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The Importance of Full Impedance Tensor Analysis for 3D Magnetotelluric Imaging the Roots of High Temperature Geothermal Systems:Application to the Taupo Volcanic Zone, New Zealand

G. A. Newman[1], N. J. Lindsey[1], E. Gasperikova[1], E. A. Bertrand[2] and T. G. Caldwell[2]

Lawrence Berkeley Laboratory, MS 74R316C, One Cyclotron Road, Berkeley CA 94720, USA

[2]GNS Science, Wellington, New Zealand

ganewman@lbl.gov

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ABSTRACT

Roots of extractable geothermal resources (typically less than 3 km) originate at much greater depths, where fluids extract heat from high temperature sources (i.e. magma) and transport it to the surface. The fluid pathways required for this are not well understood; nor is the associated deep-seated permeability. Besides sourcing hydrothermal systems from which electricity can now be generated, these deep-rooted geothermal fluids also represent untapped energy resources themselves, which in the coming years may well be exploited with advances in deep drilling technology. Thus a very good case can be made to expand our knowledge on the roots of geothermal systems to better extract the existing resource base as well as tap into new sources of geothermal energy, including sources beyond current conventional extraction depths.

We are investigating the roots of various high temperature geothermal systems present in the Taupo Volcanic Zone (TVZ) in New Zealand's North Island using magnetotelluric (MT) soundings. Over 23 geothermal systems are known in the TVZ, yet a better understanding of the roots these systems could constrain how they yield an extraordinarily high heat flux. It is currently believed that high temperature convection plumes that extend down to depth of 8 km provide the fluids for these systems. However, much remains uncertain about the basement structure and mechanisms of heat transport and rock permeability below depths of 3 km, which is the present maximum drilled depth. Our ongoing analysis shows clear evidence of deep-seated electrically conductive plumes down to 10 km depth, which are manifested in the near-surface expressions of hydrothermal activity and clear permeable pathways for transporting geothermal fluids.

Our experience with the MT data modeling of a complex three-dimensional (3D) environment, such as in the TVZ, showed that it is necessary to analyze the full MT impedance tensor, since the analysis using only principal component tensor data (the off-diagonal components) can produce artifacts in the imaging process. While using only off-diagonal elements might be justified when the imaging grid is aligned with preferred structural trends in the data, for truly 3D environment this may be difficult if not impossible to achieve. Nevertheless, full MT tensor analysis also has its own challenges, especially how one treats data noise for all components in the impedance tensor, where individual entries can vary by several orders of magnitude at a fixed period. In these instances, the accuracy of noise estimates in the data and weights assigned to the components of the impedance tensor are very important.

1. INTRODUCTION

High-temperature, economic geothermal resources are currently restricted to drillable depths (typically less than 3 km). However, the roots of these geothermal resources originate at much greater depths, where fluids extract heat from high temperature sources (i.e. magma) and are transported to the surface. This convective process that is believed to be at work is not well understood; nor is the associated deep-seated permeability required. In this paper, we probe mechanisms of heat exchange and fluid transport beneath high-temperature geothermal systems in the Taupo Volcanic Zone (TVZ) using one of the largest 3D magnetotelluric (MT) arrays ever assembled (259 MT soundings; 1250 km^2). We demonstrate the necessity of full tensor 3D MT modeling by applying a different data processing and 3D inversion to data previously analyzed by Bertrand et al. (2012), retrieving many of the same dominant resistivity features. We expand upon their study by using 90 additional MT soundings that cover a new area to the NW, and consider two geothermal systems not discussed in the previous work. It is currently believed that high temperature convection plumes extending down to depths of 7 km provide the fluids for these systems (Bibby et al., 1995). However, there is a high degree of uncertainty regarding the structure of basement rocks (greywacke meta-sediments), mechanisms of heat transport and rock permeability below the present maximum-drilled depth of 3 km. In recent analysis of broadband MT survey data, which covered 875 km^2 of the TVZ, Bertrand and his colleagues illuminated some of the mechanisms. Here we show preliminary results from 3D inversion of off-diagonal and full tensor MT data recorded across the Taupo Volcanic Zone on the North Island of New Zealand.

2. MT DATA ANALYSIS

259 MT broadband (100 – 0.001 Hz) soundings were recorded in the south-eastern TVZ between 2009—2013 forming a rectangular array (25 x 50 km) extending from the south-eastern rift margin to beyond the Atiamuri geothermal system (see Figure 1). The data were robustly processed by GNS Science using a remote reference to eliminate local and cultural noise (Bertrand et al., 2012).

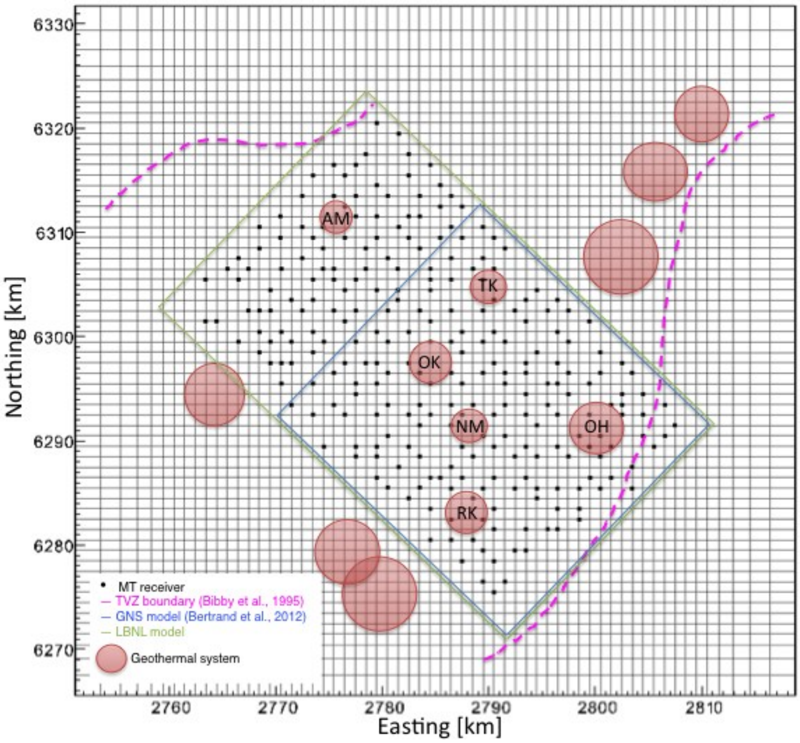

Figure 1: Map of Taupo Volcanic Zone (TVZ) after Bertrand et al. (2012). Green and blue boxes outline MT receivers (dots) used in this study and Bertrand et al. (2012), respectively. Red circles indicate currently-exploited geothermal systems, identified by DC resistivity (Bibby et al., 1995). The MT array probes six geothermal systems (OH=Ohaaki; RK=Rotokawa; NM=Ngatamariki; OK=Orekei Korako; TK=Te Kopia; AM=Atiamuri). Bertrand et al. (2012) discuss OH and RK. This study compares modeling results at OH and RK, and discusses new results from NM and AM

Preliminary analysis indicated that full tensor inversion is going to be required. Our use of the full MT impedance tensor is motivated by recent studies of synthetic and real MT data, which show that full tensor analysis is required to accurately image deep resistivity variations (Farquharson & Craven, 2009; Patro & Egbert, 2011; Tietze & Ritter, 2013; Kiyan et al., 2013). For instance, Kiyan et al. (2013) showed that the off-diagonal response to a simple elongated low-resistivity dike in a surrounding high-resistivity Earth was inaccurate unless the 3-D model mesh and data were rotated into geoelectric strike, or the on-diagonal components were included in the inversion. It seems implausible to define a single geoelectric strike across the entire 1250 km^2 area of the Taupo Volcanic Zone. Furthermore, Farquharson & Craven (2009) showed that the on-diagonal components control along-strike model variations. Thus, full tensor inversion is required to accurately image deep-rooted geothermal structures within the TVZ.

The inversion process solves Maxwell's equations for 3D resistivity variations and plane wave source excitation at a discrete set of frequencies. We invert only the low frequency data (1 — 0.001 Hz) on a modeling mesh with 1000 m cells across interior. We will refine this model in future work using the high frequency data to add resolution above 2 km depth. To stabilize the inversion, additional constraints were added such as spatial smoothing of the resistivity model. This inversion workflow has been shown to retrieve 3D images of geothermal systems in an accurate and efficient manner (Lindsey & Newman, in review). The 3D MT preconditioned inversion code (Newman & Alumbaugh, 2000; Newman & Boggs, 2004) was run on approximately 4000 cores of NERSC Cray XT4 Hopper system.

2.1 The Importance of Data Weighting

While it is possible to invert only the off-diagonal (Z_{xy} and Z_{yx}) tensor elements and retrieve an accurate model of shallow (<3 km) geothermal features, full tensor analysis is necessary to image deeper features of geothermal systems (>6 km) because on-diagonal (Z_{xx} and Z_{yy}) elements generally increase in amplitude with decreasing frequency (Kiyan et al., 2013; Tietze & Ritter, 2013). While it may be possible to improve the model with off-diagonal data, our findings thus far show that the grid needs to be properly aligned with the regional geological strike for acceptable results. For treatment of full tensor data, we may be relived of this burden, but acceptable results require careful analysis of appropriate data weighting schemes for treating full tensor data. Unfortunately, assigning data weights for full tensor inversion is non-trivial, because on-diagonal impedance tensor elements are of relatively low amplitude and higher variance. In this paper we explore a data weighting by which we down-weight data with high variance and use conservative error floors based on impedance element amplitude: 15% for Zxx and Zyy; and 3% for Zxy and Zyx. While a more aggressive assignment of the error floors is certainly possible. They are much more tedious and expensive to assign, especially with full tensor data. Moreover all noise models have to be verified though 3D inverse modeling. If the noise model is too aggressive the inverse iteration may fail to converge to an acceptable data fit.

2.2 Bias of Imaging Only Off Diagonal Component Data

Inverting just the off-diagonal data in a 3-D model mesh fails to retrieve significant geologic features identified in previous studies. For example, a low-resistivity (<5 Ohm-m) 'plume', which Bertrand et al. (2012) showed dips to the northwest beneath the Ohaaki geothermal field, is absent in our off-diagonal model. We retrieve a strong low-resistivity feature located northwest of Rotokawa geothermal field at 5 km b.s.l., however this conductor is elongated in the direction of mesh and data orientation, which is at a ~45^o angle to this feature in the Bertrand et al. (2012) model, where full tensor data were rotated to the assumed regional geological strike of the TVZ. These observations suggest that the off-diagonal model is potentially biased by our choice of mesh orientation (Kiyan et al., 2013).

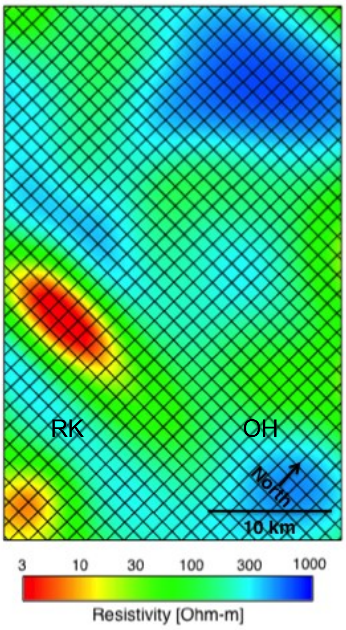

Figure 2: Horizontal slice (vertical axis SE-NW and horizontal axis SW-NE) at 5 km bsl through the 3D resistivity model retrieved through inverting only the Zxy and Zyx data in a N-S model mesh (unrotated). Area of figure is footprint of MT array, and RK and OH indicate surface locations of Rotokawa and Ohaaki geothermal fields (see Figure 1). Misfit between model and off-diagonal data is 1.32% of the original misfit with a final RMS of 2.48.

2.3 Full Tensor Treatment

When we invert the full tensor using the data weighting described we retrieve a model (Figure 3) that is more consistent with the resistivity model of Bertrand et al. (2012). Note further that we did not rotate our data to the assumed geological strike direction as was done in the Bertrand et al (2012) analysis. Low-resistivity 'plumes' are imaged beneath both Ohaaki and Rotokawa. Additional low-resistivity features, due to the expanded data array, are evident beneath geothermal systems to the northwest (i.e., Atiamuri, Te Kopia). While these results are encouraging, it must be stressed that further analysis is required to place these results in a geologic context. Nevertheless our resistivity model, suggest sustained convection cells that extract energy and volatiles from quasi-plastic rock at ~5 – 7 km, elevating fluid density. Hot saline fluids migrate upward from this depth, potentially controlled by heavily fractured zones (i.e., fault accommodation zones), depressing resistivity as they are transported to the geothermal systems. Intrusive volcanics may also contribute to the low resistivity features imaged between 3 and 7 km. Some selected data fits over the different geothermal systems, indicated in Figure 3, are illustrated in Figure 4 using the data weighting scheme outlined in section 2.1. In general, excellent fits are observed for the off diagonal components and reasonable good fits are produced for the diagonal components.

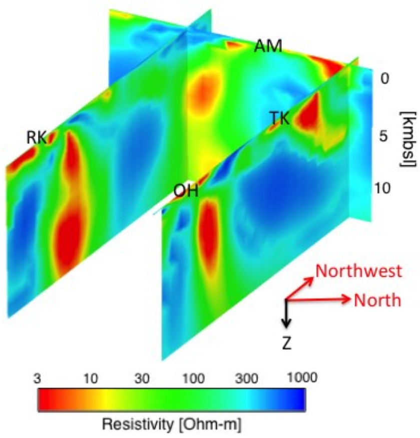

Figure 3. SE-NW and SW-NW vertical slices through the 3D resistivity model retrieved by inverting full tensor MT data. Surface expression of different geothermal systems are indicated as in Figure 1; see Figure 4 for example data fits at these locations. Model-data misfit for the full tensor is 2.67% of the original misfit with a final RMS of 2.54.

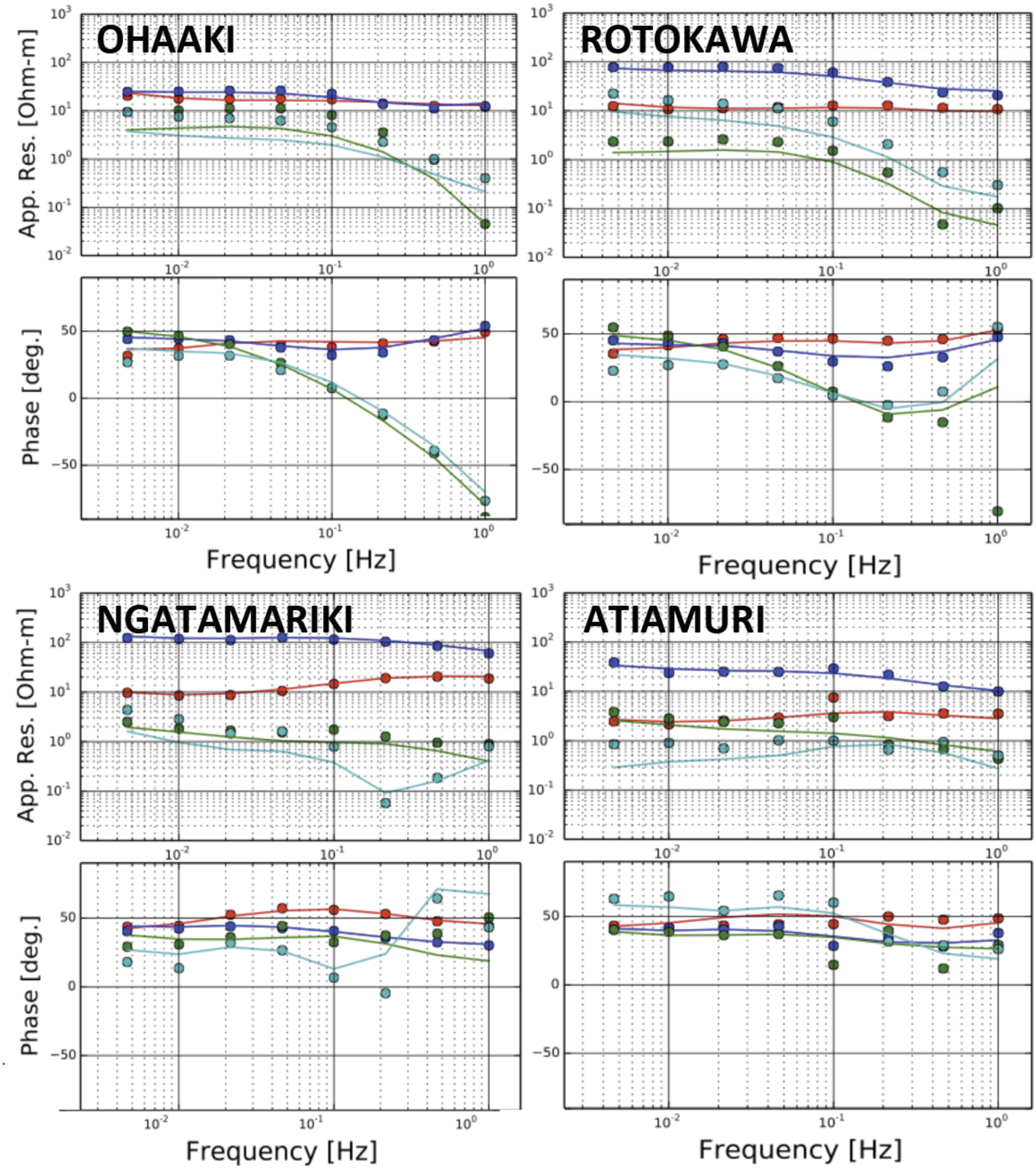

Figure 4. Example model predictions (solid lines) from the 3D model shown in Figure 3. Each example is located at the surface location of a different geothermal field. Circles indication inverted data. Color scheme is: Zxy=red; Zyx=blue; Zxx=green; Zyy=cyan).

CONCLUSIONS

Our experience with the MT data modeling of complex 3D geothermal systems and their roots show that it is necessary to analyze the full MT impedance tensor, since the analysis using only principal component tensor data (the off-diagonal components) can produce artifacts in the imaging process. Using only the off-diagonal elements might be justified when the imaging grid and data coordinate system are aligned with preferred structural trends in the data; however, for truly 3D environments this might be difficult if not impossible to achieve because such trends rotate with period and location (e.g., Simpson, 2000; Bedrosian, et al., 2004). Increasing the footprint and target depth of the MT survey, as in the case of the TVZ MT survey considered here, necessitates inversion of all tensor components in order to accurately image spatial complexity and resolve oblique conductive structures. Full MT tensor analysis has its own challenges, especially how one treats data noise for all components in the impedance tensor, where individual entries can vary by several orders of magnitude at a fixed period. In these instances, the accuracy of noise estimates in the data and the way these noise estimates are used to assign weights to the data during the imaging process becomes very important and can greatly influence the final inversion results. Yet, the selection of data weights based upon noise estimates is an inexact science. Therefore, additional appraisal procedures beyond plausible data weighting schemes, including use of multiple starting models, model regularization levels and different a priori information within the inversion process, will be required to test the robustness and reliability of key resistivity model structures and their relation to geothermal systems.

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