THREE-DIMENSIONAL MAGNETOTELLURIC IMAGING OF THE REPOROA / WAIOTAPU GEOTHERMAL SYSTEM, NEW ZEALAND

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ABSTRACT

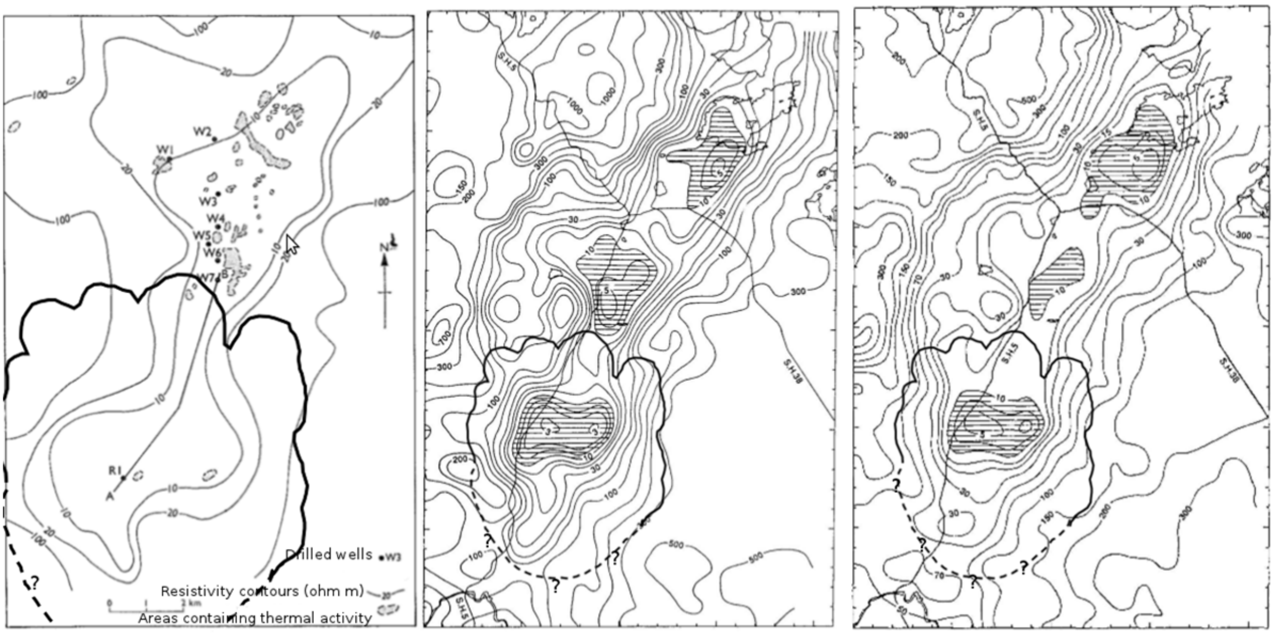
Broadband magnetotelluric (MT) measurements at 230 sites have been used to create a 3D resistivity model of the Taupo Volcanic Zone (TVZ). This paper focuses on the northeastern part of this model that gives an image of the structures at the Reporoa / Waiotapu geothermal systems down to several kilometres depth.

Preliminary interpretation suggests the presence of a thin, low resistivity, hydrothermally altered layer at 200-500 m depth. Between 1-2 km a more extensive low resistivity zone, which infills the Reporoa caldera, was also identified. This feature was attributed to hydrothermal alteration by past and present convecting geothermal fluids. A plume-like structure near the northern boundary of the caldera located between the Reporoa and Waiotapu systems was attributed to the upflow of the geothermal system heated from below by a magmatic intrusion in the 6-10 km depth range.

1. INTRODUCTION

The Taupo Volcanic Zone (TVZ) hosts the majority of New Zealand's geothermal systems. Several of those are currently utilized for power generation, like Wairakei, Ngatamariki and Ohaaki. Others have been declared protected fields as they are a valuable tourist attraction as well as sites of special cultural significance, such as Waiotapu and Waimangu. The Reporoa geothermal field is the only field that has been classified as a research geothermal system. Due to its location and possible connection to the protected Waiotapu geothermal system, the Reporoa system needs to be well characterized before utilization can be considered.

For the last 40 years it has been argued whether Reporoa is an independent geothermal system or is just an outflow structure of the Waiotapu geothermal system to the north. Healy and Hochstein initiated this discussion in 1973 when they reported D.C. resistivity measurements in that area (Healy and Hochstein, 1973). They mapped out an elongated pattern of low resistivity spanning over Waiotapu and Reporoa (see Figure 1(a)). Temperature measurements



(a) Healy and Hochstein (1973) (b) Bibby et al. (1994) (500m) (c) Bibby et al. (1994) (1000m)

Figure 1: Contours of apparent resistivity (Ωm) after Healy and Hochstein (1973) with nominal penetration depth of 0.61 km (a) and after Bibby et al. (1994) for nominal Schlumberger array spacing of 500m (b) and 1000m (c). The approx. location of the caldera outline after Cole and Spinks (2009) has been added to the maps.

from two boreholes in Waiotapu and Reporoa show a decreasing horizontal temperature gradient from north to south. Healy and Hochstein concluded from these observations that the southern part (Reporoa) is only a horizontal outflow zone from the northern part of this low resistivity area (Waiotapu).

Bignall (1990) described the results from the RP-1 drillhole (Fig. 5), which was drilled in 1966 to a depth of 1338 m, in more detail. The well log shows a temperature inversion between 400 m and 670 m with hot water of about 204 °C at 300 m flowing above cooler water of 166 °C at 550 m, and a second temperature maximum at a depth of 853 − 975 m of 225 °C. Overall, Bignall supported the idea of a lateral flow of hot water from Waiotapu to Reporoa but noted that the aqueous geochemistry had not been considered in sufficient detail.

A more detailed analysis of the reservoir fluids was undertaken by Giggenbach et al. (1994). He found geochemical evidence that suggested a hydrological link between Waiotapu and Reporoa. For example, the waters at Reporoa contain Cl as their major anion, but have a higher relative HCO_3 content than fluids collected at Waiotapu. Since the water-rock interaction at decreasing temperatures favours the formation of HCO_3, this indicates that the water collected at Reporoa could originate from the Waiotapu waters. On the other hand, Giggenbach et al. also found evidence in the geochemical analysis that favours the concept of Reporoa being an independent geothermal system. A depletion of the soluble gas species NH_3 and H_2S as well as a high content of N_2 and CH_4 which are not very soluble and easily lost gas species at Reporoa suggest an injection of volatiles and possibly heat from a local heat source into the system.

The existence of a possible magma body underneath Reporoa was also postulated by Nairn et al. (1994). They discovered the Reporoa Caldera in 1994 and identified the caldera as the source of the Kaingaroa Ignimbrites that cover an area of ∼ 100 km^3. Since this large volume of lava erupted only within the last 0.24 Ma, residual magma bodies could still exist at depth and function as a heat source for the geothermal system. Nairn et al. were able to map the northern and eastern caldera margins due to the clear surface expression, unlike the southwestern margins. After the initial resistivity survey conducted by Healy and Hochstein in the 70's, Bibby et al. (1994) conducted two further resistivity surveys in that area; one using the Schlumberger array with fixed spacing of 500 m and one with 1000 m (see Figures 1(b) and 1(c)). Bibby et al. (1994) came to a different conclusion from Healy and Hochstein (1973). Their map showed a distinct low resistivity anomaly with sharp boundaries at Reporoa, Waiotapu and Waimangu, and higher resistivity values between those fields. The 1000 m array produced very low resistivity values which would indicate a considerable hydrothermal alteration of the host rocks at Reporoa.

During the same time as Bibby et al. (1994), Risk et al. (1994) also made measurements in the Reporoa-Waiotapu area using a multiple-source bipole-dipole array that can detect changes in resistivity to several kilometres depth. Their results were very similar to those obtained using the Schlumberger arrays, and also showed a distinctive low resistivity zone at Reporoa. But Risk et al. also mentioned in the discussion of their results a shallow conductive layer in the north of the field that they thought could represent the southward flowing thermal waters suggested by Healy and Hochstein (1973).

These previous studies thus suggested that the geothermal system at Reporoa could be both an outflow structure from Waiotapu and an independent geothermal system. The purpose of this work is to address that dichotomy and resolve the existence and geometry of interconnectivity between these systems.

2. GEOLOGICAL SETTING

The Taupo-Reporoa basin is a NE-SW elongated area on the eastern side of the Taupo Volcanic Zone (TVZ). At its northern end lies a depression located between the Kaingaroa Plateau to the southeast and the eastward tilted Paeroa Block to the northwest (see Figure 2). The Paeroa Block hosts the Waimangu and Waiotapu geothermal systems. It is bounded to the northwest by the Paeroa Fault Zone and the Taupo-Rotorua depression that is a NE-SW running rift system and one of the most intensely faulted areas in New Zealand (Wood (1994)).

The Reporoa depression was first recognized as a caldera by Nairn et al., (1994). It was identified as the source of the Kaingaroa Ignimbrites that erupted about 0.24 Ma ago and are therefore one of the youngest rhyolitic pyroclastic flow deposits within the TVZ (Nairn et al., 1994). A negative gravity anomaly associated with the depression/caldera was observed in 1959 and was modelled by Modriniak and Studt (1959) as an 1800 m deep basement depression with a steep eastern edge and a sloping western one. Results from a later refraction seismic and gravity survey by Stagpoole (1994) put the basement in the caldera at a depth of 2.5 km with a vertical displacement at the caldera boundary of ∼1 km. The gravity data from Stagpoole's survey suggested that the eastern edge of the Reporoa Caldera lies about 1 km west of the scarp and is not, as has been previously mapped, the Kaingaroa Fault, which these surveys put further east under the plateau and not under the Kaingaroa Scarp.

3. MAGNETOTELLURIC DATA

Magnetotelluric (MT) surveys utilize naturally–occurring, time-varying electromagnetic (EM) fields recorded at the surface to determine subsurface electrical resistivity structures (Chave and Jones, 2012). Temperature, porosity and fluid content, as well as hydrothermal alteration, have significant effects on patterns of subsurface electrical resistivity. Therefore, MT is well suited for imaging the different parts of a geothermal system, and is accordingly one of the most utilized geophysical techniques for identifying subsurface structures in geothermal reservoirs.

3.1 Survey description

Broadband MT measurements at 230 sites covering an area of approx. 40 km^2 have been recorded in the TVZ. The data were acquired during three separate surveys over the past four years. The measurements (about 190), which were collected as part of the 'Hotter and deeper' FRST2 project, were recorded over two days. Data quality is typically good to about 1000 s period. Station spacing for this survey was approximately 2 km. The data near Reporoa and Waiotapu were recorded overnight, and reached a maximum of 100 s. But the station spacing was in part much denser, with

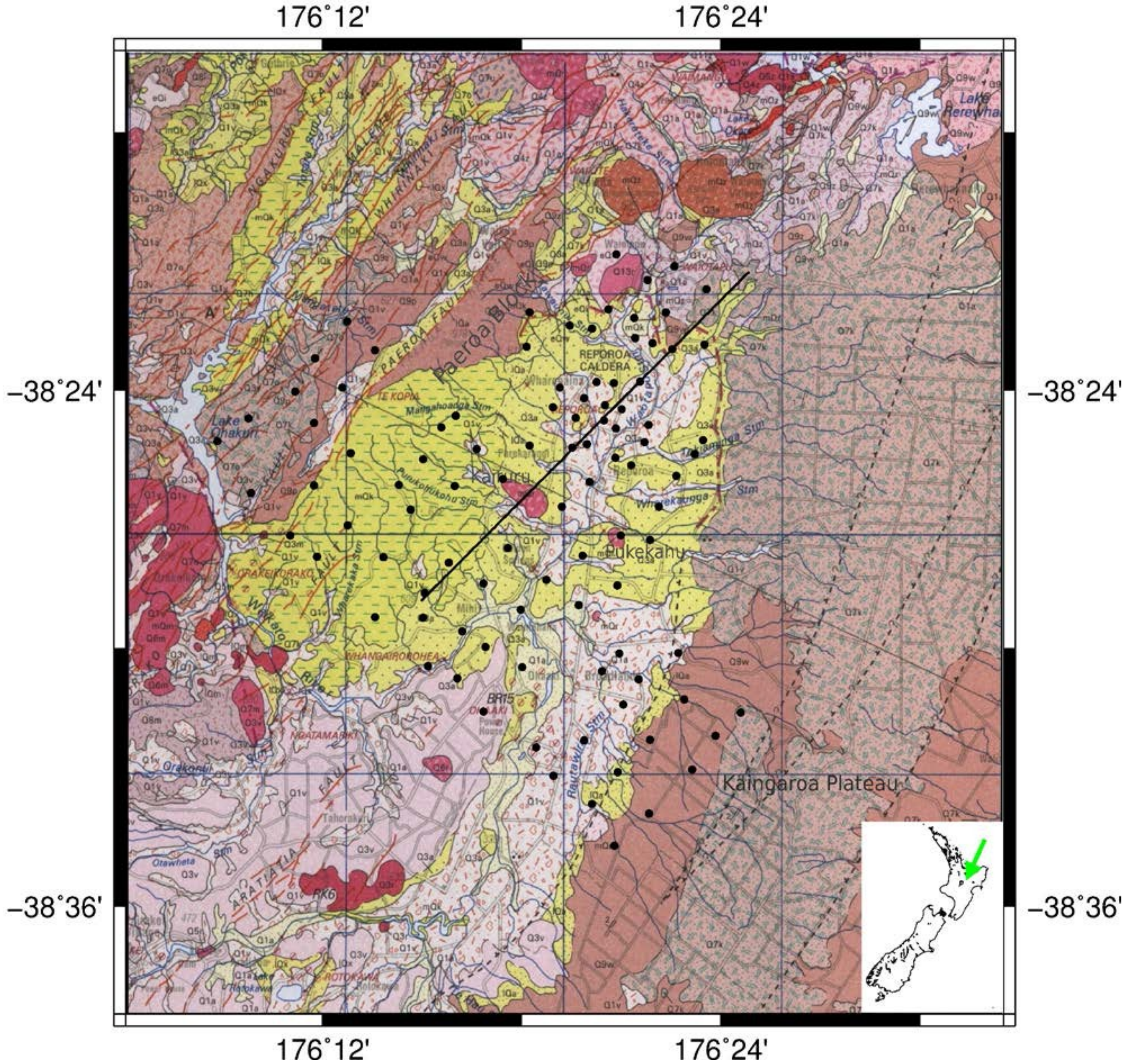


Figure 2: Subset of station locations close to Reporoa (black dots) on top of a geological map by Leonard et al. (2010). Black line indicates the location of the cross-section in Figure 3.

spacing varying from 500 m to 2 km. Due to the measurements being made mainly on farmland, much of the data are heavily affected by electromagnetic noise from electric fences and have no useful data at periods longer than 1 s. Overall, the data quality is average due to the location of the study area in a dairy farming region.

3.2 Data processing and inversion

The data have been processed using robust processing techniques with remote-referencing. All data points that were obviously affected by electric fence noise have been removed prior to modelling. The modelling was carried out using the 3D inversion algorithm ModEM (Egbert and Kelbert, 2012). ModEM is a non-linear conjugate gradient method and includes topography and bathymetry.

The 3D mesh used in this inversion has a horizontal grid spacing in the study area of 500 m and a logarithmically increasing mesh with depth. Four frequencies per decade have been chosen between 0.01-1000 s, making for a total of 20 inverted periods. The input data included the full impedance tensor as well as the tipper data.

The inversion was run in two parts. During the first run, the error for the entire impedance tensor was set to 5% of the off-diagonal components as well as 5% for the tipper components. The inversion was stopped after 54 iterations (3 days of computation) with an RMS misfit of 1.78. The inversion was then restarted from this iteration output with more tightly constrained impedance tensor data with an error of 3%. The inversion exited after another 38 iterations reaching a minimum with an RMS misfit of 2.2.

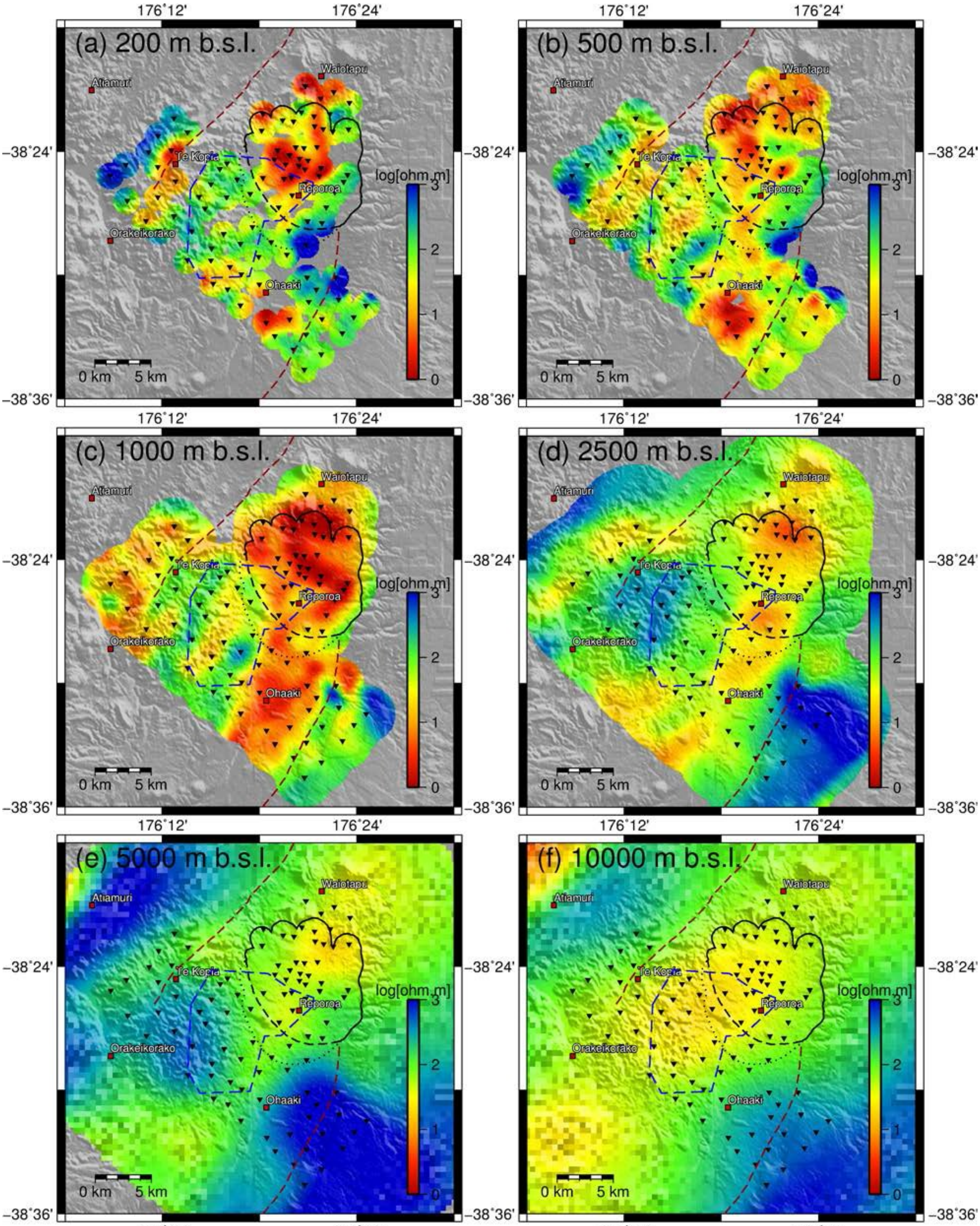


Figure 3: Depth slices through 3D inversion result at a) 200m b.s.l., b) 500m b.s.l., c) 1000m b.s.l, d) 2500m b.s.l., e) 5000m b.s.l and f) 10000m b.s.l. The solid black line outlines the northern and eastern marigins of the Reporoa caldera; the dotted black line the western and southern caldera margin after Nairn et al. (1994) and the dashed black line the western and southern caldera margin as suggested by this resistivity data; the dashed blue line a buried dome complex (Soengkono and Hochstein, 1996) and the red dashed line the Kaingaroa Fault (SE) and the Paeroa Fault (NW).

4. 3D INVERSION RESULTS

For the study of the Reporoa / Waiotapu geothermal systems, this paper will focus on the northeastern part of the inversion domain that is covered by about 100 MT stations. The results of this part of the inversion are shown in Figure 3. The figure shows six slices through the resistivity model at varying depths. In order to give an approximate estimate of the data coverage due to the station spacing, the resistivity model is only displayed within a distance equivalent to twice the depth of the resistivity slice.

The depth slice at 200 m b.s.l. agrees well with the DC resistivity map of Bibby et al. (1994, 1995) (see Fig. 1b) that correlates the low resistivity areas with geothermal systems. It shows clearly the Reporoa, Waiotapu, Ohaaki and Te Kopia fields.

The depth slice at 1000 m b.s.l. shows a conductive region in the Reporoa caldera that extends southward to Ohaaki. This anomaly appears to be bounded by the Kaingaroa fault in the east. Figure 4 shows a vertical cross-section through the model running SW-NE through the Reporoa geothermal field (as marked in Figure 2). It shows again the conductive anomaly that fills the caldera. In Figure 4 the edges of the caldera are determined from the extent of the conductive anomaly. The depth to basement suggested by the resistivity model is about 2 km b.s.l., which is well in agreement with the gravity modelling of Stagpoole (1994). The northwestern margin also agrees well with previous studies (e.g. Nairn et al., 1994, Cole and Spinks, 2009). However, the southwestern margin, if defined by the extent of this low-resistivity feature, appears to be further to the north than previously assumed. The depth slices in Figure 3 show the new (dashed line) and old (dotted line) caldera margins. This newly defined southern caldera boundary crosses the Kairuru and Pukekahu rhyolite domes. Nairn et al. (1994) interpreted this boundary as an inner caldera ring fault.

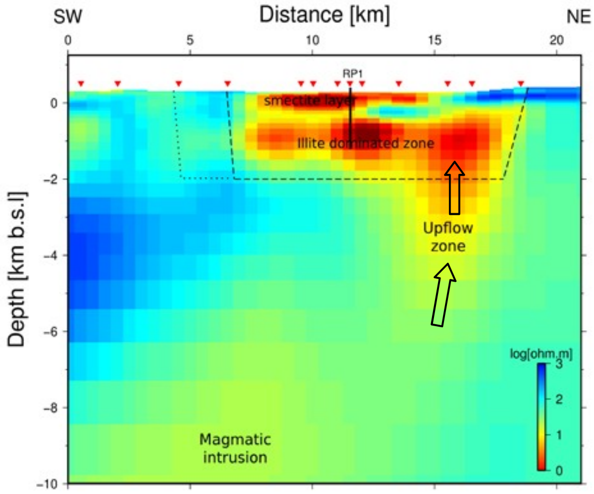


Figure 4: SW-NE cross-section through Reporoa caldera. Dashed line defines new outline of caldera, and dotted line the old southern caldera margin. Red triangles show approx. station locations near the cross-section.

The cross-section through the caldera also clearly shows that there is a thin, conductive layer overlying this larger conductive feature. This thin, conductive layer between 200 – 500 m appears to be connected to the Waiotapu geothermal system in the north. Both conductors are separated by more resistive layer at about 200 m b.s.l.. This agrees well with the temperature profile of the Reporoa well (see Figure 4). The depth of the minimum in the temperature inversion matches well with the depth of the resistive layer, therefore showing a distinct correlation between resistivity and temperature. The well log shows the presence of mainly smectite as an alteration clay mineral above 400 m b.s.l., and illite dominating beneath this, which is in agreement with the temperature profile since illite forms at higher temperatures. Therefore there also seems to be a correlation between the resistivity and the alteration pattern. However, generally researchers assume that illite is a less conductive clay mineral than smectite, and therefore we should be seeing a change in resistivity between the two conductive layers. Typical values that are expected for these clays are 1-10 Ohm-m for a smectite zone and 20-100 Ohm-m for illite dominated zones (Anderson et al., 2000). However, the resistivities seen in both conductive layers in this model are less than 5 Ohm-m.

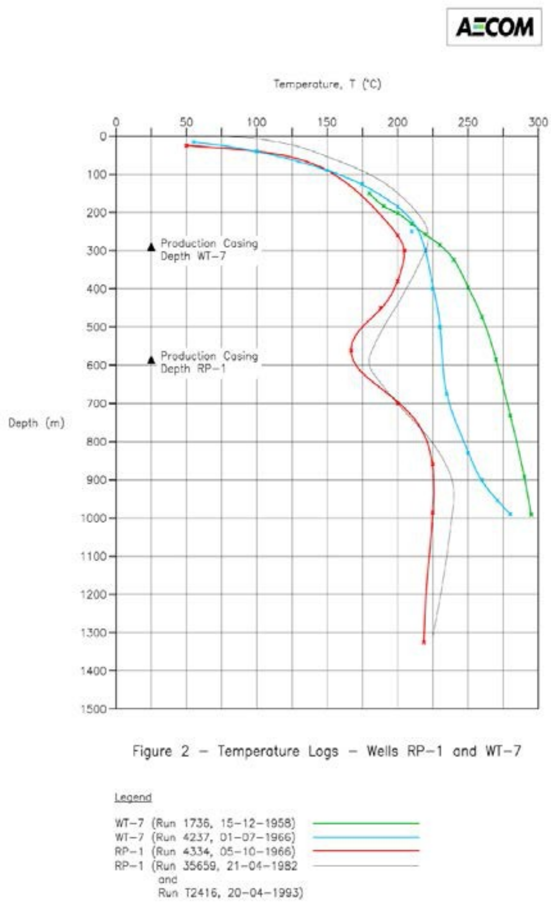


Figure 5: Temperature profile of RP-1 and WT-7 (AECOM report (2011)).

Furthermore the outline of a buried rhyolite dome complex, as modelled by Soengkono and Hochstein (1996) and marked onto the maps in Figure 3, seems to correlate well with a resistive structure southwest of Reporoa and to mark the northwestern boundary of the low-resistivity band from Reporoa to Ohaaki. However, the data suggest that the dome complex extends much further to the west and south than indicated by Soengkono and Hochstein (1996).

The depth slices in Figure 3(d)-(f) show the resistivity structure underneath the caldera floor. They indicate a deepening of the conductive feature along the northern caldera fault. This can be more clearly seen in Figure 4. A similar feature can be seen along the newly defined southern caldera fault, but this one is not as pronounced as in the north. To test whether the deepening conductor was required by the MT data, or just an artefact of the inversion, the feature was removed from the resistivity model below 2500 m. The inversion was then restarted from this new modified model. This again resulted in a deepening of the caldera conductor along the northern margins. Furthermore the phase tensor misfit (after Heise et al., 2007) between the forward responses of the models with and without conductor was calculated. This analysis showed a 5-7% change at stations near the removed structure, similar to the misfit observed by Bertrand et al. (2012) in their study of a conductive plume at Ohaaki and Rotokawa (see Figure 6). Interestingly there is also a 5-7% change at the stations in the centre of the caldera. This can probably be attributed to the fact that every conductive area below 2500 m has been set to background resistivity values underneath the caldera, not only the region on the caldera rim. Figures 3(f) and 4 show that there is also a conductive region at depth, whose removal might be responsible for the phase tensor misfit on stations in the centre of Reporoa caldera.

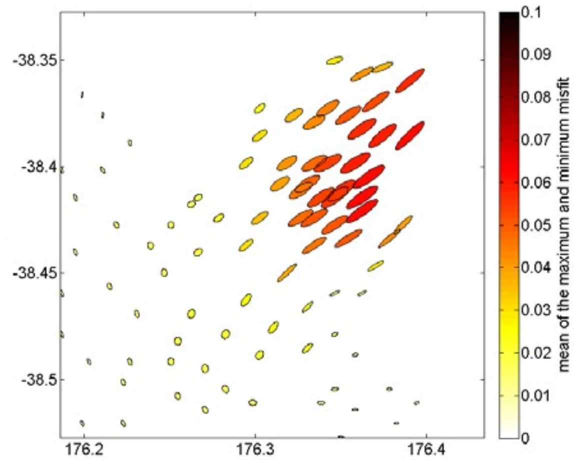
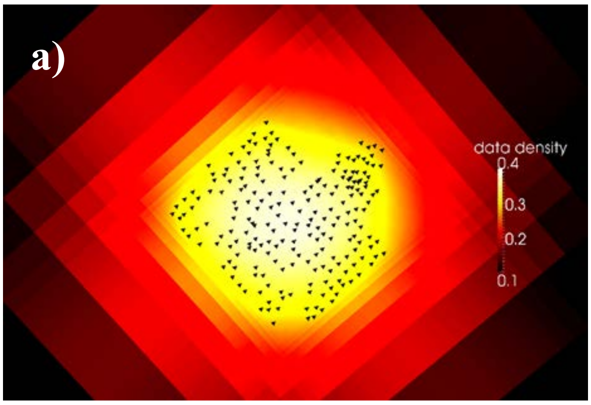


Figure 6: Phase tensor misfit plots at a period of 100 s.



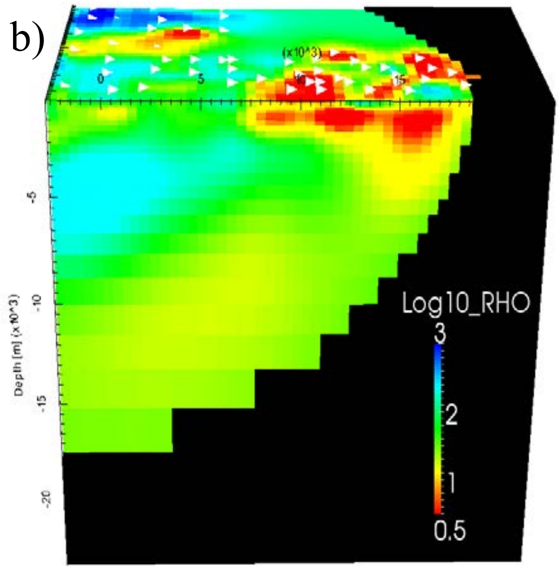


Figure 7: (a) Data density distribution at sea level. (b) SW-NE cross-section through Reporoa overlain with data density limit.

The MT technique yields impedance tensors for a range of frequencies with lower frequency estimates conveying information about structures at greater distances from the measurement site. We claim that the more stations which yield data on a given structure the better constrained that structure will be when the data are inverted. Figure 7 graphically represents the spatial variation in the number of measurement sites which constrain each model block. Using the skin depth relation where δ_{SD} is the skin depth, ρ_a is the apparent resistivity of one the off-diagonal elements of the impedance tensor and T is the period at which the impedance tensor is evaluated:

$$\delta_{SD} = 500\sqrt{\rho_a T} \, ,$$

we can calculate an estimate of the hemisphere of the modelling domain which influences an impedance tensor estimate at a given frequency. For each frequency these influence zones have been calculated and then for each block the number of overlapping influence zones and hence the number of stations which yield information about that block has been estimated.

Using this information we calculated a density distribution of the number of data points used in the inversion that contributed information to each cell of the 3D inversion domain (see Figure 7a). An image of this, zoomed in on the same cross-section of the Reporoa geothermal system as in Figure 4, can be seen in Figure 7b. Only the part of the grid with more than 25% data coverage is shown. This limit is based on the density distribution near the surface, as shown in Figure 7a. The zone of >25% data coverage has been chosen, somewhat arbitrarily, as the zone where the resistivity structures are better constrained. These zones are largely governed by the station locations. Figure 7b shows that the plume-like structure, as well as the conductor at depth, are still in this 'tolerance zone' and should therefore be regarded as well covered by this dataset. However, these structures are at the limit of the tolerance threshold and are only partially constrained. There is therefore some uncertainty in resolving structures in the northern part of the study area below 5 km depth.

5. DISCUSSION

The resistivity contrast between the caldera infill and the surrounding rocks is prominent. The comparison with the temperature profile from the Reporoa well shows a clear correlation between resistivity and temperature, and with the alteration clay minerals. The structure seen at 1-2 km in the caldera seems much more conductive than what is generally expected from an illite dominated zone at >200 °C. One possibility would be that the geothermal fluid present in these conductive layers is itself highly conductive, which would imply high salinity, and therefore increasing the overall conductivity. The chemical analysis of the water discharged from the Reporoa well however does not indicate an above average salinity for geothermal chloride waters (Giggenbach et al., 1994). Therefore it is unlikely that this is the reason for the high conductivities. Another factor that could influence the resistivity values is porosity. A back-of-the-envelope calculation with Archie's law however shows that values of more than 60% porosity would be needed to explain the high conductivities. This all indicates that the matrix resistivities should dominate the overall values, suggesting that the low resistivity zone is heavily hydrothermally altered and that the illite dominated zone has a lower bulk resistivity than indicated by the study of Anderson et al. (2000).

The resistivity pattern reflects the superposition of alteration from past and present hydrothermal activity. It is therefore possible that the newly defined southwestern caldera margin shows the extent of the paleo-fluid flow in the caldera. Possibly the caldera eruption occurred in stages, and this boundary is the latest caldera fault. The hydrothermal alteration also appears to be much stronger outside the buried rhyolite dome complex than inside, which implies that the rhyolite is less permeable than the caldera infill.

The interpretation of the plume-like structure on the northeastern caldera boundary is somewhat more difficult. Its existence is supported by the forward modelling and the phase tensor misfits. Nonetheless, the data quality was strongly affected by noise and the individual error bars at each site/period are often larger than the change created by the plume, raising the possibility that the structure is a modelling artefact. Our analysis strongly suggests that the low resistivity plume structure is required by the data since we have been unable to generate a low misfit model that does not contain the plume. Traditionally, conductive areas in geothermal systems are associated with a smectite zone that forms at lower temperatures (~ 70 °C) through hydrothermal alteration, creating the 'clay-cap' of the system. The hot part of the system is usually seen as a more resistive zone (e.g. Jones and Dumas, 1993). Researchers traditionally did not look for any conductive structures beyond those clay-caps in the TVZ (e.g. Sewell et al. (2012). Bertrand et al. (2012) were one of the first researchers to attempt to resolve structures below the clay cap. They imaged vertical conductive zones under Rotokawa and Ohaaki, and argued that they are convective upflow zones of hot geothermal fluids, but that geological structures also influence the heat transport. The vertical conductive zones at Reporoa / Waiotapu support this theory, since they seem to be associated with the caldera faults which provide a fluid flow pathway for conductive (i.e. highly saline) fluids.

The deeper conductor than can be seen in Figure 3f and 4 is similar to the one imaged by Heise et al. (2010), although with a slight variation in location. This conductive structure is at a depth of 8-10 km. Heise et al. (2010) interpreted this region as a rising plume of interconnected conductive partial melt, which agrees with the hypothesis of Nairn et al. (1994) who suspected that magma bodies could still be present under Reporoa. The only problem with the deep conductor imaged in this study lies again in the limitation of the dataset. Firstly, as mentioned earlier, the error bars are quite large, especially on impedance tensor estimates at longer periods. Secondly, it is usually very difficult to image conductive regions underneath very conductive layers; the rule-of-thumb is that a conducting anomaly must have a total conductance greater than the sum of the conductances of the anomalies above it. Since the top 2 km around Reporoa is very conductive, any body below it with equal or lesser conductance would be difficult to image with EM methods. Theoretically, given the uniqueness theorem that states that every unique resistivity structure produces a unique impedance tensor response across a range of frequencies (Bailey, 1970) if we have high enough data quality we can resolve such structures. However because our data quality is low due to cultural noise, these structures are difficult to resolve unambiguously. Therefore we cannot confirm the existence of a deep intrusion underneath Reporoa with certainty solely from the MT data.

This study imaged the top 3 km very well. The measurements in the southwest from the FRST2 survey with long-period data helped constrain the Reporoa data. More stations to the north would certainly improve the model further.

6. CONCLUSION

A low resistivity zone infilling the Reporoa caldera to a depth of 2 km was identified from the MT data. The cause of this low resistivity was ascribed to extensive hydrothermal alteration due to current and past geothermal activity. The well log identifies illite as the main alteration mineral in this zone. It is overlain by a cap of smectite clay in the upper 200 - 500 m. The illite dominated zone at Reporoa appears to be much less resistive than in other studies.

Below this zone there is an indication of a magmatic intrusion in the 8-12 km depth range, which feeds a conductive upflow into the Reporoa geothermal system.

This study yields a new estimate of southwestern caldera boundary placing it about 2 km northeast of the area indicated by previous studies (Nairn et al., 1994, Cole and Spinks, 2009). Furthermore the conductive structures associated with the Waiotapu / Reporoa / Okhaaki region could be imaged and new evidence which better constrains a buried rhyolite dome complex southwest of Reporoa first identified by Soenkono and Hochstein (1996) was found.

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REFERENCES

AECOM, *Review of Reporoa Geothermal system*. Report to Te Aroha Group Holdings, May 2011, 13 pp.,(2011).

Anderson, E., Crosby, D. and Ussher, G. *Bulls-Eye! Simple resistivity imaging to reliably locate the geothermal reservoirs*. Proceedings World Geothermal Congress 2000.

Bailey, R. C., *Inversion of the Geomagnetic Induction Problem, Proc. R. Soc. London*, Vol. 315, No. 1521, 185-194 , 24 February 1970.

Bertrand, E. A., Caldwell, T. G., Hill, G. J., Wallin, E. L., Bennie, S. L., Cozens, N., Onacha, S. A., Ryan, G. A., Walter, C., Zaino, A. J. and Wameyo, P., *Magnetotelluric imaging of upper-crustal convection plumes beneath the Taupo Volcanic Zone, New Zealand*. GRL, Vol. 39., (2012).

Bibby, H. M., Bennie, S. L., Stagpoole, V. M., and Caldwell, T. G. (1994). *Resistivity structure of the Waimangu, Waiotapu, Waikite and Reporoa geothermal areas, New Zealan*d. Geothermics, 23(56):445-471

Bibby, H. M., T. G. Caldwell, F. J. Davey, and T. H. Webb, *Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation*, J. Volcanol. Geotherm. Res., 68, 29–58, (1995).

Bignall, G., *Hyrdology and hydrothermal alteration, Reporoa well (1), Reporoa, New Zealand*. In Proc 12th New Zealand Geothermal Workshop, pages 257-263. (1990).

Chave, A. D. and Jones, A. G., *The Magnetotelluric Method*, Cambridge University Press, 2012.

Cole, J. W. and Spinks, K. D., *Caldera volcanism and rift structure in the Taupo Volcanic Zone, New Zealand.* From: MURPHY , J. B., KEPPIE , J. D. & HYNES , A. J. (eds) Ancient Orogens and Modern Analogues. Geological Society, London, Special Publications, 327, 9–29 , (2009).

Egbert, G. D., Kelbert, A. *Computational recipes for electromagnetic inverse problems.* Geophysical Journal International, 186 pp. 251-26. (2012).

Giggenbach, W. F., Sheppard, D. S., Robinson, B. W., Stewart, M. K., and Lyon, G. L. (1994). *Geochemical structure and position of the Waiotapu geothermal field, New Zealand*. Geothermics, 23:599-644.

Healy, J. and Hochstein, M. P. *Horizontal flow in hydrothermal systems*. Journal of Hydrology (New Zealand), 12(2):71-82. (1973).

Heise, W, Bibby, H. M., Caldwell, T. G., Bannister, S. C., Ogawa, Y., Takakura, S. and Uchida, T., *Melt distribution beneath a young continental rift: The Taupo Volcanic Zone, New Zealand*. GRL, Vol. 37, (2007).

Heise, W., Caldwell, T. G., Bibby, H. M. and Bennie, S. L., *Three-dimensional electrical resistivity image of magma beneath an active continental rift, Taupo Volcanic Zone, New Zealand*, GRL, Vol. 37. (2010).

Hochstein, M. P., *Assessment of the Reporoa field and its classification in the regional plan*. Technical report, UniServices. (2005).

Jones, A. G., and Dumas, I., *Electromagnetic images of a volcanic zone*, Phys. Earth Planet. Inter., Vol. 81, pp. 289-314 (1993).

Leonard, G. S., Begg, J. G., and Wilson, C. J. N. *Geology of the Rotorua area*. Technical report, GNS 1:250000 Geological Map 5. (2010)

Modriniak, N. and Studt, F. E. *Geological structure and volcanism of the Taupo-Tarawera district*. New Zealand Journal of Geology and Geophysics, 2(4):654-684. (1959).

Nairn, I., Wood, C., and Bailey, R. *The Reporoa caldera, Taupo Volcanic Zone: Source of the Kaingaroa ignimbrites.* Bulletin of Volcanology, 56:529-537. (1994).

Sewell, S. M., Cumming, W. B., Azwar, L. and Bardsley, C., *Integrated MT and natural state temperature interpretation for a conceptual model supporting reservoir numberical modelling and well targeting at the Rotokawa geothermal field, New Zealand*. PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 30 - February 1, 2012.

Soengkono, S. and Hochstein, M. *The interpretation of magnetic anomalies over the Reporoa geothermal field, Taupo Volcanic Zone, New Zealand*. Proceedings 18th NZ Geothermal Workshop 1996.

Risk, G. F., Caldwell, T. G., and Bibby, H. M., *Deep resistivity surveys in the Waiotapu-Waikite-Reporoa region, New Zealand*. Geothermics, 23:423- 443. (1994).

Stagpoole, V. M. *Interpretation of refraction seismic and gravity data across the eastern margin of the Taupo Volcanic Zone, New Zealand. Geothermics*, 23:501-510. (1994).

Wood, C. P. *Aspects of the geology of Waimangu, Waiotapu, Waikite and Reporoa geothermal systems, Taupo Volcanic Zone, New Zealand. Geothermics*, 23:401-421 (1994).