Observations and Implications of Magnetotelluric Data for Resolving Stratigraphic Reservoirs Beneath the Black Rock Desert, Utah, USA

Christian L. Hardwick[1], Rick Allis[1], and Philip E. Wannamaker[2]

[1]Utah Geological Survey, Salt Lake City, UT
[2]Energy and Geoscience Institute, Salt Lake City, UT
christianhardwick@utah.gov

Keywords

Black Rock Desert, magnetotelluric, gravity, resistivity, sedimentary basins, stratigraphic reservoirs

ABSTRACT

Magnetotelluric (MT) data are an integral part of geothermal resource exploration throughout the world. The Black Rock Desert (BRD), Utah, may be unique, with large datasets of MT soundings and gravity measurements in combination with oil exploration wells extending to 5 km depth possessing a variety of geophysical logs, and proven high heat flow in the central part of an underlying basin (temperatures exceeding 240°C at 3 m depth). Wireline geophysical data indicate basin fill signatures of 1 to 10 ohm-m and bedrock signatures of 10 to over 1000 ohm-m. Throughout the BRD, are large variations in lithology and, consequently, resistivity. Massive salt sections, when emplaced in clay-rich basin fill, show resistivities on the order of 100 ohm-m. The upper portions of the 1D, 2D, and 3D resistivity models have reasonable agreement with the wireline data, whereas in the central part of the basin, the deeper portions of the wells and the models have disparities that are an order of magnitude different. Possibly the most striking difference is the bottom of the Pavant Butte well where temperatures reach 240°C and in-situ resistivities are 100 ohm-m, but the modeled resistivities are an order of magnitude lower (<10 ohm-m). Possible explanations for this difference are the existence of aligned conductive fracture networks deep within the bedrock with a small fraction of crustal fluids in the pore space or differences in the averaging scale of MT data versus downhole wireline data. While emergent signatures of a deeply rooted system are more than likely detected with MT soundings, the signature of our specific target (stratigraphic reservoir) remains elusive.

Introduction

In geothermal exploration, resistivity surveys have been a key method in identifying and characterizing a resource. The magnetotelluric (MT) method (Chave and Jones, 2012) has been frequently used to delineate potential geothermal reservoirs beneath volcano-hosted systems using the low-resistivity (< 10 ohm-m), clay-alteration cap as an indicator of a more resistive (10 to 200 ohm-m), propylitic-altered reservoir at greater depth (Gasperikova et al., 2011; Anderson et al., 2000). Gasperikova et al. (2011) noted that in Iceland there are sufficient exceptions to the relationship between alteration, resistivity and temperature that in order to minimize unproductive drilling, information about the presence or absence of a deep heat source is also needed. MT interpretations of resistivity features deeper within the crust of geothermal regions, such as the Great Basin (western U.S.), the Taupo Volcanic Zone (New Zealand), and Iceland, have identified near-vertical, low-resistivity chimneys extending down to mid-crustal depths, and laterally extensive low resistivity at mid-to lower crustal depths. These features have been attributed to magmatic underplating and saline fluid upflow zones, as well as deep sedimentary structures (Wannamaker et al., 2008, 2013a,b, 2015; Gasperikova et al., 2011; Bertrand et al., 2012; Lindsey et al., 2014).

The purpose of this paper is to use an unusually large dataset of MT soundings (270) around the Black Rock Desert (BRD) of central Utah acquired by the Utah Geological Survey to compare the interpreted resistivity at depth with that measured in several deep oil exploration wells in the same area. The combination of high heat flow, wells extending to 5 km depth with a variety of geophysical logs, and large datasets of MT soundings and gravity measurements is probably unique. Our focus here is the resistivity variations within the uppermost 5 km, which is where there is the greatest potential for naturally permeable geothermal reservoirs (Allis et al., 2015a). This permeability is primarily stratigraphic, and therefore sub-horizontal, although it may be enhanced by faulting. Our objective here is to assess the value and challenges of using MT soundings to identify and delineate these geothermal reservoirs. A parallel paper (Wannamaker et al., 2015) uses the same MT dataset to map 3D resistivity variations throughout the entire crust with a new inversion technique.

The BRD is one of the largest basins in central Utah, with a residual gravity low anomaly of up to 30 mgal (a result of harboring as much as 3 km of Cenozoic basin fill), widespread late Quaternary volcanism, and active extensional faulting that approximately follows the north-south axis of the basin (figure 1). One of the oil exploration wells in the central BRD, Pavant Butte 1, has temperatures of greater than 240°C below 3 km depth, and Cambrian carbonate and siliciclastic units in the bedrock at this depth have been suggested as a reservoir target (Gwynn et al., 2013; Allis et al. 2015b). However, the southern end of the BRD seems to be cooler (about 150°C at 3 km depth) due to deeply circulating groundwater in the underlying Devonian-Silurian carbonate units. The bedrock beneath the ranges west and east of the BRD is even cooler (about 100°C at 3 km depth) despite typical Great Basin heat flow (~ 80 to 90 mW/m^2) due to its much higher thermal conductivity compared to basin fill. About 10 km southeast of the BRD is the Cove Fort geothermal field, where the reservoir is hosted in permeable lower Paleozoic carbonates with a temperature of 150 °C between 1 and 2 km depth. The variety of lithology contrasts (less resistive basin fill versus more resistive carbonates, silicilastics and Precambrian units), laterally varying temperature at potential reservoir depths, and pore fluid resistivity variations (salt units are present in the north of the BRD and absent in the south) provide challenges for using MT soundings to characterize the geothermal reservoir potential.

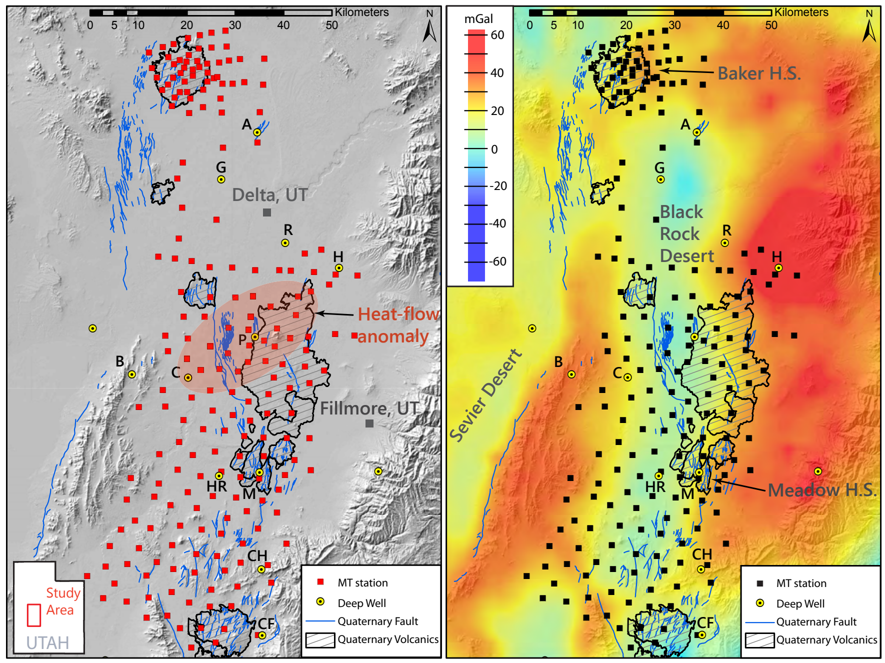


Figure 1. Shaded relief maps of Black Rock Desert showing locations of MT stations and deep oil, gas and thermal exploration wells (left) and isostatic residual gravity (right). The left panel highlights a high heat flow anomaly around the Pavant Butte well where temperatures are more than 240°C at 3 km depth. In the right panel, the approximately 30 mgal low anomaly highlights the north-south trending basin which has up to 3 km of basin fill. Deep wells are labeled as follows: A, Argonaut; B, Black Rock 1-29; C, Cominco Federal 2; CF, Cove Fort; CH, Caroline Hunt; G, Gronning; H, Henley; HR, Hole-in-Rock; P, Pavant Butte 1; M, Meadow; R, Rocky Ridge. Hot springs (H.S., > 50°C) exist at Baker, Meadow, and in the Cove Fort geothermal field.

Resistivity Signatures of the Black Rock Desert

A number of deep oil and gas exploration wells within the BRD (Figure 1) contain downhole logging information such as resistivity, sonic porosity, temperature and gamma. Though in some cases incomplete, this information is key when assessing a prospect as well as during the modeling and interpretation stages. Wireline log resistivity data from deep wells are shown in Figure 2. Basin-fill resistivity values vary from 1 to 10 ohm-m, but all values increase quickly when near the basement interface. Basin-fill resistivity values in the central part of the basin are lower than values near the basin margins. This is thought to be caused by changes in lithology from conductive clay-rich, paleo-lake sediments of the central basin to more resistive sand and gravel fan deposits on the margins. The increase of resistivity in the basin-fill sediments as depths approach the bedrock interface can also be attributed to this same lithologic change. Bedrock resistivity values vary from 10 to over 1000 ohm-m depending on whether the lithology is a quartzite or carbonate (limestone/dolomite). Although there appears to be a general increase in bedrock resistivity with increasing depth, this is mostly an artifact of the lower resistivity of the upper Precambrian siliciclastic units (interlayered shale and quartzite) at 1 – 2.5 km depth in the Cominco well, and the relatively high resistivity of the lower Paleozoic carbonate units and quartz monzonite between 3 – 5 km depth in the Meadow well.

Another interesting resistivity feature worth noting relates to the massive salt formations encountered in the deep wells of the northern BRD. Figure 3 shows wireline resistivities for the Argonaut and Rocky Ridge wells. For both wells the resistivity decreases rapidly (down to 1 ohm-m or less) just before reaching the depth of a massive salt layer where resistivity is around 100 ohm-m. This rapid change of resistivity is inferred to be a brine layer or saline pore fluid in strata immediately on top of the, dry massive salt sections. Although less pronounced, this pattern is also observed at the bottom of the massive salt section.

When comparing MT soundings to wireline logs there are inherent differences and implications. First, in order to have valid models, assumptions about dimensionality need to hold—1D models are appropriate for 1D conditions; 2D models for both 1D and 2D conditions; 3D models for 1D, 2D and 3D conditions—and those constraints largely sidestep considerations of intrinsic anisotropy versus small-scale heterogeneity in MT responses. Unavoidably, we are making measurements in a 3D world and simplified assumptions can be valid under particular circumstances or when an appropriate scale is considered. Here we present 1D, 2D and 3D resistivity models from the BRD study area and compare to resistivity values obtained from wireline logs of deep wells. We note that wireline logs only measure material within a few meters of the well, whereas MT soundings sense averages of lithologic response over larger areas, especially as depth increases.

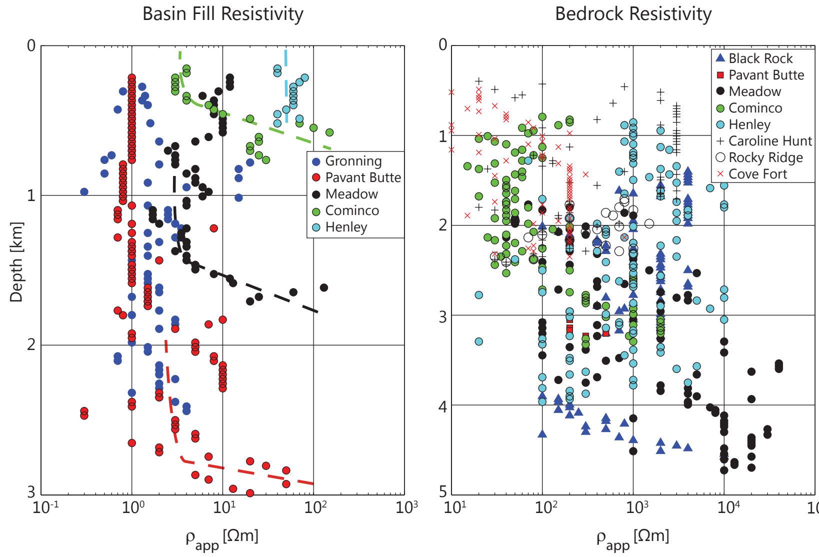


Figure 2. Wireline log resistivity vs. depth for select deep wells in the Black Rock Desert study area. Left panel shows resistivity trends of basin-fill sediment; right panel shows resistivity values of bedrock. Dashed lines highlight trends in the basin-fill resistivity measurements for some wells.

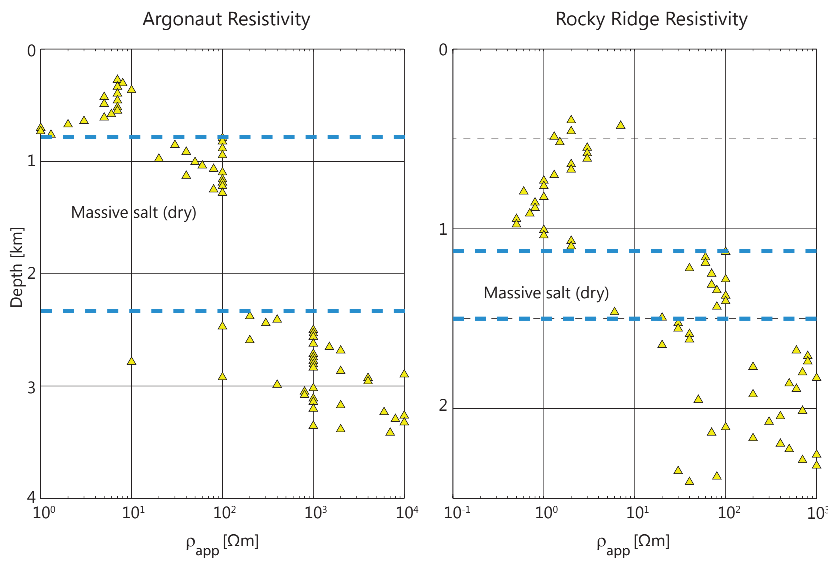


Figure 3. Wireline log resistivity for the Argonaut and Rocky Ridge wells. Dashed blue lines show the top and bottom of the massive salt section.

For eight deep wells we have created simplified, layered (1D) models from both well log resistivities and the MT data of adjacent (within 3 to 5 km) stations for comparison purposes (Figures 4 and 5). The well log resistivity trends are based on average resistivity over 100 ft depth intervals from long-spaced resistivity logs. The 1D MT models were derived using layered earth Marquardt inversion using a code written following the method of Petrick et al. (1977). For the latter, we utilize the nominal transverse electric (TE) mode of the MT response corresponding to electric current flow in an assumed N-S average strike direction. Also, we are limited to interpreting short-period, high-frequency data since in most cases the longer periods approach 2D and eventually 3D conditions, and models either will not provide a good fit to higher dimensional data or may give inaccurate structure.

In general, there is reasonable agreement between well log and 1D modeled MT resistivities down to about 3 km depth. However, a few wells (Black Rock, Cominco and Henley) have differences and/or required minor adjustments. The closest MT site to the Black Rock well is 10 km south (on top of sedimentary fill) so the model was adjusted to account for the fill since the deeper bedrock material is assumed the same. At the Cominco well, near-surface (< 0.5 km depth; basin fill) values are similar but the underlying bedrock is inferred (1000 ohm-m) to be more than an order of magnitude higher than well log data (10 to 100 ohm-m) until a depth of 3 km where models agree. The Cominco well is close to a major fault along the west margin of the BRD basin, so it is possible the MT station is located over a lower Paleozoic (high-resistivity) bedrock section rather than the upper Precambrian siliciclastic section encountered by the well. The Henley well models are off by an order of magnitude with the well log data being higher resistivity. This difference could be due to the fact that the MT sounding is farther out into the basin. The Henley models have been adjusted to compensate for lower resistivity fill compared to inferred alluvial fan deposits intersected at the well.

Below about 3 km depth, 2D and 3D effects start to be more significant, and there is a poor fit between the well log and the MT curves at the corresponding periods. Apart from this effect, two wells (Pavant Butte and Caroline Hunt) show significant differences between the observed deep resistivity from averaged logs and the resistivity inferred from 1D inversion. At the Pavant Butte well, there is reasonable agreement between the models down to approximately 3 km depth, but significantly lower resistivity is inferred from the MT sounding than what is observed in the upper 300 m of bedrock in the well. At 3 km, below the bedrock interface, the well log resistivities are on the order of 100 ohm-m and the inferred resistivity from MT at 10 ohm-m. This well is in the deepest and hottest part of the basin. At 5 km depth the temperature is inferred to be more than 300°C (Allis et al., 2015b), so we are uncertain whether more complex 2D or 3D effects in the MT explain the difference, or whether the MT model reflects much lower resistivities in very hot rock at greater depth within the MT resolution.

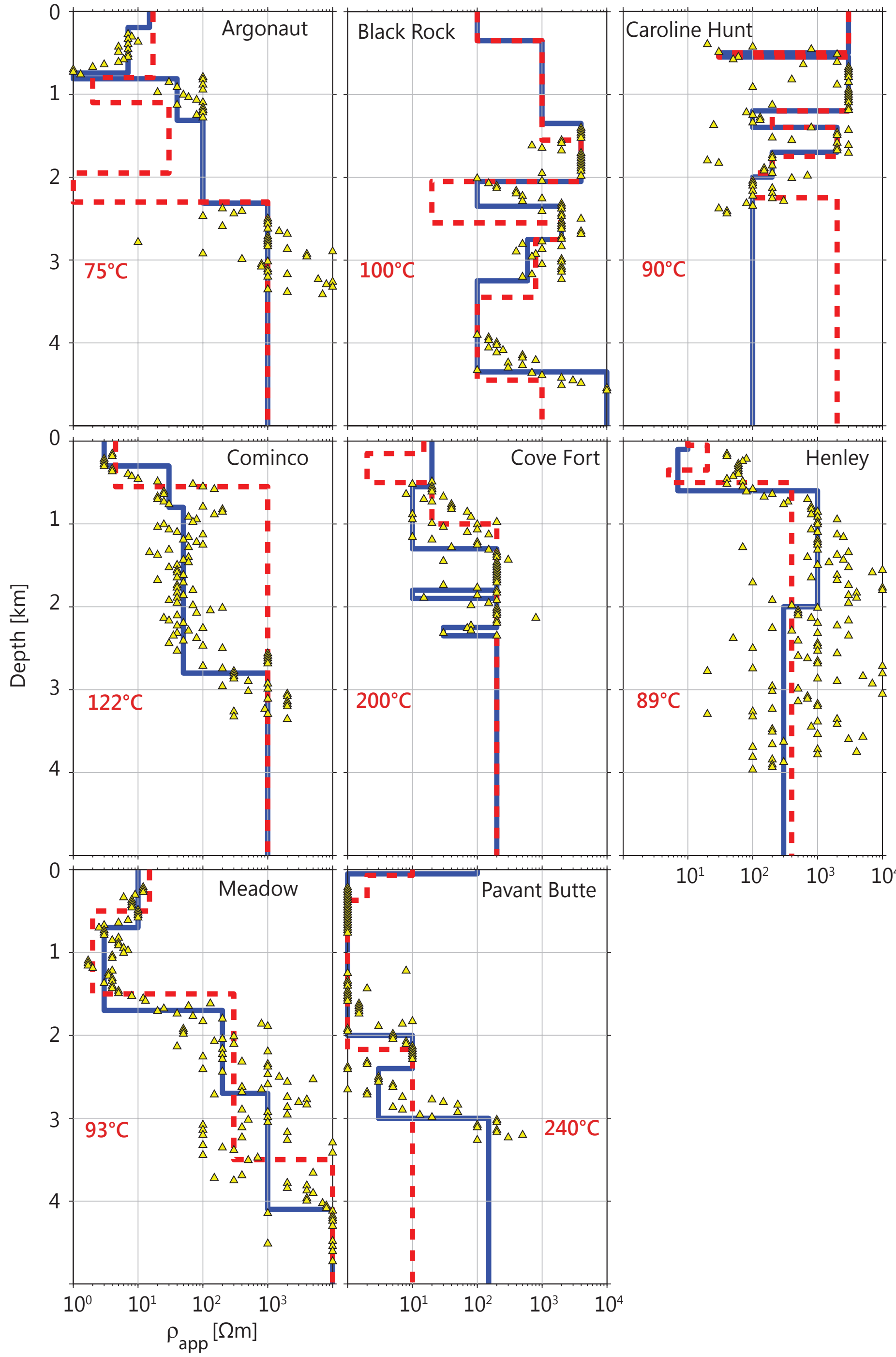


Figure 4. Wireline log resistivity values (triangles) for deep wells (see Figure 1) and 1D forward models of adjacent MT soundings. Blue lines are best-fit models to log resistivities and red dashed lines are best-fit models from MT soundings. Indicated temperatures are extrapolated from the updated estimates of Gwynn et al. (2013) at 3 km depth.

In contrast, at the Caroline Hunt well the MT detects much higher resistivity(>1000 ohm-m) below 2.5 km depth than the model based on logged resistivities (<100 ohm-m). Here we suspect the projected resistivity (based on well logs) below the well bottom is incorrect. If the deep resistivity is similar to that observed in lower Paleozoic bedrock below 3 km depth in the Meadow well (20 km to the north), then the observed and inferred resistivity from the MT would be in agreement. Inferred temperatures from Gwynn et al. (2013) at 3 km depth are also shown in Figure 4 though there does not appear to be any clear relation between resistivity and temperature. Any possible relationships could very well be masked by the large variation in lithologies within and between wells.

When considering the fit to the MT curves in Figure 5, the apparent resistivity maps (Figure 6), and the phase tensor maps in Figure 7, it is important to realize the large change in effective skin depth (approximation of penetration depth) with increasing period between the center of the low resistivity basin fill, and the resistive bedrock outcropping in the adjacent ranges. The skin depth (in meters) is given by (e.g., Chave and Jones, 2012): where skin depth () is dependent upon apparent resistivity (and period (T). For example, at the Pavant Butte well, with an average basin-fill resistivity of 2 ohm-m to at least a period of 10 seconds, the skin depth is 2 to 2.5 km, and at that period, the underlying bedrock is poorly sensed. However, with the Caroline Hunt well situated on an outcrop of carbonate rocks, the 300 ohm-m average resistivity to a period of 10 seconds is theoretically sensing to about 25 km depth (assuming purely 1D conditions). At this average resistivity, the skin depth of 2.5 km corresponds to a period of 0.1 seconds.

Figure 6 shows apparent resistivity values plotted in specified periods for the TE mode. The low-resistivity basin fill is well defined in apparent resistivity at 10 seconds, and there are subtle indications of the very low resistivity zone getting narrower at 20 seconds. Although most of the MT stations were sited within the basin, a few of the stations to the west and the southeast are close to outcrops of bedrock. These stations show the high-resistivity bedrock at all periods.

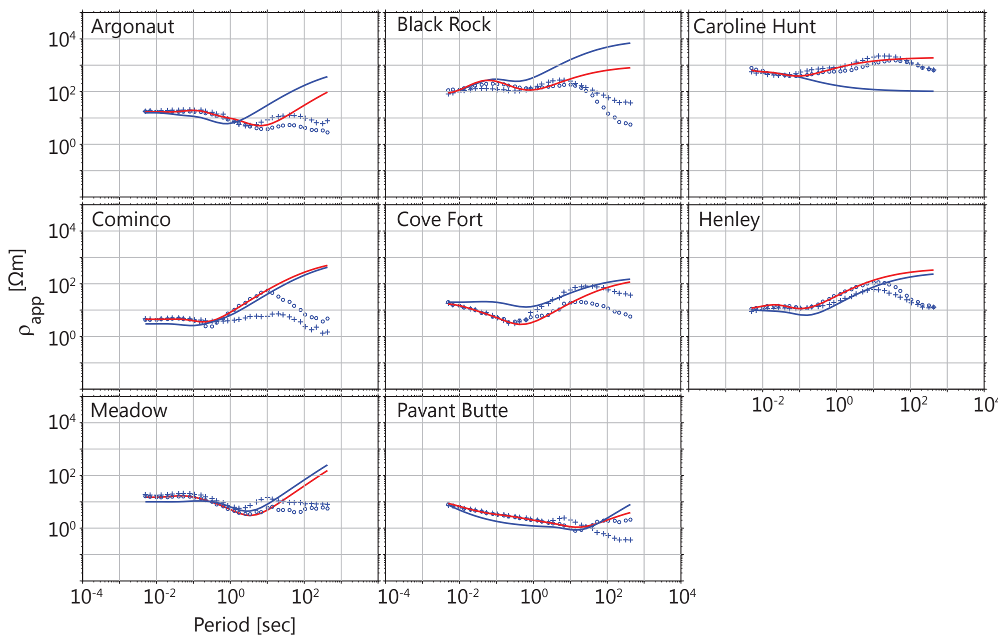


Figure 5. Apparent resistivity curves for MT soundings near deep wells (see Figure 1) in the BRD. Blue lines are best-fit models to well log resistivities and red lines are best-fit 1D models to assumed TE (transverse electric) mode of the MT sounding data. Open circles are TE mode and crosses are TM (transverse magnetic) mode.

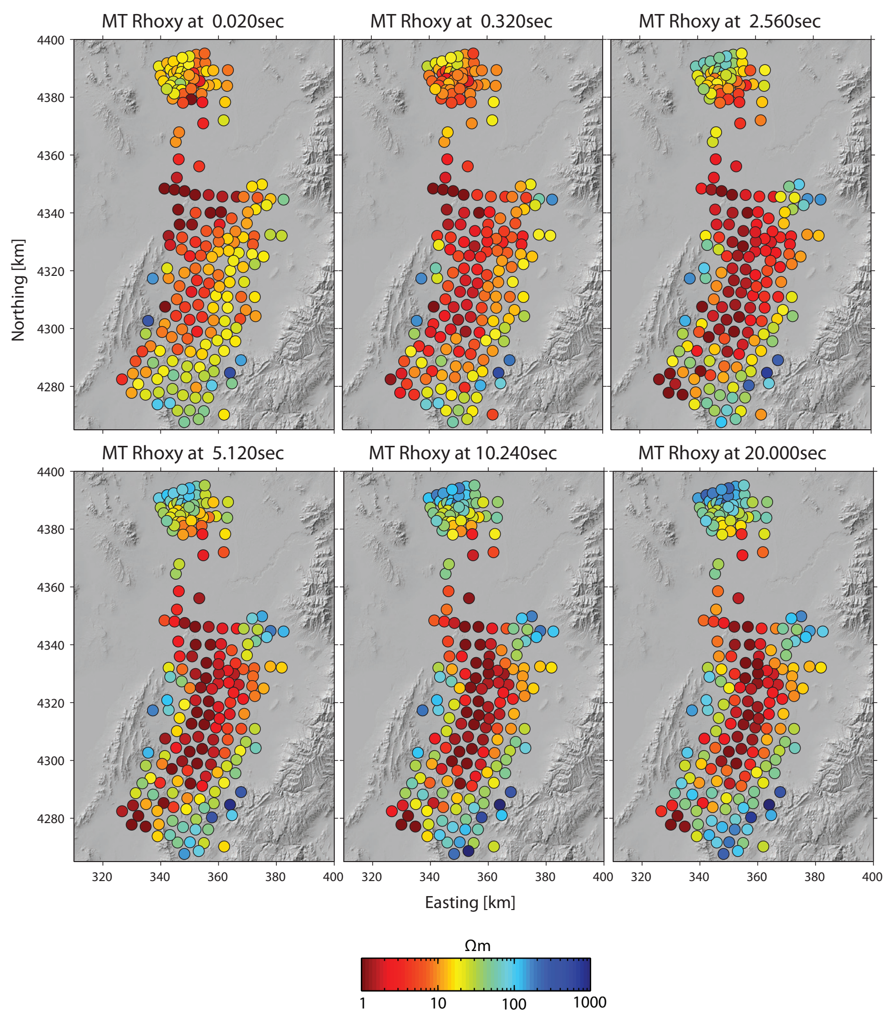


Figure 6. Maps of MT apparent resistivity by period for the Black Rock Desert study area. Low resistivities (<10 ohm-m) are typical of the basin-fill sediments and the basin signature is more prominent in the longer periods when juxtaposed against typical bedrock values (>100 ohm-m).

Quality and Dimensionality Analysis of the MT Response

Preliminary examination of the MT data allows us to determine its quality as well as carry out general interpretations. One method for analyzing MT data is phase tensor analysis following Caldwell et al., (2004). The coherency and quality of the data can be screened in general by plotting the phase tensor ellipses by period per station or in map view. Clear trends, patterns, or groupings of similarity both spatially and by period should be present, especially with tightly spaced surveys. Any variation in the phase tensors is expected to be smooth and continuous for periods sensing a common volume, whereas abrupt changes may be an indication of poor data quality. In Figure 7, we plot a graphical representation of the phase tensor for specific periods from 0.02 to 20 seconds. The shape of the phase tensor indicates 1D (circular shape), 2D, or even 3D (ellipse shape) conditions. At short periods, the data appear to be primarily 1D, and transition to 2D/3D at longer periods. By 10 seconds, the data no longer appear to include any 1D conditions. From an earlier phase tensor analysis, followed by 2D resistivity models (Hardwick, 2013), the MT data are of high quality and have good coherency both spatially and by period. The additional MT soundings acquired in 2012 and 2014 in the BRD are of the same high quality and appear to fit seamlessly with the earlier data according to the phase tensor parameters.

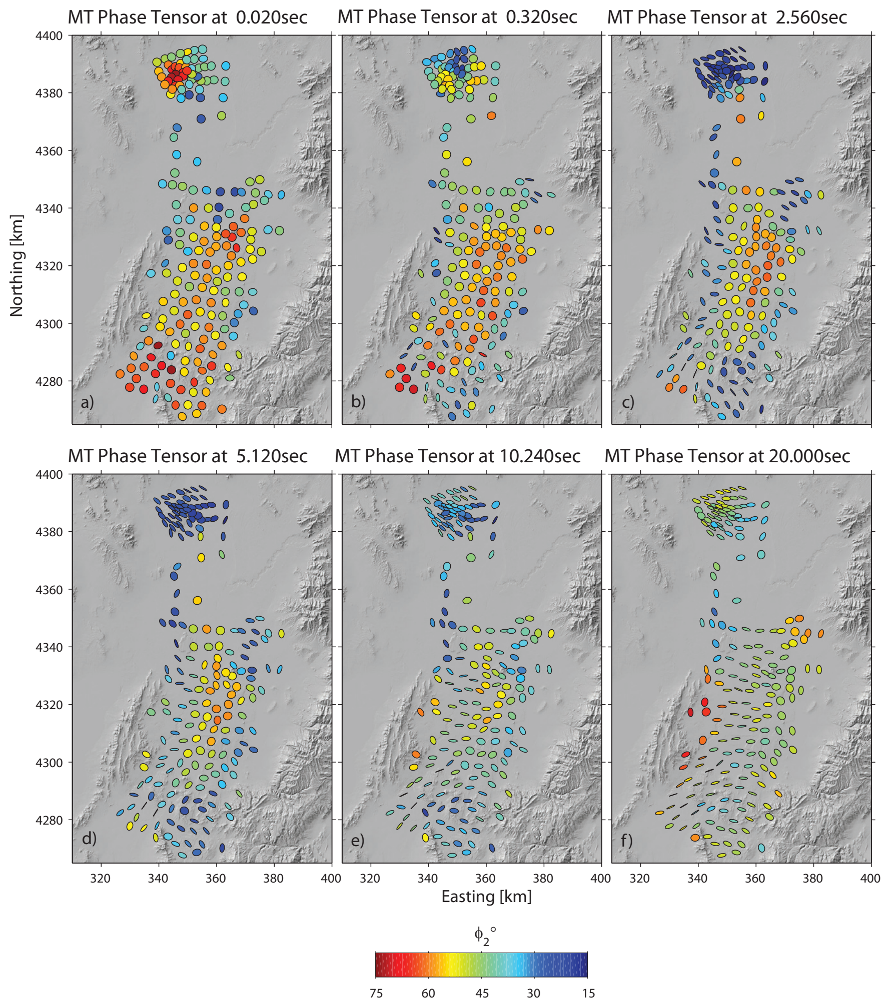
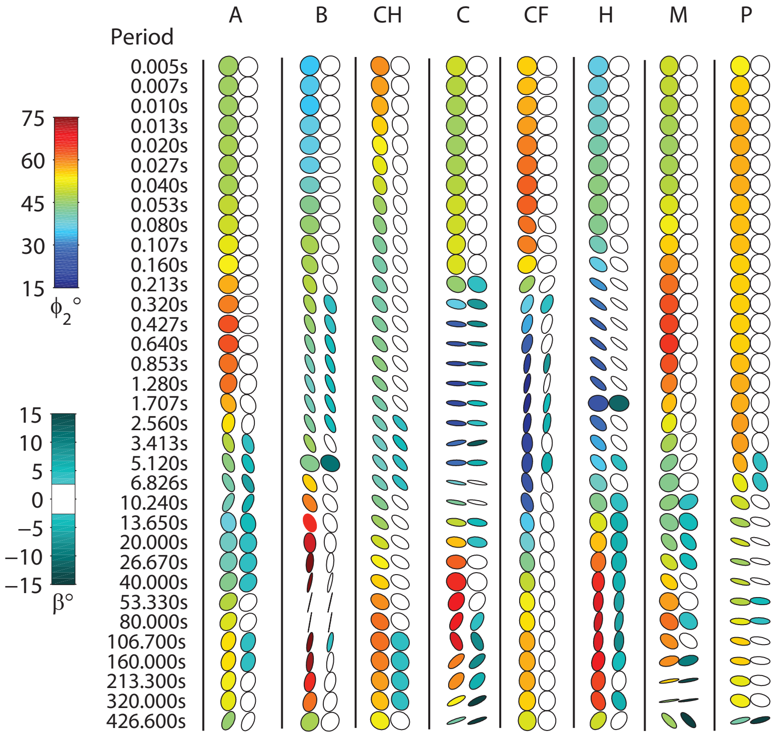


Figure 7. Maps of MT phase tensor diagrams by period for the Black Rock Desert study area. Phase tensors at shorter periods are circular, indicating 1D conditions, and change to ellipses at longer periods, indicating 2D and 3D conditions. Phase tensor color is the geometric mean of the minimum and maximum phases and signifies the conductivity gradient of subsurface resistivity structure. Low phase values appearing at the margins of the basin are interpreted as detection of the resistive bedrock. In the central part of the basin, the low resistivity of the basin fill is reflected in the high phase values.

The direction of the ellipse axes aligns parallel or perpendicular with the geoelectric strike (current flow direction) but a 90 degree ambiguity requires external information (regional structure, MT induction vectors, etc.) to distinguish the true strike. In the BRD, we can use gravity field information (Figure 1) to determine geoelectric strike direction and resolve the ambiguity. The gravity field of the study area shows that the regional trend of the body of interest (sedimentary basin) is in a mostly north-south direction with an amplitude on the order of 30 mGal. When modeled, this results in basin fill thicknesses on the order of 2 to 3 km as 2D models of Hardwick and Chapman (2012), Hardwick (2013), and Allis et al. (2015a) have shown.

The phase tensors are colored by the invariant parameter ϕ_2 (geometric mean of the minimum and maximum phases) which indicates the conductivity gradient of the subsurface structure (< 45 deg is more resistive toward depth and > 45 deg is more conductive). Spatially, the phase tensors indicate that a transition to a more resistive structure is detected around the margins of the basin (interpreted as bedrock), whereas the center of the basin is more conductive. Figure 8 illustrates the variation of the phase tensor parameters by period for the 1D forward modeled wells above. In general, the phase tensors smoothly vary by period with a few exceptions that are likely noisy data points. The right-hand side of the pair of tensors for each well is colored according to the skew (β) parameter which gives a sense of the dimensionality of the MT data for that specific period. Where the phase tensor ellipses are uncolored ($|\beta| \leq 3°$) it is generally accepted as the boundary of quasi-2D conditions (as suggested by Booker, 2014). MT sites (co-located with wells) showing transitions to

Figure 8. MT Phase tensor profiles plotted by period for sites (locations in Figure 1) used in the 1D models. Deep wells are labeled as follows: A, Argonaut; B, Black Rock; CH, Caroline Hunt; C, Cominco Federal 2; CF, Cove Fort; H, Henley; M, Meadow; P, Pavant Butte 1. Phase tensor color of the left-hand column is the geometric mean of the minimum and maximum phases and the right-hand column is the skew parameter.



3D at shorter periods (0.2 seconds) according to β are found on the margins of the basin (Black Rock, Cominco, and Cove Fort). The MT sites exhibiting β values below the threshold of ≤ 3° until longer periods (3 to 10 seconds) are found in the basin near the wells where fill is thick (Argonaut, Meadow, and Pavant Butte).

Previous work focusing on geothermal characterization of the BRD includes smooth 2D resistivity models (Hardwick and Chapman, 2012; Hardwick, 2013) as well as 3D resistivity models (Wannamaker et al., 2013a). Since these previous studies, 50 MT soundings have been added to the southern study area and are being included in a revised 3D resistivity model for the entire study area (Wannamaker et al., 2015). The 2D models (model example shown in Figure 9) were limited to data periods up to 10 seconds due to strong 3D behavior observed at longer periods in the initial phase tensor analysis. The consequence of essentially "chopping" the data is that areas where skin depth is small (i.e., areas of low resistivity) end up with an unintended downward smearing effect in the model space. With regard to the BRD basin-fill resistivities of 1 to 10 ohm-m, the skin depth is on the order of 1.5 to 5 km. In the center of the basin we may not be able to truly resolve the bedrock interface, whereas at the margins it is more likely to be resolved in the model. Gravity data for the basement interface show the basin margins to be somewhat resolved in the MT model, while the basin center is not. One of the main modeling disparities is the difference in resistivity between the MT model (<10 ohm-m) and the well-log-based bedrock resistivity (100 ohm-m) from the Pavant Butte well.

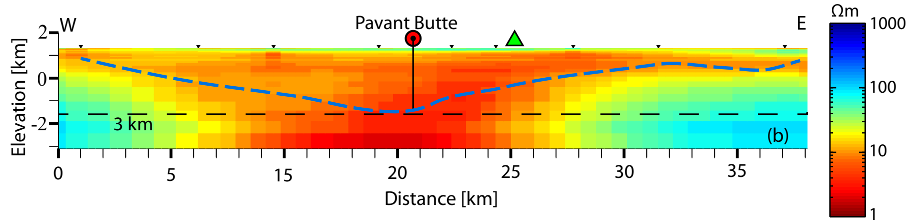


Figure 9. 2D MT resistivity model modified from Hardwick and Chapman (2012). MT stations indicated by black triangles, green triangle is Pavant Butte volcano, red circle is Pavant Butte well, dashed black line is 3 km depth, and dashed blue line is the bedrock interface inferred from gravity data.

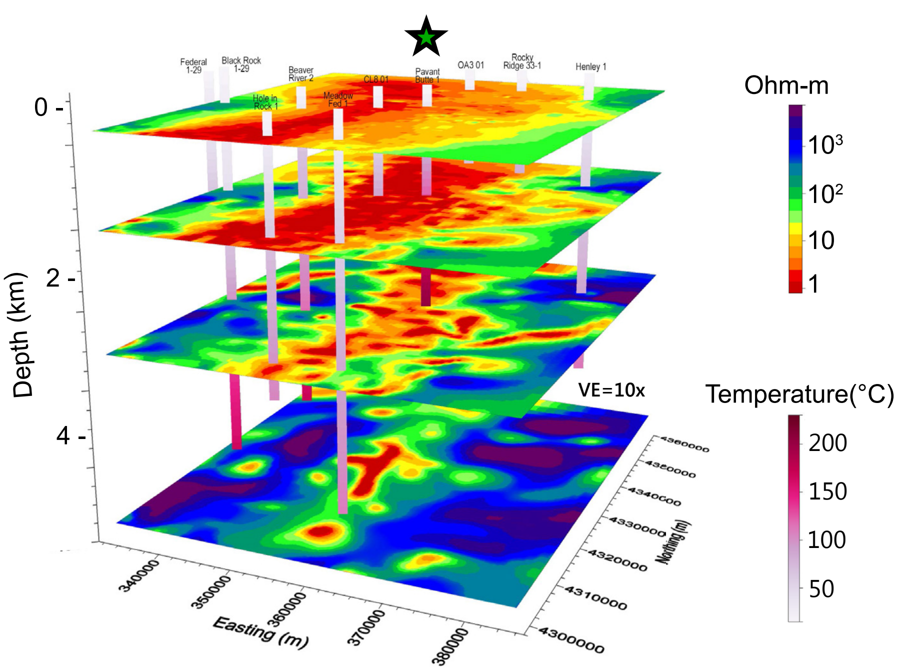


Figure 10. Subset of the BRD 3D resistivity model from the work of Wannamaker et al. (2015). Deep wells with thermal information are shown and a green star indicates location of Pavant Butte well.

Following the initial 2D MT modeling (Hardwick and Chapman, 2012; Hardwick, 2013), Wannamaker et al. (2013a) created a preliminary 3D MT resistivity model incorporating data from 34 new MT soundings acquired in 2012. In 2014, an additional 50 new MT soundings were acquired which extended data coverage through the south end of the BRD. In Figure 10, we show a subset of a recently updated 3D MT model from Wannamaker et al. (2015). The data periods used in the 3D inversion were 0.08 to ~212 seconds (more than 1 order of magnitude greater than the imposed 2D modeling constraint), allowing the modeling of deeper structure. Comparison of the 3D resistivity models of Wannamaker et al. (2013a, 2015) to the 2D models of Hardwick and Chapman (2012) show there is reasonable agreement. The deep, low-resistivity root is present in both, but the resolution of the resistivity structure is much higher in the 3D model than in the prior 2D models. At the bedrock interface in the Pavant Butte well, the 3D model has a value of around 10 ohm-m, as do the 2D models. Wannamaker et al. (2013a) viewed the resistivity disparity as an averaging scale issue where the Pavant Butte well may have passed into a local resistive block or the conductive axis of the basin comprises a network of conductive fractures in a resistive matrix not intersected by the well.

Conclusions

Wireline geophysical data from deep oil explorations in the BRD indicate basin-fill resistivity signatures of 1 to 10 ohm-m and bedrock signatures of 10 to over 1000 ohm-m. Throughout the BRD there is a large variation in lithologies and, consequently, resistivities. With such a large range in lithologies and resistivities, it is not practical to infer temperature field differences from resistivity models alone due to inherent complexities. Massive salt sections in clay-rich basin fill show resistivities on the order of 100 ohm-m (not low-resistivity targets). The upper portions of the 1D, 2D, and 3D MT resistivity models have reasonable agreement with the wireline resistivity data. In the central part of the basin, measured resistivity and MT models for the deeper portions of the wells can differ by an order of magnitude. Possibly the most noticeable difference occurs at the bottom of the Pavant Butte well (3 km depth) where temperatures reach 240°C and are of significant geothermal interest. The resistivities from the well log are 100 ohm-m and the modeled MT resistivities are an order of magnitude lower (<10 ohm-m). One possible explanation for this difference is the existence of an aligned conductive fracture network at depth with a small fraction of crustal fluids in the pore space, as was a considered in Dixie Valley by Wannamaker et al. (2013b). A second possibility for the discrepancy is the averaging scale (resolution) of MT data versus downhole logs (Wannamaker et al., 2013a). Lastly, with a new and unconventional geothermal target (stratigraphic reservoir) it is possible that the MT method requires a slightly modified approach when addressing the resistivity signatures of this new target. One possibility would be to constrain more structures independently so that the model could focus more on specific stratigraphic layers and their properties. A question for geothermal exploration involving stratigraphic reservoirs is whether MT can accurately resolve a reservoir target overlain by conductive fill material in a 3D setting. While strong signatures of a deeply rooted system are more than likely detected, the signature of a stratigraphic reservoir target remains subtle, if not obscure, for the time being.

As in any natural resource investigation using surface methods, it is important to understand the strengths and limitations of the technique used. The optimal analysis is more than likely going to be one that combines multiple techniques for an area of interest. The caveat of using any surface method (gravity, magnetics, electromagnetics, resistivity, seismic, etc.) is that resolution degrades with increasing distance from the target of interest. In the case of BRD geothermal characterization, our proposed target is 3 to 5 km below the surface where the most important aspect, porosity, is at a seemingly undetectable scale unless measured directly from core or with downhole logging tools. With the fragile viability of geothermal energy being a consequence of real risk and high cost up front, the ability to remotely sense or measure the most critical parameters (porosity, temperature) is a key requirement. Further work is needed to improve understanding of the relationships between variations of temperature, resistivity, fluid chemistry and lithology on a basin scale for the BRD study area as well as any other stratigraphic reservoir targets.

Acknowledgements

This work was partially supported by the Geothermal Technologies Office of the Department of Energy through award DE-EE0005128. We also acknowledge the use of ARRA funds from the Utah Office of Energy Development. We thank the reviewers for providing valuable constructive criticism and editing to improve the overall quality of this manuscript. MT data from Cove Fort were kindly donated by ENEL Inc. (A. Rael, PoC) to P. E. Wannamaker for our research.

References

Allis, R., Gwynn, M., Hardwick, C., Mines, G., and Moore, J., 2015a. Will stratigraphic reservoirs provide the next big increase in U.S. geothermal power generation? Submitted Geothermal Resources Council Transactions, this volume.

Allis, R., Hardwick, C., Gwynn, M., and Johnson, S., 2015b. Pavant Butte geothermal prospect revisited. Geothermal Resources Council Transactions, this volume.

Anderson, E., Crosby, D., and G. Ussher, 2000. Bulls-eye! - Simple resistivity imaging to reliably locate the geothermal reservoir. Proceedings, World Geothermal Congress, Kyushu-Tohoku, Japan, p. 909-914.

Bertrand, E. A., Caldwell, T. G., G. J. Hill, E. L. Wallin, S. L. Bennie, N. Cozens, S. A. Onacha, G. A. Ryan, C. Walter, A. Zaino, and P. Wameyo, 2012. Magnetotelluric imaging of upper crustal conductive plumes beneath the Taupo Volcanic Zone, New Zealand. Geophysical Research Letters, 39, doi: 1029/2011GL050177, 6 pp.

Booker, J., 2014. The magnetotelluric phase tensor: a critical review. Surveys in Geophysics, v. 35, p. 7-40.

Caldwell, T. G., Bibby, H. M., and C. Brown, 2004. The magnetotelluric phase tensor, Geophys. J. Int., 158, 457-469.

Chave, A. D., and Jones, A. G., Eds, 2012. The Magnetotelluric Method: Theory and Practice, Cambridge University Press, 552 pp.

Gasperikova, E., G. Newman, D. Feucht, and K. Arnason, 2011. 3D MT characterization of two geothermal fields in Iceland, Geothermal Resources Council Transactions, Vol. 35, 2011, p. 1667-1671.

Gwynn, M., R. Blackett, R. Allis, and C. L. Hardwick, 2013. New geothermal resource delineated beneath Black Rock Desert, Utah. Proceedings, Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, 1511-1519, SGP-TR-198, 9 p.

Hardwick, C. L., 2013. Geothermal Resources in Southwestern Utah: Gravity and Magnetotelluric investigations, Master's thesis, University of Utah, 67 pp.

Hardwick, C. L., and D. S. Chapman, 2012. Geothermal Resources in the Black Rock Desert, Utah: MT and Gravity surveys, Geothermal Resources Council Transactions, Vol. 36, p. 903-906.

Lindsey, N. J., and G. A. Newman, 2014. Improved workflow for 3D inverse modeling of magnetotelluric data: examples from five geothermal systems. Geothermics, v. 53, p. 527-532.

Petrick, W. R., W. H. Pelton, and S. H. Ward, 1977. Ridge regression inversion applied to crustal resistivity sounding data from South Africa. Geophysics, v. 42, p. 995-1005.Wannamaker, P. E., D. P. Hasterok, J. M. Johnston, J. A. Stodt, D. B. Hall, T. L. Sodergren, L. Pellerin, V. Maris, W. M. Doerner, and M. J. Unsworth, 2008. Lithospheric dismemberment and magmatic processes of the Great Basin-Colorado Plateau transition, Utah, implied from magnetotellurics: Geochemistry, Geophysics, Geosystems, 9, Q05019, doi:10.1029/ 2007GC001886.

Wannamaker, P. E., D. P. Hasterok, J. M. Johnston, J. A. Stodt, D. B. Hall, T. L. Sodergren, L.Pellerin, V. Maris, W. M. Doerner, and M. J. Unsworth, 2008. Lithospheric dismemberment and magmatic processes of the Great Basin-Colorado Plateau transition, Utah, implied from magnetotellurics: Geochemistry, Geophysics, Geosystems, 9, Q05019, doi:10.1029/2007GC001886, 36 pp.

Wannamaker, P. E., V. Maris, and C. L. Hardwick, 2013a. Basin Rift Structure of the Central Black Rock Desert, Utah, and Initial Thermal Implications, From 3D Magnetotellurics, Geothermal Resources Council Transactions, Vol. 37, p.41-44.

Wannamaker, P., V. Maris, J. Sainsbury, and J. Iovenitti, 2013b. Intersecting fault trends and crustal-scale fluid pathways below the Dixie Valley Geothermal Area, Nevada, inferred from 3D magnetotelluric surveying, Proceedings, Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-198, 9 p.

Wannamaker, P. E., J. N. Moore, K. L. Pankow, S. D. Simmons, G. D. Nash, V. Maris, C. Batchelor, and C. L. Hardwick, 2015. Play Fairway Analysis of the Eastern Great Basin extensional regime, Utah: preliminary indications, Geothermal Resources Transactions, this volume.