hydrothermal clays from relict clays as well as those formed under diagenetic alteration. Also, we confirmed a broad temperature formation range of between 59±15 °C and 199±20 °C for the electrically conductive smectite clay. Finally, by applying a simple heat transfer model that captures vertical conductive and advective heat flow through the inferred clay cap, we estimated a lower bound of 380±21 MW for the system heat output.

Additionally, we tested the incorporation of the clay cap inferred from MT inversions into geothermal reservoir simulations. The inferred clay cap was mapped to a reservoir permeability model to simulate temperatures with the reservoir simulator AUTOUGH2. Modelled temperatures were then compared to observed temperature logs as well as prior models using standard techniques (i.e., without MT information). We applied this scheme to a calibrated permeability model for the Wairakei-Tauhara geothermal field. Results indicated that our inclusion of the low permeability structure led to reductions in the model misfit to temperature logs.

The developed methods allow studying uncertainties when inferring clay cap properties in high-temperature geothermal fields. Imaging the clay cap serves as a guide for developing conceptual models and for defining drilling targets, so the uncertainty inferred for these estimations is of great importance.

1. DATASET

We work with a multi-channel dataset from the Wairakei-Tauhara Geothermal Field (Figure 1) comprising an MT survey, temperature logs from most deep geothermal wells in the field, along with MeB data and lithology for some of the wells. This extensive dataset from an extensively studied geothermal field provides a unique opportunity to explore relationships between different physical properties that can reveal new aspects of these complex systems. All these datasets are somehow indicative of the clay cap presence.

MT is a passive electromagnetic geophysical technique used to map the electrical resistivity distribution of the subsurface to several depths. An MT survey comprising 250 stations (Figure 1) was carried out at Wairakei-Tauhara geothermal field in 2010, commissioned by Contact Energy Ltd, the geothermal field operator. The survey's MT station spacing was about 500 m on a semi-regular grid with 14 hr overnight recording time. registered in different periods. Details on the MT data including quality assessment and dimensional analysis can be found in Ardid, 2021c.

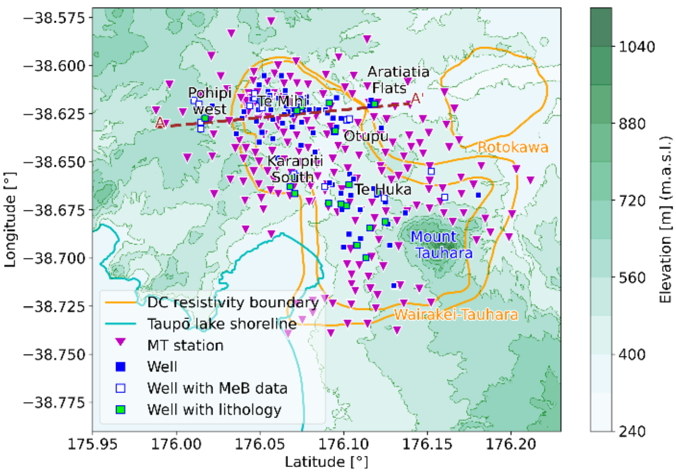

Figure 1: Map of the Wairakei geothermal field, with the locations of MT stations and wells, highlighting those with available lithology and MeB data. The background shows an elevation map and the Taupō Lake shoreline. The orange contour shows the DC resistivity boundary (~250 m depth; Risk, 1984) delineating the inferred clay cap of the Wairakei-Tauhara and neighbouring Rotokawa Geothermal Fields.

We have at our disposal temperature logs for 150 geothermal wells (Figure 1). Wells are commonly distributed in geothermal fields according to their use. Typically, they are found clustered in production (Te Mihi, Te Huka) or injection zones (Otupu, Karapiti South). MeB analyses, an indicator of conductive clay content, were performed by Contact Energy Ltd for drill cuttings in 36 wells that were provided for this study (Figure 1). Since MeB analysis is a relatively new technique (Gunderson et al., 2000), wells analysed are predominantly newer assets (drilled in the last two decades). We also have at our disposal lithology for 23 geothermal wells (Figure 1). Examples for the multiple well logs can be found in Ardid, 2021c.

2. CONDUCTOR BOUNDARIES AND CLAY CAP FORMATION TEMPERATURES

In this section, we use a joint Bayesian inversion of MT and MeB data (Ardid et al., 2021a) to establish uncertain intervals for the upper and lower boundaries of the conductor reflective of the clay cap that vary across the field. Then, we interpolate temperature data across the inferred clay layer to estimate clay formation temperatures and temperature gradients.

It is important to notice that our modelling assumes the clay cap as a continuous low permeable formation. The Huka Falls Formation that hosts most of the clay cap in Wairakei-Tauhara has a middle sequence (Mid Huka), a permeable breccia and hosts a confined aquifer. We make this assumption because we intend to model general aspects of the system using simple and efficient methodologies that enlighten key information for developing better conceptual models and assessing the decision-making process of the geothermal companies.

2.1 MT-MeB inversion: uncertain depths to the top and bottom of the conductor

When modeling MT data, gradient-based deterministic inversion has been the standard. However, for geothermal energy developers interested in knowing the clay cap boundary location, an undesirable aspect is the inherent non-uniqueness and the implied uncertainty that is not properly captured when inferring the conductor geometry from deterministic inversions. Also, when selecting a single model from a set of plausible models, such as the optimal solution derived from deterministic inversions, incorrect inference on conductor thickness and resistivity is likely being made. Consequently, operational decision-making – drilling, resource estimation – that relies on these could be compromised. In this situation, it is preferable to present the set of plausible models derived from a stochastic inversion that explicitly represents the irreducible uncertainty as estimated depth intervals for clay cap boundaries.

We inverted the MT dataset along with MeB data using the Bayesian inversion (Ardid et al., 2021a), that returns an ensemble of 1D three-layer models at each station, characterizeised by posterior distributions over two thickness and three resistivity parameters to infer under uncertainty the shallow conductor boundary reflective of the clay cap.

Figure 2 shows the spatial distribution of depths to the top of clay cap inferred from the conductor estimation. Our MT inversion model results show that for the north and west areas of Wairakei, there is a good correlation between inferred clay layer and the shallow DC resistivity boundary. An exception is at Pohipi West where the presence of clay is inferred outside the DC resistivity boundary, likely due to relict clays observed at >300 m depth (Sepulveda et al., 2012). However, the largest discrepancy is in the Aratiatia Flats region where the MT reveals a deep conductor outside the conventional Wairakei boundary. The conductor here dips gently east and then plateaus at more than 400 m depth where it abuts the nearby Rotokawa geothermal field.

A 2D east-west section through the north of Wairakei (profile AA' in Figure 2) reveals a mushroom-shaped low-resistivity layer inferred as a hydrothermal clay-cap (Figure 3), flattened near the surface in the centre of the field and dipping away at the edges. The depth of this clay-layer largely correlates with the Huka Falls Formation, the primary aquiclude, as confirmed by stratigraphy and MeB profiles from four wells located in the infield Te Mihi region (WK124A, WKM14, WKM15 and WK317; Figure 3). The low permeability of the lacustrine sediments encourages formation of swelling clays at the high temperatures (~200 °C) that occur in the geothermal upflow at Te Mihi (Sepulveda et al., 2012). The lowest extent of the clay layer appears to correlate with the top of the Waiora formation, notwithstanding the larger uncertainty attached to this boundary.

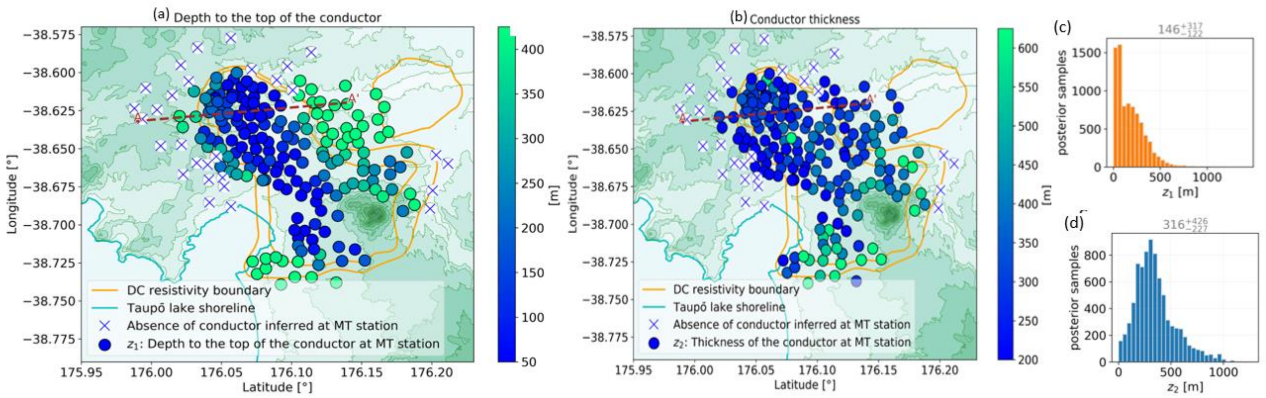

Figure 2: Scatter circles show the mean 1D inverted depth to the inferred top of the clay cap (a) and clay cap thickness (b) at the location of magnetotelluric (MT) stations. Crossed circles indicate locations where a shallow electrical conductor (i.e., clay cap) was not imaged by the MT data. Orange lines indicate the boundary of the Wairakei-Tauhara geothermal field. The background shows an elevation map and the Taupō Lake shoreline; (c) and (d) panels show histograms for the samples from inferred depth to the top of the clay cap (a) and clay cap thickness (d) at the top and the bottom of the conductor from temperature well data (z1 and z2 respectively). Figure modified from Ardid et al. 2021b.

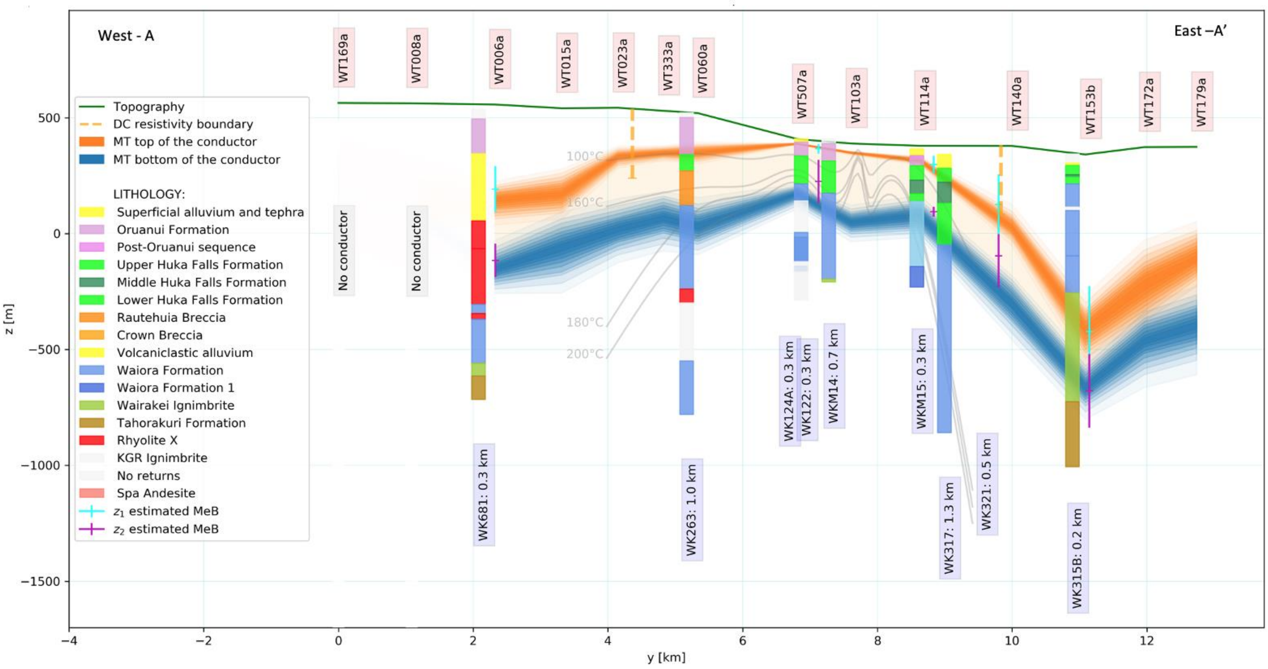

Figure 3: Profile AA′ (Figure 2), showing the inferred clay cap boundaries derived from 1D magnetotelluric (MT) inversion models, along with estimates of the clay distribution estimated from methylene blue data (MeB) in wells. Temperature isotherms (gray contours) interpolated from wellbore measurements using a cubic spline. Lithology for some of the wells close to the profile is also shown. MT locations and station names are shown as red boxes (top) and well locations and names as blue boxes (bottom) with perpendicular distance to the profile. Interception of the profile with the resistivity boundary is indicated by vertical dashed orange lines to a depth of 300 m. Figure modified from Ardid et al. (2021b).

Exceptions are at the field margins such as the Aratiatia Flats region east of the upflow where the clay layer deepens to be hosted in the Wairakei ignimbrite beneath the Waiora. Further east, it shallows toward the Rotokawa geothermal field suggesting a hydrothermal connection between the two fields. However, well data indicate low temperatures and the conductor is contained within the Wairakei ignimbrite. Ignimbrites under prolonged low-temperature regimes can undergo diagenetic alteration giving rise to conductive networks of clays and zeolite minerals. This has been observed in the TVZ and has caused misunderstandings about the nature and genesis of the conductor (Bibby et al., 2005).

Thus, consideration of the temperature data alongside the MT suggest the deep conductor plateau observed at the Aratiatia Flats region is likely diagenetic and not hydrothermal alteration (ignimbrites under prolonged low-temperature regimes can undergo diagenetic alteration giving rise to conductive networks of clays and zeolite minerals). In the outfield west of Wairakei AA', the conductor is absent (station WT169a; Figure 3) and first appears in Poihipi West (station WT006a; Figure 3). Inspection of temperature and well logs in the nearest well (well WK681; Figure 3) suggests no obvious stratigraphic or thermal control on the clay, which is formed in the volcanic alluvium and rhyolite. Cold temperatures suggest this is a relict of past geothermal activity.

2.2 Clay cap formation temperatures

The rock resistivity signature in geothermal fields is controlled by variations in multiple physical parameters (porosity, temperature, fluid salinity, and conductivity of the rock matrix, which has potentially been hydrothermally altered). So, the correct interpretation of resistivity models from MT inversions in geothermal fields requires comparison with direct observation in wells of key parameters, such as temperature, lithology, and clay content. Typically, comparisons between multiple datasets are performed qualitatively, but the derived interpretations could be subjective. Joint inversion/modeling schemes of multiple datasets offers a different perspective. They could provide new insights on rock property correlations consistent with multiple sources of information in a way that can be replicated and evaluated under standard metrics.

For joint modeling, we constructed temperature distributions for the clay cap boundary across Wairakei-Tauhara by mapping the temperature logs onto the clay cap inferred by the MT-MeB inversion. First, we generated estimates of the upper and lower limit of clay at the location of each well by interpolating posterior samples from the MT-MeB inversion. Then, temperatures at the inferred top and bottom boundaries are sampled from the temperature profile in the corresponding well and aggregated to produce distributions for the field (Figure 4).

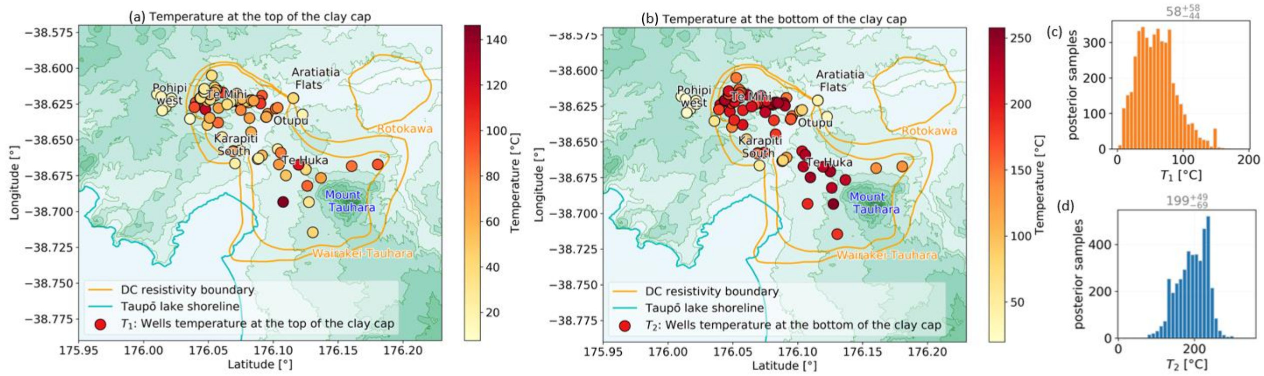

Figure 4: Scatter circles show the temperature at the top (a) and bottom (b) of the inferred clay cap in well locations, along with the DC resistivity boundary for the Wairakei-Tauhara geothermal field; (c) and (d) panels show histograms for the temperature samples at the top and the bottom of the conductor from temperature well data (T1 and T2 respectively). Figure modified from Ardid et al. 2021b.

Regional temperature trends show the central upflow as the hottest part of the field, with cooling towards and outside the boundary (Figure 4). The highest temperatures at the base of the clay cap (>250 °C) are found in the Te Mihi, Western Borefield, and Te Huka areas, and west of Mount Tauhara. Within the field resistivity boundary, low temperatures (<100 °C) are observed in the Otupu region and north of Te Mihi (one well). A cooling transition zone coinciding with the boundary occurs east of Poihipi West and Karapiti South. Outfield, cold temperatures (<50 °C) are observed in Poihipi West and Aratiatia Flats, consistent with the relict and diagenetic nature of clays in these areas. Overall, the median temperatures at the top and bottom of clay boundaries are 58 °C and 199 °C, respectively (Figure 4). These values are consistent with the 50 to 200 °C formation range for smectite and smectite-illite clays proposed by Browne (1978) for high temperature volcanic-hosted, neutral pH geothermal systems. However, there is also substantial variability in the clay cap boundary temperatures, with a two-sigma median- centred range of 20 to 120 °C for the upper boundary and 130 to 250 °C for the lower boundary (Figure 4). This variability suggests that correlation between clay formation and temperature needs to be interpreted cautiously (particularly where clay presence is inferred from geophysics and not confirmed by wells). Also,

3. HEAT FLUX THROUGH THE CLAY CAP

Using clay cap thicknesses and boundary temperature inferences, we computed effective linear temperature gradients across the field, which had a two-sigma distribution of 476^{+175}_{-336}°C/km (Figure 5a). For a typical thermal conductivity of 2.2 W/m °C, this corresponds to a conductive heat flux of $1.05^{+0.15}_{-0.22}$ W/m^2 (Currie et al., 2010).

We constructed an improved model for vertical heat transfer by also considering advection, which is the heat transported by upwelling of hot water through the clay cap (details on how to calculate the heat flux density through a homogenous layer with vertical fluid flow can be found in Ardid et al., 2021b and Ardid, 2121c). Across the field, the distribution of vertical heat fluxes obtained is $2.2^{+5.9}_{-1.2}$ W/m^2 (Figure 5b), with a total estimated heat flow for the field of 380±21 MW (Figure 5c). The largest contribution is concentrated around the production zones at Te Mihi, south of Te Huka, and north of Mt. Tauhara.

We interpret the total heat flow through the clay cap as a lower bound on the total heat flow of the geothermal system. Notably, this estimation does not consider heat that escapes the reservoir via lateral outflows below (or within) the clay cap or through localised high permeability pathways whose thermal signature has not been sampled by nearby wells. These pathways that may feed localised surface features like geysers, mud pools or steam vents could represent substantial heat flow. Previous estimates of Wairakei-Tauhara heat output (530 MW; Bibby et al., 1995, Hunt et al., 2009) based on geochemical considerations are about 40% higher than ours. However, high uncertainties of 25% are expected for chloride/enthalpy ratio methods, where the overall accuracy is difficult to judge (Bibby et al., 1995). On the other hand, our method has several advantages over prior estimates in that it directly utilises observations of wellbore temperatures and geometrical constraints on the clay cap from MT and MeB data. Many well-characterised fields have temperature and MT data, so a similar method can be applied. Nevertheless, at an early exploration phase geochemistry based methods may be preferred until MT and temperature data are available.

4. EXPLICIT INCLUSION OF THE CLAY CLAP IN THE AUTOUGH2 MODEL

Numerical simulations are commonly performed to study fluid and heat flows in subsurface environments using various simulation codes. A common used geothermal reservoir numerical simulator is AUTOUGH2 (Yeh et al., 2012). Geothermal reservoir simulation is now a mature technology routinely used in assessing, developing, and managing geothermal resources.

In this section, we integrate the inferred clay cap geometry revealed by the MT and MeB joint inversion to geothermal reservoir numerical simulations. The aim is to study the impacts on simulated temperature by the explicit incorporation of the inferred clay cap. Using our results for the Wairakei-Tauhara geothermal field (Figures 2 and 3), we map the inferred clay cap as a low permeable formation into a Wairakei-Tauhara calibrated AUTOUGH2 permeability model (Figure 6). Then we run several simulations until natural state conditions are achieved, to finally compare changes in predicted temperature distributions between the original calibrated model and our recalibrated version that explicitly include the inferred clay cap (An extended version of this section can be found in Ardid, 2021c).

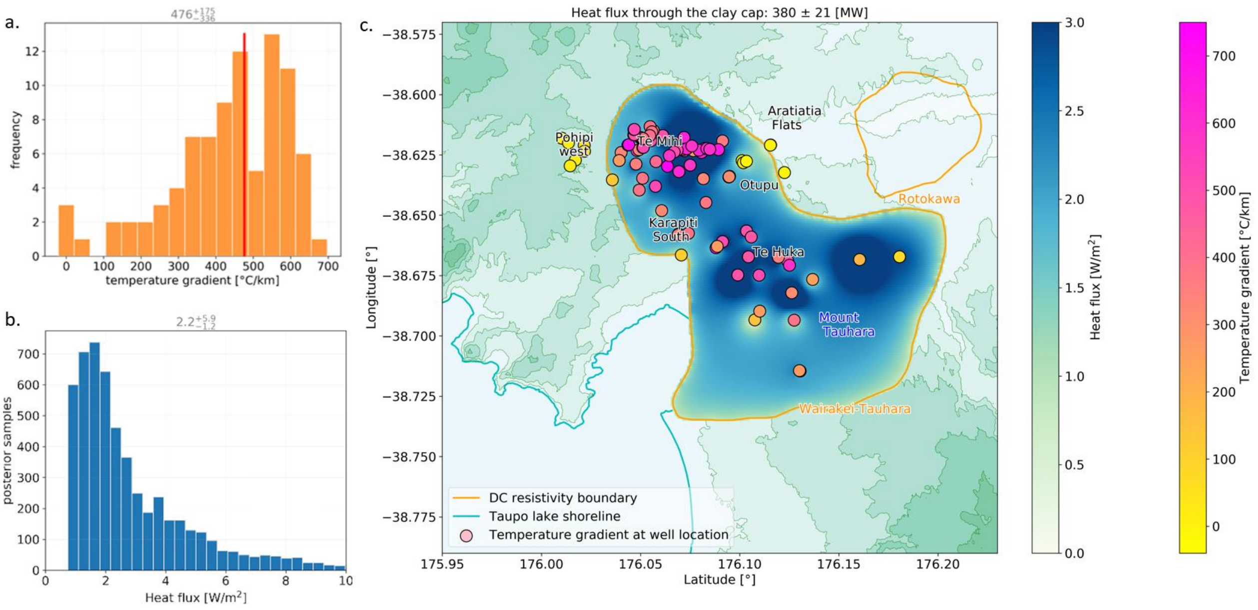

Figure 5: Scatter circles show the linear temperature gradient in well locations, along with the DC resistivity boundary for the Wairakei-Tauhara geothermal field. The background shows the estimated natural state heat flux through the clay cap for the geothermal field interpolated from well samples and well locations. Upper left panel shows the distribution of temperature gradients with the median value indicated by the red bar. Lower left panel shows Posterior samples of heat flux density modelled by a 1D conduction-advection model fit to temperature logs.

4.1 AUTOUGH2 Wairakei-Tauhara Model

The calibrated model used for this study was developed by Uniservices in the University of Auckland for Contact Energy Ltd as of 2010 (Yeh et al., 2010; McDowell et al., 2020). This model version is characterised by 9011 blocks covering an area of ~500 km^2. A vertical slice and horizontal plan view of the grid can be seen in Figures 6 and 7. The simple 9011 blocks model allows us to run several models with enough accuracy to test how prior structural information from geophysical inferences can be incorporated into the AUTOUGH2 reservoir simulations.

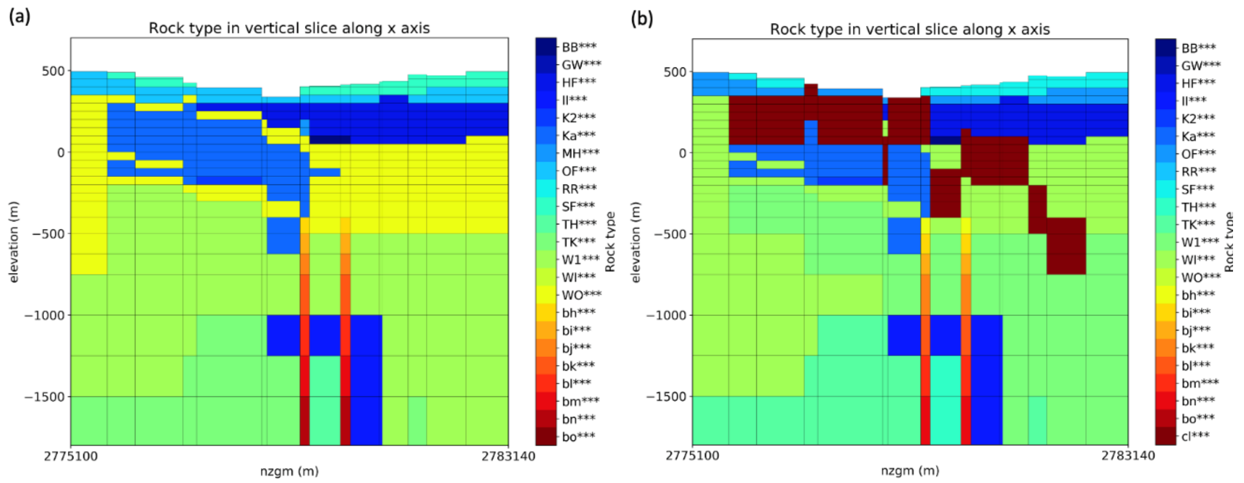

Figure 6: Vertical slice of the Wairakei-Tauhara previously calibrated (a) and recalibrated (b) AUTOUGH2 permeability model. The recalibrated version is constructed by changing to a low permeability (10^{-16} mD) those blocks inside the inferred clay cap volume by the MT-MeB joint inversion. Colourbar indicates permeability of each block (mD). The brown blocks indicate the introduced clay cap (cl in Colourbar).**

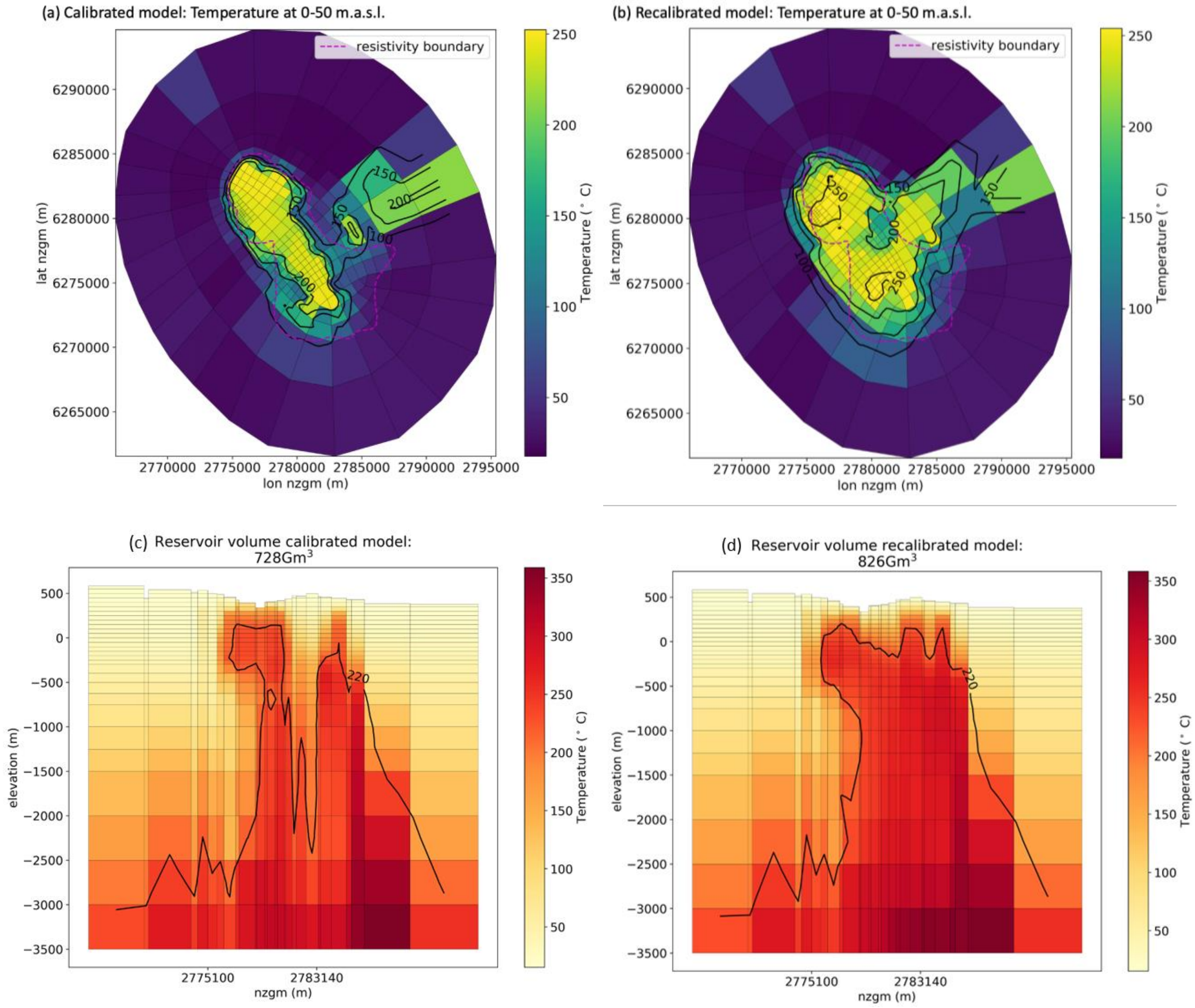

Figure 7: Temperature plain view at 0-50 m.a.s.l and vertical slice for Wairakei-Tauhara simulations as a result of the calibrated (a and c) and recalibrated (b and d) AUTOUGH2 natural state permeability models. The 200 °C isotherm is highlighted indicating the main reservoir. The reservoir volume indicated by the volume wrapped by the 200 °C isotherm is indicated in the title of (c) and (d).

4.2 Mapping the Clay Cap into the AUTOUGH2 Model

The geothermal system's detailed geological structure is defined by numerical values of various rock-type parameters that are assigned in the model. These are used as input for the reservoir simulator to calculate mass and energy balances for the model blocks. A total of 752 rock-types were used to account for the detailed geology of Wairakei-Tauhara. A thermal conductivity of 2.5 $Wm^{-1}K^{-1}$ and specific heat of 1000 J $kg^{-1}K^{-1}$ were applied uniformly to all rock-types.

The procedure to map the clay cap inferred by the MT-MeB inversion for Wairakei-Tauhara geothermal field onto the AUTOUGH2 calibrated permeability model goes as follows:

First, we import the field's resistivity boundary contour (e.g. Figure 1) and the inferred top and bottom boundaries of the clay cap inferred at each MT station (e.g. Figure 3) to reference a region (volume) of where the clay cap is located in the subsurface. Then, we loop over the model blocks and recalibrate their permeability (by defining a new rock type that we called 'clayc' assigning low vertical permeability value (10^{-17} mD) for blocks with centres inside of the selected region (Figure 6). The recalibrated model can then be run until a steady-state temperature is reached for comparison purposes with the calibrated model (Figure 7). For every step in the modelling we used PyTOUGH, a Python scripting library for automating AUTOUGH2 simulations (Croucher, 2011).

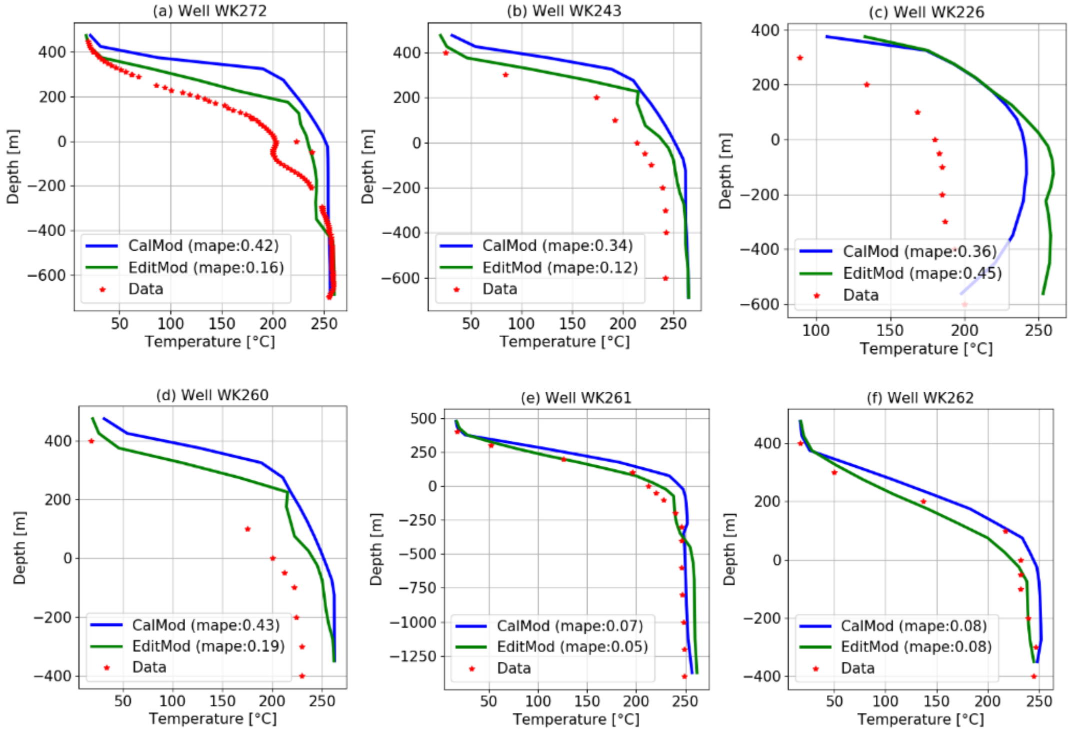

Figure 8: Temperature profiles in six well locations around Te Mihi on the Wairakei-Tauhara geothermal field comparing observed data, and temperature predictions from calibrated and recalibrated permeability models. The recalibrated model is built by mapping the inferred clay cap from MT inversion into the calibrated model. Temperature predictions are generated using the reservoir simulator AUTOUGH2.

4.3 Well temperature comparison

This section compares temperature results from the calibrated and recalibrated permeability models against observed temperature logs for some geothermal wells from Wairakei. This gives us an insight into which model is matching the observations better.

We begin by testing how different clay cap thicknesses fit individual temperature logs. From the bottom of the clay cap imported from the MT-MeB inversion (mean envelope, see Figure 3 as reference), we recalibrated the rock types (to a permeability of 10^{-17} mD) for blocks on top of this surface for multiple thicknesses and ran the models until steady-state. The best fit was obtained for 300 m thickness. Next, considering the 300 m thick clay cap permeability model, we evaluated the temperature data fit for multiple wells. Figure 8 shows temperature fit on six wells for the calibrated and the recalibrated model. For most wells, the recalibrated model performs better, averaging a misfit value of ~0.18 against ~0.28 by the calibrated model (Table 1).

Well / Model	Calibrated	recalibrated
WK272	0.42	0.16
WK243	0.34	0.12
WK226	0.36	0.45
WK260	0.43	0.19
WK261	0.07	0.05
WK262	0.08	0.08
Average	0.28	0.18

Table 1: Temperature misfit (between observed data and model predictions) base on m.a.p.e. (mean average percentage error) for six wells in the Wairakei-Tauhara geothermal field for the calibrated and recalibrated permeability models.

To evaluate the performance of permeability values used for the rock type, we run three models with low permeabilities of 10^{-16}, 10^{-17} and 10^{-18} mD, and compared results to temperature data in six wells. Table 2 indicated that the best misfit average is obtained for a permeability value of 10^{-17} mD.

Well/Perm.	10^{-16} mD	10^{-17} mD	10^{-18} mD
WK272	0.36	0.16	0.21
WK243	0.28	0.12	0.28
WK226	0.38	0.45	0.37
WK260	0.32	0.19	0.31
WK261	0.15	0.05	0.24
WK262	0.18	0.08	0.32
Average misfit	0.27	0.18	0.28

Table 2: Temperature misfit (between observed data and model predictions) based on m.a.p.e. (mean average percentage error) for six wells in the Wairakei-Tauhara geothermal field for three plausible permeabilities assigned to the clay cap model. Clay cap models are built by mapping the inferred clay cap from MT-MeB inversion into the calibrated model.

5. CONCLUSIONS

The methods presented could improve conceptual models of shallow geothermal hydrology, provide additional constraints for geothermal reservoir simulations, and support decision-making processes that define drilling targets or field management strategies. Further, by integrating multiple data sets, we generate a holistic image of the upper part of the magmatic-hydrothermal system that is consistent with the constituent parts each data type is informative of. These help us understand the clay alteration distribution in geothermal fields, how it relates to temperature, the heat flux of the system, and, by quantifying uncertainty, define appropriate limits on those inferences.

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