# LINKS BETWEEN VOLCANIC, TECTONIC AND GEOTHERMAL SYSTEMS SHOWN BY ARRAY MT DATA IN THE TAUPO VOLCANIC ZONE, NEW ZEALAND

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## ABSTRACT

The Taupo Volcanic Zone (TVZ) is an actively rifting volcanic arc, characterised by recent rhyolitic volcanism, large collapse calderas and more than 20 high-temperature liquid-dominated geothermal systems that convectively discharge ~ 4 GW of heat. During the past 6 years, over 500 broadband magnetotelluric (MT) measurements (at 2 km site spacing) have been made that form two arrays in the northern and southern parts of the central TVZ. 3-D inversion models of these data provide a detailed picture of the electrical resistivity structure of the brittle upper crust, and clarify the relationship between the underlying magmatic system and the overlying system of hydrothermal (convective) heat transport.

In particular, the majority of the geothermal fields encompassed by these MT data are associated with deep low-resistivity zones located at the margins of low-gravity anomalies. This association suggests that geological structure (in particular collapse calderas) and shallow magmatic intrusions play a more direct role in the pattern of convective heat transport than previously envisaged. While several of the geothermal fields appear to be underlain by shallow (~3 km depth) bodies of crystallising magma, others are not. A model of episodic intrusion in a region focused around the geothermal fields is consistent with both the resistivity structure and geological evidence for temporal changes at the geothermal fields in response to nearby magmatic events.

## 1. INTRODUCTION

Since 2002, GNS Science has collected broadband (0.01 - 1000s period) magnetotelluric (MT) data in the Taupo Volcanic Zone (TVZ). Initial data acquisition was designed to investigate the regional electrical resistivity structure beneath the young continental rift and included more than 200 measurements spaced ~5-7 km apart (Heise et al., 2007; 2010). 2-D and 3-D resistivity inversion models of these regional MT data imaged melt distribution at mid- and lower-crustal depths. In particular, a broad zone of low-resistivity at ~10 km depth was interpreted as a layer with an interconnected melt fraction of ~4%, consistent with low S-wave velocities observed in receiver function analysis (Bannister et al., 2004). This regional resistivity structure supported the conceptual model of magmatic heat transport in the TVZ (Bibby et al., 1995). Specifically, this layer of partial melt was interpreted as the basal source of heat driving hydrothermal convection of fluid at hydrostatic pressure in the upper brittle crust; transporting magmatic heat from depth to the geothermal fields at the surface.

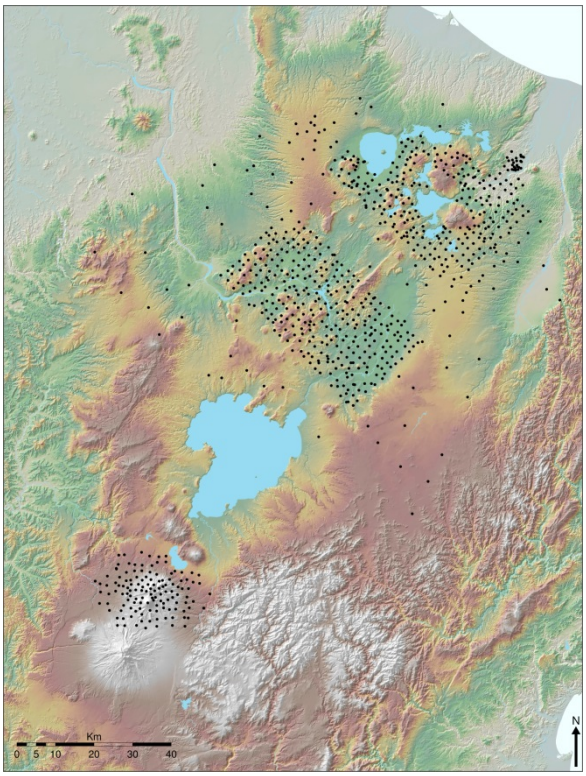


**Figure 1: Digital elevation model with black dots showing the locations of > 800 broadband MT measurements made in the TVZ since 2002.**

In 2008 a multi-disciplinary research program was funded by the government of New Zealand to explore for geothermal signatures in the basement meta-sedimentary (greywacke) rocks beneath the TVZ (Bignall, 2010). This 'deep-geothermal' research program involved array MT data collection with measurements spaced 2 km apart to image the electrical resistivity structure of the brittle (seismogenic) part of the crust (between ~3-7 km depth), and below the present maximum drilled depth (~3 km) for geothermal exploration. During 2009 and 2010, 200 broadband MT measurements were made that form a 700 km$^2$ array in the southeastern part of the TVZ. This initial array covered 5 high-temperature geothermal fields (Rotokawa, Ngatamariki, Ohaaki, Orakei Korako and Te Kopia) (Figure 2). 2-D and 3-D inversion models of these MT data showed distinct, quasi-vertical low-resistivity zones, interpreted to mark the locations of deep-rooted up-flows that feed the overlying geothermal fields (Bertrand et al., 2012). These resistivity models provided the first images linking the shallow hydrothermal (geothermal) systems to their deeper magmatic heat source.

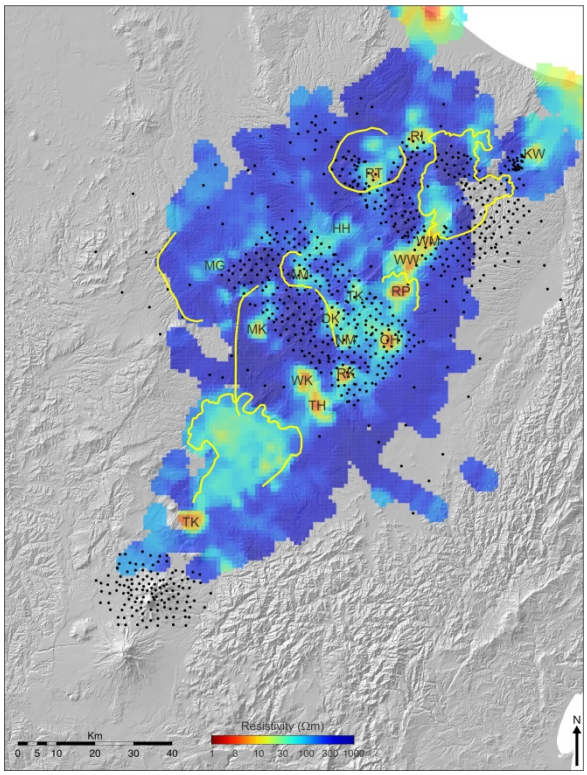


**Figure 2: Map of MT data in the TVZ with the background digital elevation model overlain by the DC apparent resistivity map (Bibby et al., 1995) that correlates low resistivity zones to geothermal systems: TK – Tokaanu, TH – Tauhara, WK – Wairakei, RK – Rotokawa, MK – Mokai, NM – Ngatamariki, OK – Orakei Korako, OH – Ohaaki, TK – Te Kopia, MG – Mangakino, AM – Atiamuri, RP – Reporoa, WW – Waiotapu Waikiti, HH – Horohoro, RT – Rotorua, WM – Waimangu, RI – Rotoiti and KW – Kawerau. Yellow lines show collapsed caldera boundaries constrained by topographic margins (Wilson and Leonard, 2008) and labelled in Figure 3.**

Building upon the original 'deep-geothermal' research program, GNS Science has continued to collect MT data in the TVZ as part of GNS's direct crown-funded Geothermal and Volcanology research programs, and with co-funding received from the Bay of Plenty and Waikato Regional Councils, Contact Energy and Ngati Tuwharetoa Geothermal Assets. At present, the initial 200-site southern array has been extended to the western margin of the TVZ and includes more than 300 measurements, covering an area of 1200 km$^2$. Support from the Bay of Plenty Regional Council was the catalyst for an additional ~250 measurements that form a separate northern array covering an area of ~1000 km$^2$ and encompassing the Rotorua and Waimangu geothermal fields, and large parts of the Rotorua and Okataina calderas (Figure 3).

With a vision to eventually produce a 3-D resistivity model of the upper 10 km beneath the entire TVZ (which will require lake-bottom MT measurements), our current data coverage permit generating separate 3-D resistivity models of the southern and northern MT arrays. These models provide evidence for the existence of shallow magmatic intrusions and show a more direct relationship between volcanic structure and the location of geothermal fields then was previously thought (Bibby et al., 1995).

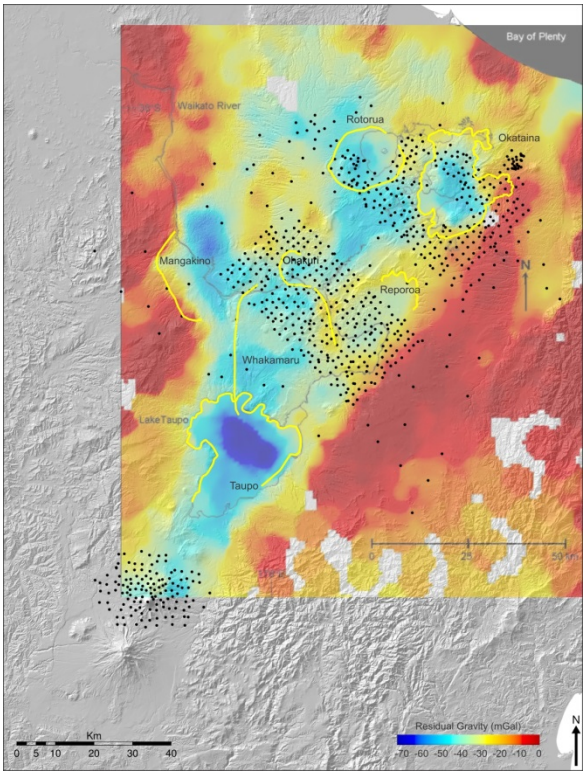


**Figure 3: Map of MT data in the TVZ with the background digital elevation model overlain by the Residual Gravity map (Bibby et al., 1995) that (in general) correlates low gravity zones with the thinned crust beneath the TVZ, and in local areas with caldera collapse. The Taupo, Whakamaru, Mangakino, Ohakuri, Reporoa, Rotorua and Okataina caldera boundaries are shown (Wilson and Leonard, 2008).**

## 2. MT DATA

To avoid the distorting effects produced by localised near-surface resistivity heterogeneities, we use the MT phase tensor Φ (Caldwell et al., 2004) to present the measured data. Properties of Φ can be represented graphically as an ellipse with principal values ($\Phi_{max}$ and $\Phi_{min}$) corresponding to the lengths of the major and minor exes. Any asymmetry in the phase tensor is represented by a skew angle (β), which along with $\Phi_{max}$ and $\Phi_{min}$ is coordinate invariant. Figures 4-5 show phase tensor ellipse maps overlaid on the residual gravity map of the TVZ (Bibby et al., 1995). In general, the smooth variations of phase tensor shape, orientation and colour between neighboring sites indicates good data quality across the entire survey area and period range measured.

Figure 5 shows different domains of phase tensor behaviour at 3 s period. At this period the phase tensors show the pattern of 3-D resistivity structure within the meta-sedimentary (greywacke) basement rocks of the TVZ (at ~5 km depth). In some areas, the orientation of the phase tensor ellipses correlate with residual gravity gradients and/or with geologically inferred caldera boundaries (yellow lines). This correlation in the measured MT data

suggests that basement resistivity and volcanic structure are linked. At longer periods (Figure 6), sensitive to greater depths where we expect the crust to be ductile, the phase tensor ellipses show less structure that is consistent with regional trends; the exception being a zone of narrow ellipses located at the eastern margin of Rotorua caldera, marking a strong resistivity gradient.

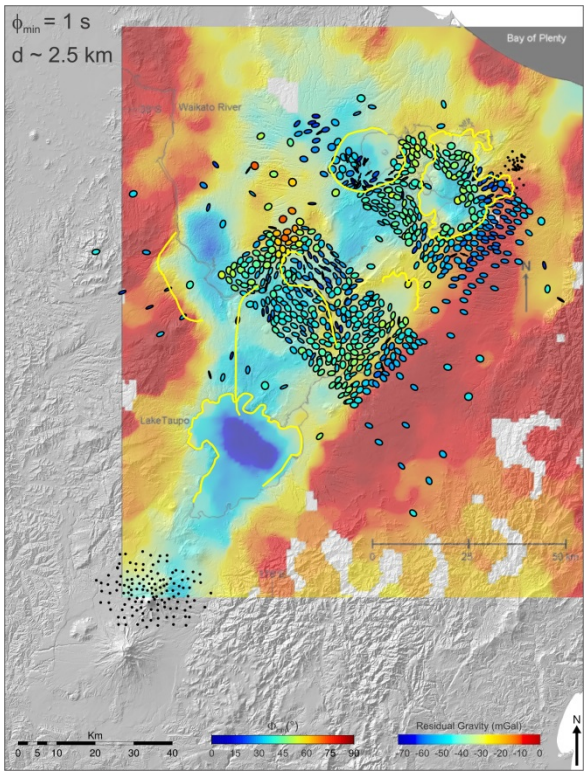


**Figure 4: Measured (normalised) phase tensor ellipses at 1 s period filled with colour that represents $\Phi_{min}$, overlaid on the TVZ residual gravity map.**

## 3. INVERSION MODELLING

Parallel implementations of the 3-D MT inversion algorithms WSINV3DMT (Siripunvaraporn et al., 2009) and ModEM (Kelbert et al., 2014) are installed at GNS Science on a high-performance computer (HPC) with 448 processing cores and 3584 Gbytes of memory. With this HPC, resistivity inversion models of datasets with 300 sites can be generated in approximately 1 weeks' time. Thus, the computation of multiple models with different control parameters (e.g. smoothing constraints) and error floors (which set a minimum data error) to test the robustness of key model features is feasible, although time consuming.

In the discussion that follows we use the results from a WSINV3DMT inversion model of a subset of 169 MT measurements made at 2 km spacing in the southern array (Bertrand et al., 2015). This model covers the high-temperature geothermal fields at Rotokawa, Ngatamariki, Ohaaki, Orakei-Korako and Te Kopia. Impedance tensor data (4 complex components) at 18 periods were inverted using a model mesh comprised of 3-D blocks with 500 m lateral dimensions (i.e. a quarter of the station spacing). Block dimensions are larger outside of the region of data coverage, and increase in thickness by a factor of 1.2 from an initial value of 25 m at the surface. Total block numbers in the x, y and z directions were 88, 84 and 44, respectively. The model mesh was oriented N45°E, aligning to the strike of the southeast margin of the TVZ (Heise et al., 2007).

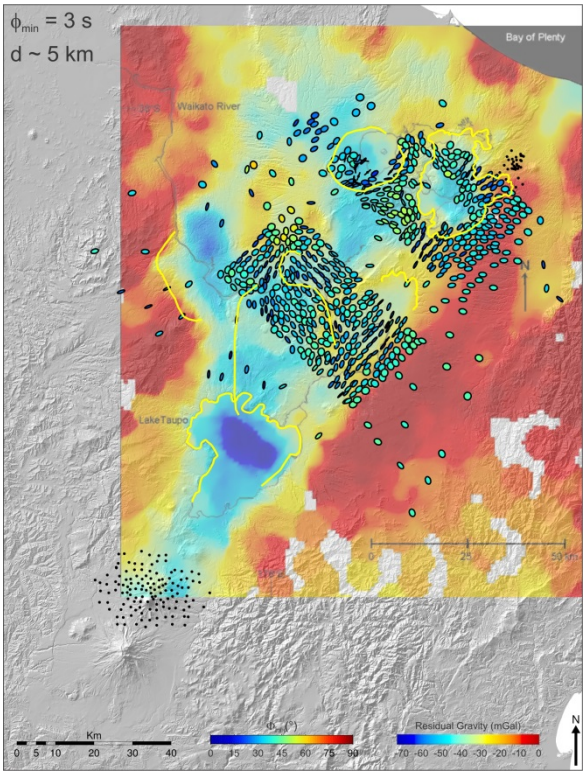


**Figure 5: Measured (normalised) phase tensor ellipses at 3 s period filled with colour that represents $\Phi_{min}$, overlaid on the TVZ residual gravity map.**

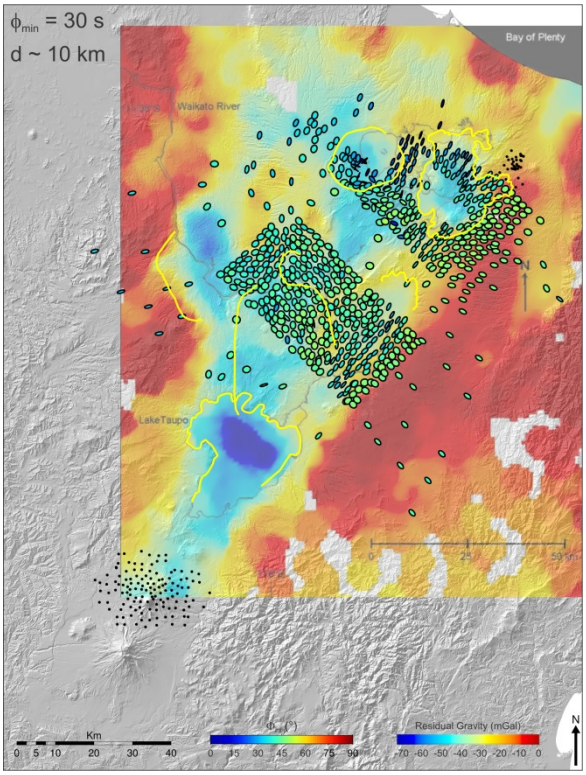


**Figure 6: Measured (normalised) phase tensor ellipses at 30 s period filled with colour that represents $\Phi_{min}$, overlaid on the TVZ residual gravity map.**

Using 10% error floors for the impedance tensor components yielded a final normalised r.m.s. (root-mean-squared) misfit of 1.8, within the accepted range for regularized inversions.

A single overall (average) model misfit can be an unreliable value to assess a 3-D inversion model (Tietze and Ritter, 2013). Figure 7 shows individual normalised r.m.s. misfit values for all 169 sites inverted. These site-misfits range between values of 1 to 3, and show the data are well fit by the model.

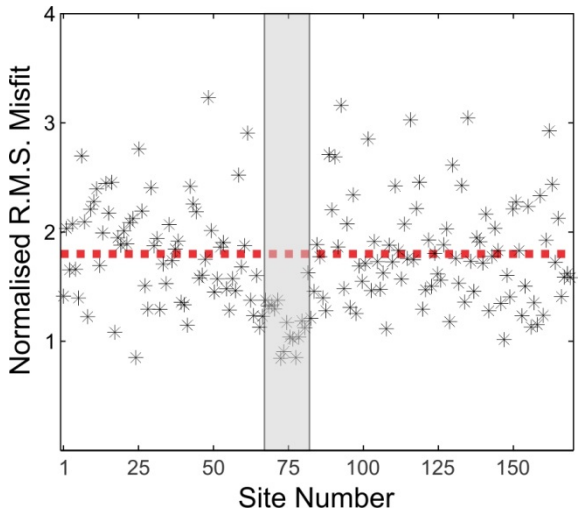


**Figure 7: Normalised root-mean-squared (r.m.s.) misfit for all 169 MT sites included in the final 3-D resistivity inversion model. Red dashed line shows the total model misfit value of 1.8. Grey region shows 20 measurements made during a period of intense solar activity in March 2012, resulting in high-quality data and low misfits.**

## 4. DISCUSSION

Figures 8 and 9 show slices through the 3-D resistivity inversion model (from Bertrand et al., 2015) with key resistivity structure and implications discussed below.

The Rotokawa geothermal field (Figure 2) hosts a high-temperature liquid reservoir in andesite rock from ~1 - 2.5 km depth that directly overlies the basement greywacke. The geology at Rotokawa exemplifies the description of the TVZ as a 'rifted arc' (Wilson et al., 1995) with former andesite volcanoes in the central part of the TVZ down-faulted and now buried by silicic volcanics derived from large caldera-forming rhyolitic eruptions occurring within the past ~2 Myrs. Measured temperatures at geothermal wells beneath Rotokawa approach that of the brittle-ductile rheological transition, e.g. a measured temperature of 332°C at only 910 m depth beneath the southern part of the field (Hunt and Harms 1990). Below the shallow low-resistivity structure at Rotokawa (Heise et al., 2008), a deep low-resistivity 'plume' is imaged (Bertrand et al., 2012; 2015) that rises to ~3 km depth. The upper part of this plume correlates with a cluster of earthquake hypocentres (Bertrand et al., 2015). These earthquakes are largely induced from high thermal gradients caused by fluid re-injection (Sherburn et al., 2015), and cut-off below ~3.5 km depth, which we assume to mark the brittle-ductile transition where temperatures are above 350°C. Key to understanding the implications of the MT resistivity model is to ask: is the deep low-resistivity plume caused by saline fluids, partial melt or a combination of the two? Using measurements of soil $CO_2$ flux at Rotokawa (Bloomberg et al., 2014), an average heat flux is calculated for the field of 1255 mW/m$^2$ (similar to values in Bibby et al., 1995). Assuming a thermal conductivity typical for felsic rocks and assuming conductive heat transport, a thermal gradient of ~500°C/km is required to support this heat flux. Therefore, ~ 1 km below the cut-off of seismicity (at a depth of ~4.5 km) temperatures would be on the order of 800°C, within the range of 730-850°C inferred for TVZ silicic melt (Sutton et al., 2000; Nairn et al., 2004).

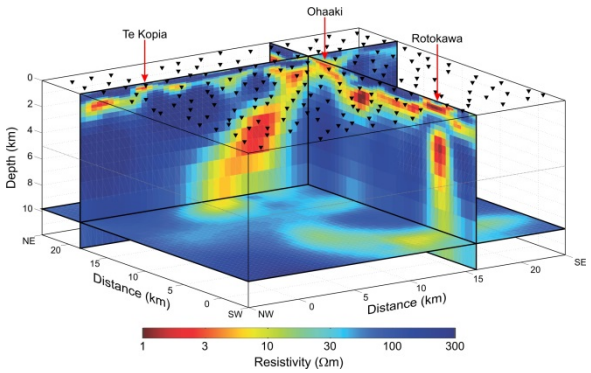


**Figure 8: Fence-diagram of the 3-D resistivity model that cuts through the Rotokawa, Ohaaki and Te Kopia geothermal fields. MT site locations are shown by black triangles.**

We therefore interpret the deep low-resistivity plume to mark a crystallizing silicic magma, with an overlying halo of alteration and exsolved magmatic fluid at lithostatic pressure. These fluids could have a resistivity as low as ~0.01 Ωm (e.g. Heise et al., 2015) and may explain why the top of the low-resistivity plume extends shallower than the depth (~4.5 km) we infer for melt. Episodic breaches of this self-sealed halo (Fournier 1999) may produce pulses of magmatic fluid and associated seismicity. The existence of a young intrusion beneath Rotokawa is consistent with geological evidence for several large hydrothermal eruptions occurring within the last 20 kyrs (Collar and Browne, 1985).

A 5 km depth slice through this resistivity model (see Figure 6 in Bertrand et al., 2015) shows a striking correlation between the low-resistivity zone beneath Rotokawa, and the margin of a circular low-gravity zone bordered by the Wairakei, Tauhara and Rotokawa geothermal fields. We interpret this circular low-gravity anomaly to mark a caldera collapse (e.g. Stern 1982; Rogan 1982), which suggests a strong link between volcanic structure and these geothermal fields.

At a depth of 2.6 km beneath the Ngatamariki geothermal field, an intrusive complex was drilled directly below a zone of magmatic hydrothermal alteration. Although this intrusion is too old (0.7 Myr; Chambefort et al., 2014) to be the heat source for the current geothermal system at Ngatamariki, it provides a key example for interpreting the resistivity structure imaged by MT data, and to understanding the implications for heat and fluid flow in the TVZ.

Specifically, this intrusive complex provides a direct (although extinct) example of the young and hot intrusion that we interpret in the resistivity structure below Rotokawa. Recent MT models also show similar low-resistivity zones at basement depths offset to the northwest at Ohaaki (Figure 8; Bertrand et al., 2013; Mroczek et al., 2015), and located beneath the Waimangu and Rotorua geothermal fields (Heise et al., 2015). In particular, beneath Rotorua, which has an average surface heat flux of 2043 $mW/m^2$ (Bibby et al., 1995) the top of the deep low-resistivity plume rises to ~2.5 km depth below the surface.

While the intrusion located beneath the northern margin of Ngatamariki is not the heat source for the present day geothermal field, our MT resistivity modelling shows a deep low-resistivity zone located beneath an elongate rhyolite dome (Whakapapataringa) that appears to have been extruded along the boundary fault of the Whakamaru caldera (Figure 9). We interpret this low-resistivity zone to also mark a body of crystallising magma supplying heat to the present day geothermal field. If our interpretation is correct, this low-resistivity zone is evidence for the most recent of multiple magmatic intrusions in a region focused around the Ngatamariki geothermal field. This interpretation is consistent with geological evidence that the heat output of several TVZ geothermal fields has episodically waxed and waned in response to nearby magmatic events (Arehart et al., 2002; Milicich et al., 2013).

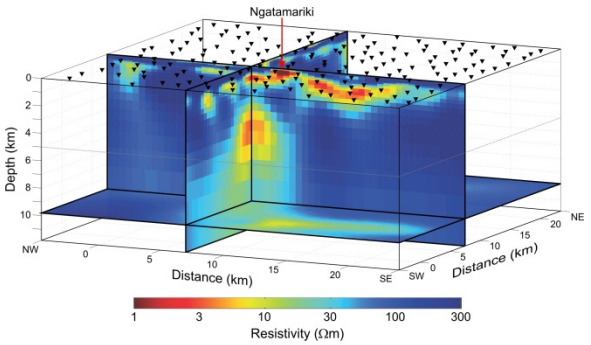


**Figure 9: Fence-diagram of the 3-D resistivity model that cuts through the Ngatamariki geothermal field. MT site locations are shown by black triangles.**

In contrast, deep (basement) low-resistivity zones are not imaged beneath the Orakei-Korako and Te Kopia (Figure 8) geothermal fields. It may be that these systems are in a waning phase and underlain by old and now resistive intrusions. Alternatively, these systems may be driven by deep fluid convection associated with enhanced permeability along the Paeroa fault.

## 5. CONCLUSIONS

MT resistivity models, interpreted with seismic, gravity and geological data provide evidence that show close spatial correlation between the margins of collapse calderas (inferred from gravity and geological data) and the locations of deep low-resistivity zones interpreted to mark bodies of crystallising magma that underlie some of the geothermal fields. Our research changes the long-held geophysical model of heat and fluid transport in the TVZ. We have clear geophysical evidence for a much closer (and shallower) association between the underlying magmatic systems and the geothermal fields. These findings have important implications for future deep geothermal exploration.

## ACKNOWLEDGEMENTS

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