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Resistivity Imaging of Geothermal Resources Using 1D, 2D and 3D MT Inversion and TDEM Static Shift Correction Illustrated by a Glass Mountain Case History

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ABSTRACT

Because it can image the low resistivity, low permeability smectite clay that caps most geothermal reservoirs, magnetotellurics (MT) is commonly used to help target geothermal wells and assess resource capacity. Increasingly, geothermal companies are specifying that MT survey acquisition include a supplementary time domain electromagnetic (TDEM) survey for static shift correction and that MT processing include 3D inversion to produce resistivity images. However, ongoing experience indicates that, although these processing and correction methods often add great value, they may be misleading when used in an inappropriate context. In many cases, a comparison of inexpensive 1D MT images that are not static corrected will highlight uncertainties in more elaborate 3D MT inversions or MT images that have been corrected for static shift using TDEM. A case history of TDEM static correction pitfalls and comparisons of 1D, 2D and 3D MT inversion images at the Glass Mountain geothermal field illustrates these issues and supports general recommendations for effective MT resistivity imaging of geothermal resources.

1. INTRODUCTION

The geophysical parameter most commonly correlated with the overall permeability distribution of geothermal fields is resistivity. Hydrothermal systems produce smectite and mixed layer smectite-illite clay alteration in rocks over a wide temperature range from under 100°C to over 200°C (Essene and Peacor, 1995). Because of its high cation exchange capacity, smectite clay is the dominant cause of the low resistivity pattern observed over and adjacent to most geothermal reservoirs (Ussher, 2000), leading to the use of resistivity as a pathfinder in geothermal exploration. However, such clays also inhibit the formation of permeable open space at the top and margins of reservoirs, even where intersected by fractures, and so understanding the geometry of the low resistivity clay alteration is important to geothermal well targeting (Davatzes and Hickman, 2009). Because MT is typically the most cost-effective method of imaging resistivity if the base of the clay cap over a geothermal reservoir dips below 500 to 1000 m depth, MT is often the default geophysics method chosen for geothermal exploration.

Figure 1 illustrates the typical pattern of low resistivity smectite clay over a generic high temperature volcanic geothermal reservoir. However, clay geometry is also diagnostic over most geothermal reservoirs, including forced convection systems like those commonly found in the western USA and Turkey (Cumming, 2009a) and convecting sedimentary reservoirs (Ershaghi et al., 1983). Over the reservoir upflow in Figure 1, the base of the smectite cap is often elevated due to the tendency of smectite to transform to more resistive illite and chlorite, clays characteristic of permeable reservoirs. Anderson et al. (2000) described how contoured closures of the elevation of the base of the clay cap derived from simple 1D inversions of averaged MT curves were used to target several geothermal reservoirs. Sometimes this approach leads to drilling a local high in the clay cap on a cooler outflow, like that below the chloride spring in Figure 1. Conceptual model approaches that integrate geochemistry and geology with resistivity maps and cross-sections can reduce risk related to such conceptual pitfalls (Cumming, 2009b) but they require realistic cross-section images, putting a higher premium on reducing MT distortion. Common sources of distortion in MT resistivity maps and cross-sections include dimensional (3D) effects in 1D and 2D inversions, static shifts, acquisition noise, and gaps in MT station coverage. The state-of-the-art methods used to address these issues in a geothermal context each have pitfalls, including 3D inversion (Uchida, 2005), TDEM correction to correct static shift (Pellerin, 1991), and various smoothing approaches to address noise distortion and data gaps.

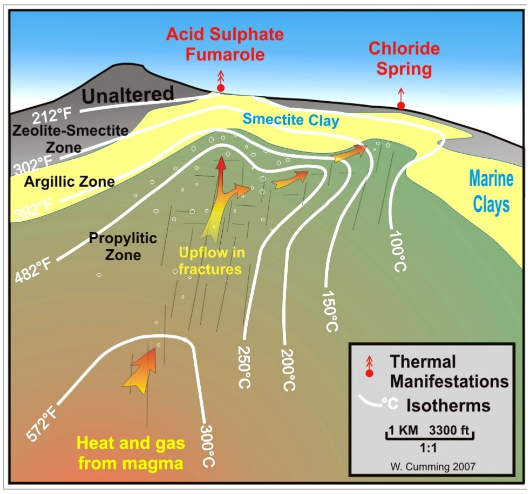

Figure 1: Conceptual model of a generic geothermal system with a deep upflow at >300°C entering a fractured >250°C reservoir capped by an impermeable smectite clay zone (yellow) that is imaged as low resistivity by MT surveys.

An MT analysis conducted at the Glass Mountain Known Geothermal Area (KGRA) illustrates issues that regularly complicate such interpretations and remedies that can be customized to the specific situation.

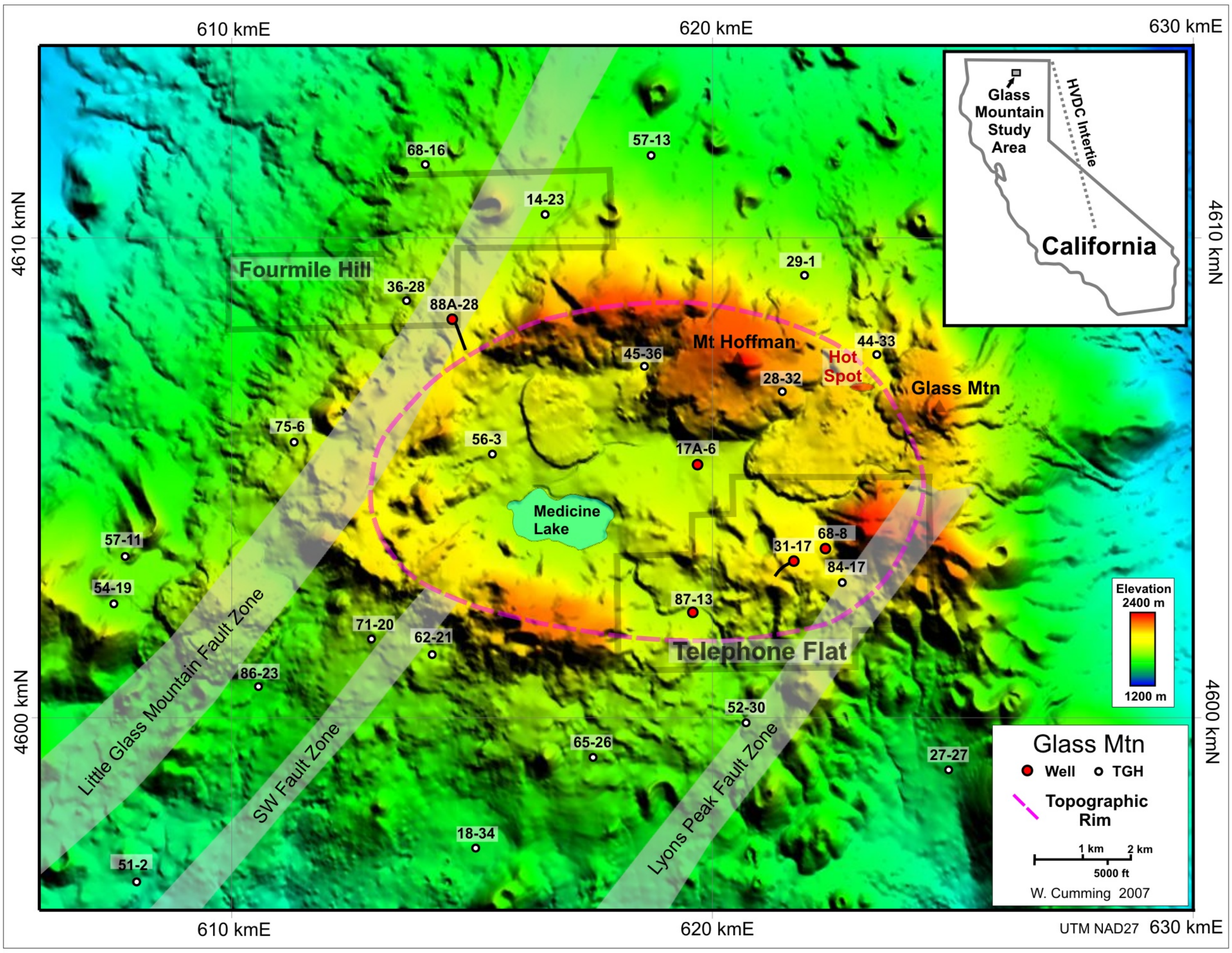

Figure 2: Glass Mountain study area with geothermal features, topography and the rim of the Medicine Lake Volcano.

2. GLASS MOUNTAIN MT AND TDEM SURVEYS

In 2005, 91 magnetotelluric (MT) and time domain electromagnetic (TDEM) stations were acquired to supplement older data including 105 MT and 200 TDEM stations covering an area of over 300 km^2 at the Glass Mountain Known Geothermal Resource Area (KGRA) in northern California (Figure 2). The prospect is located on the Medicine Lake Volcano, a basaltic shield volcano with a subsiding summit area rimmed by a coalesced ellipse of eruption centers. There is no thick ash flow consistent with a caldera collapse. The most recent eruption is the 900 year old Glass Mountain rhyolite flow. Three active northeasterly fault zone strands shown in Figure 2 are deflected where they intersect the ring fracture, creating the targets for much of the geothermal drilling. Five deep wells and 21 temperature gradient holes (TGHs) drilled since the 1980s demonstrate that several 227 to 268°C geothermal reservoirs are located in and near the Fourmile Hill and Telephone Flat Areas within the larger lease holding of Calpine Corporation (Calpine-Siskiyou Geothermal Partners L.P., 2004). The integration of the MT and TDEM data sets with temperatures, permeable zones, geology and alteration from the boreholes in a resource conceptual model has characterized prospective areas and drilling targets covered by Calpine leases (Cumming and Mackie, 2007).

Besides the exploration of the prospect, one objective of the MT and TDEM program that was supported by a grant from the California Energy Commission Geothermal Resources Development Account was a demonstration of 3D MT inversion for geothermal exploration and the integration of MT with other available data sets, including TDEM. This involved integrating several generations of MT and TDEM surveys over a period of several years while 3D MT inversion technology was rapidly evolving. The large overlapping data sets and the repeated 1D, 2D and 3D inversions that were run as new data arrived and software and computer hardware improved provided a useful perspective on the strengths and weaknesses of these approaches to MT resistivity imaging. Figure 2 illustrates some of the challenges for MT surveys at Glass Mountain, including steep topography likely to cause MT static shifts, a lake and several inaccessible rhyolite lava flows that forced gaps in coverage and a regional intertie power line that made the MT less reliable below 0.1 Hz.

3. MT STATIC SHIFT CORRECTION USING TDEM

The initial review of the MT surveys included 1D and 2D MT inversions prepared to analyze their performance relative to the 3D inversion and the well data. After editing serious noise distortion, basically by eliminating erratic data and smoothing through merely noisy data, the next step in the 1D and 2D MT analysis was usually to choose some approach to mitigate MT static distortion. The most common approach to correcting MT static shift used in the geothermal industry in the last two decades has been to use the TDEM method, which is not subject to static distortion, to provide supplementary data.

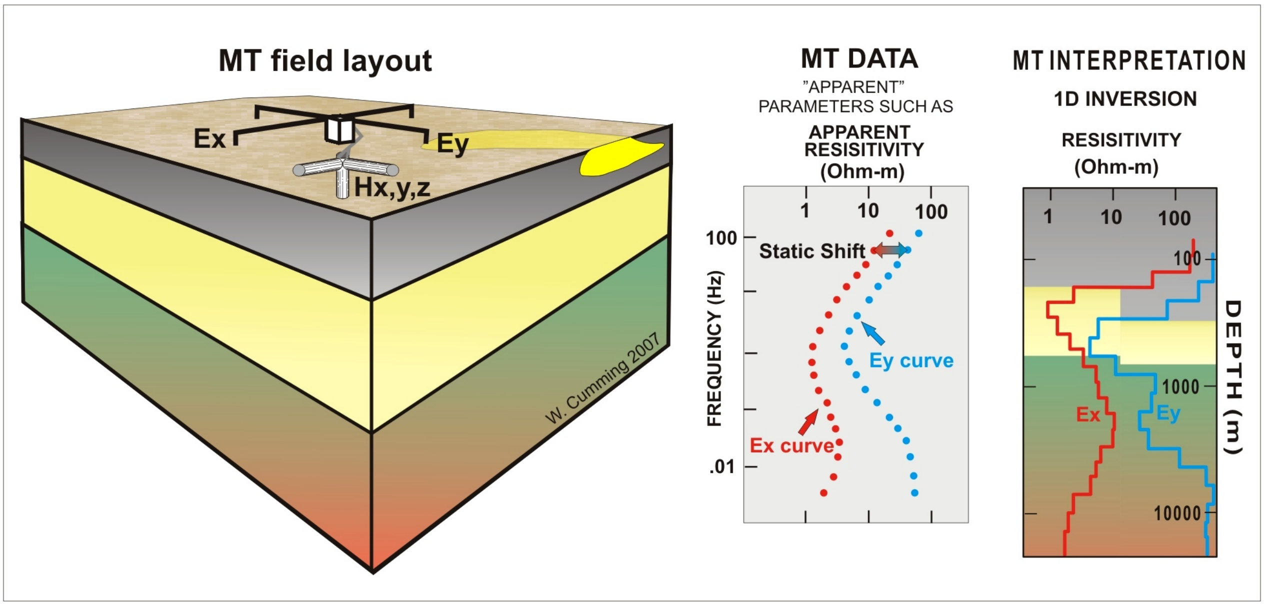

Figure 3: MT station layout and results. The apparent resistivity and 1D inversion curves show static and 2D/3D distortion.

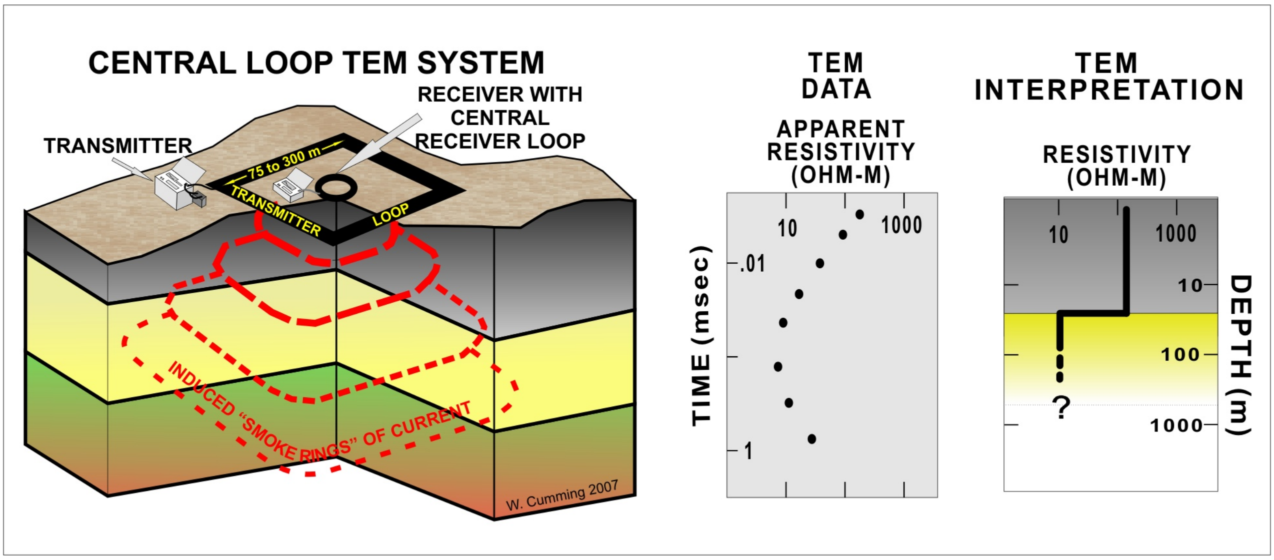

Figure 4: TDEM (also called TEM) station layout and results. The TEM has no static distortion but does not reliably image the deep resistor.

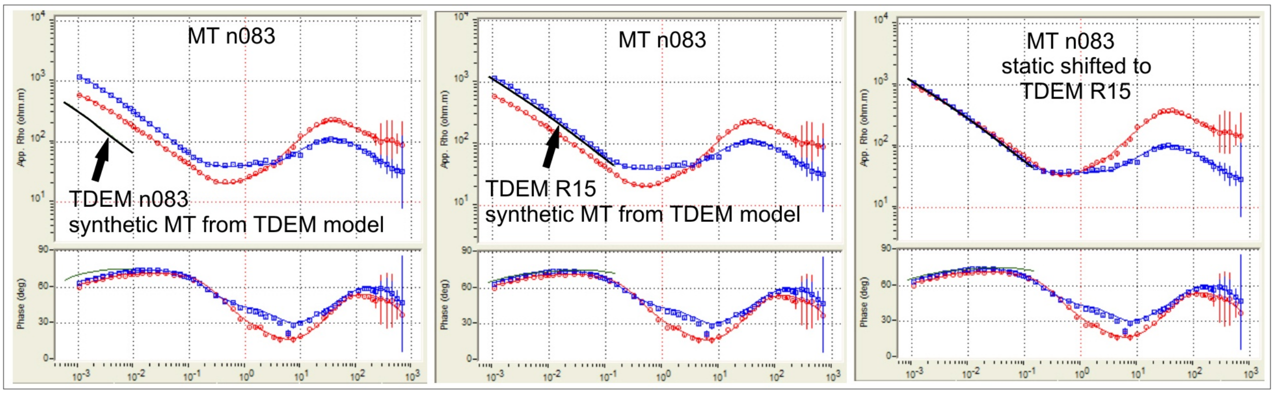

Figure 5: Ex (red) and Ey (blue) curves for MT station n083 matched to synthetic curves in black calculated from TDEM stations n083 and R15. Although the TDEM n083 curve might seem plausible, station R15 shows that it is unreliable.

The MT method illustrated in Figure 3 uses two sets of electrical field measurement lines, Ex and Ey, and three coil magnetometers, Hx, Hy and Hz, to measure the natural electric and magnetic fields at the earth's surface caused by electromagnetic waves radiated from the sun and from distant electrical storms. The magnetic field varies slowly with respect to ground resistivity while the electric field is more directly related to the resistivity at each station. Apparent resistivity can be calculated from the ratio of the electric to the orthogonal magnetic field, while the phase can be thought of as the delay, measured as an angle, between the peaks of the electric and orthogonal magnetic field waves. An MT sounding is made by computing these for a range of frequencies, typically 0.01 to 300 Hz for high temperature resources or 0.1 to 10000 Hz for geothermal reservoirs shallower than 1000 m. The electric field of a high frequency electromagnetic wave dissipates at shallow depths whereas the field at low frequencies responds to a much thicker and deeper section of the earth. Therefore, by recording MT at a wide range of frequencies, resistivity can be imaged for a wide range of depths.

Static shift is a potential source of distortion shared by most resistivity methods that use electrodes. In Figure 3, the apparent resistivity data measured for Ex and Ey are separated at high frequency. They should be equal in a uniform earth. However, in the field layout diagram in Figure 3, the yellow low resistivity body near the Ey electrode is causing a local distortion in the electric field that the Ex dipole does not detect, so the two apparent resistivity curves calculated from these electric fields, called modes, are separated by a constant offset through a wide range of frequencies. There are other causes of static shifts, most commonly significant topographic changes close to an MT station. If the static is caused by topography, it can often be compensated by including the topography in a 2D or 3D MT inversion or sometimes it is reasonable to assume that the electric field parallel to the slope is correct. It is also possible to estimate static shift by using a supplementary method that does not suffer from it.

Because TDEM does not use electrodes, it is commonly used to correct MT static shifts (Pellerin and Hohmann 1990). The central loop TDEM (also called TEM) method shown in Figure 4 relies on electromagnetic induction between an ungrounded wire loop and the earth. Because it requires no electrical contact with the earth, it is not subject to static distortion (although it can be distorted in other ways). To make a recording, the TDEM system in Figure 4 sends a steady current into a large wire loop laid out on the ground to generate a vertical magnetic field and then suddenly switches off the current, inducing decaying "smoke rings" of current in the earth as the magnetic field decays. The decaying vertical magnetic field generates a voltage in a detection coil in the center of the loop that is recorded. The voltage decay in the detector depends on the resistivity pattern of the underlying rocks. An apparent resistivity versus time is directly calculated from the voltage versus time and this is later inverted to a true resistivity versus depth as shown in Figure 4. Because the practical depth of investigation of TDEM is lower than of MT, the TDEM interpretation in Figure 4 shows only the top of the yellow conductor. TDEM can be an effective resistivity sounding method for reservoirs shallower than 500 m if the use of heavy generators and wire loops 500 to 1000 m in diameter is feasible, for example in Iceland where the wires can be towed using snowmobiles. However, this is impractical in most geothermal prospects and so TDEM has mainly been used as a supplementary method to correct MT static shifts.

Several caveats are routinely considered when correcting MT static shifts using collocated TDEM stations. Although it is focused more vertically than MT, large lateral contrasts can distort TDEM (Wilt and Williams, 1989). Pyrite and similar material can produce induced polarization effects (Raiche et al., 1985). Although coincident loop TDEM systems that combine the transmitter and receiver loops are lighter, they suffer from additional sources of distortion related to loop transients and superparamagentic soils. A common way to detect TDEM distortion is to add measurements away from the loop center, but this increases cost and complexity. Therefore, MT practitioners often assume that TDEM distortion can be reliably detected by checking whether the TDEM is consistent with a static shifted version of the collocated MT. However, the overlapping MT and TDEM surveys at Glass Mountain suggest that this assumption is unreliable, particularly where there is a thick resistive layer at the surface.

3.1 TDEM Limitations at Glass Mountain

The Glass Mountain MT-TDEM study highlighted a significant limitation in the TDEM approach to correcting MT statics. When comparing synthetic 1D MT responses derived from the TDEM stations to measured responses from MT at the same location, the synthetic curves from many Sirotem stations like n083 shown in Figure 5 commonly had lower apparent resistivity than both of the MT modes. If the synthetic phase derived from the TDEM did not fit the MT phase and the synthetic resistivity did not parallel the MT resistivity curve, the TDEM correlation would be rejected. However, many Sirotem TDEM stations at Glass Mountain, like n083, looked plausible, despite a large implied static shift to lower resistivity. A number of cases like this had older TDEM stations acquired using a larger loop and generator at the same location, like R15 in Figure 5. Most of these fit the MT data much better. The common theme of the TDEM stations that exhibited results apparently consistent with the MT, except for being too low in resistivity, was a thick surface resistive layer. The TDEM sounding apparently failed to induce significant current in the earth and the data was meaningless. That the resulting model would appear to be consistent with many MT stations was a surprise.

A review of data collected and interpreted by different companies and researchers worldwide suggests that unreliable MT static shift correction based on misleading TDEM is common in geothermal prospects with thick resistive rocks at the surface; for example, in the Cascades of the western USA and in areas with rhyolite lavas in New Zealand (Urzúa-Monsalve, 2008). Different types of TDEM systems respond to a thick surface resistor in different ways. When TDEM time series are available, they are sometimes diagnostic. Synthetic MT curves derived from portable coincident loop Sirotem systems often conform to the measured MT but have unrealistically low resistivity, typically too low by a factor of 0.1 to 0.9. Results from portable Zonge central loop systems are often distorted in such situations but usually do not misleadingly conform to the measured MT. If the high frequency MT data are not distorted by noise or capacitance coupling bias to low resistivity (Zonge and Hughes, 1985), the 1D MT inversion model before static shift correction can be checked to ensure that rocks with low enough resistivity exist at shallow enough depth to generate a signal detectable by the TDEM system. For the more portable TDEM systems, a suitable target is typically a zone of less than 20 ohm-m resistivity at a depth shallower than 100 m. A precaution that is always feasible is to prepare MT resistivity images with and without static correction to assess uncertainty.

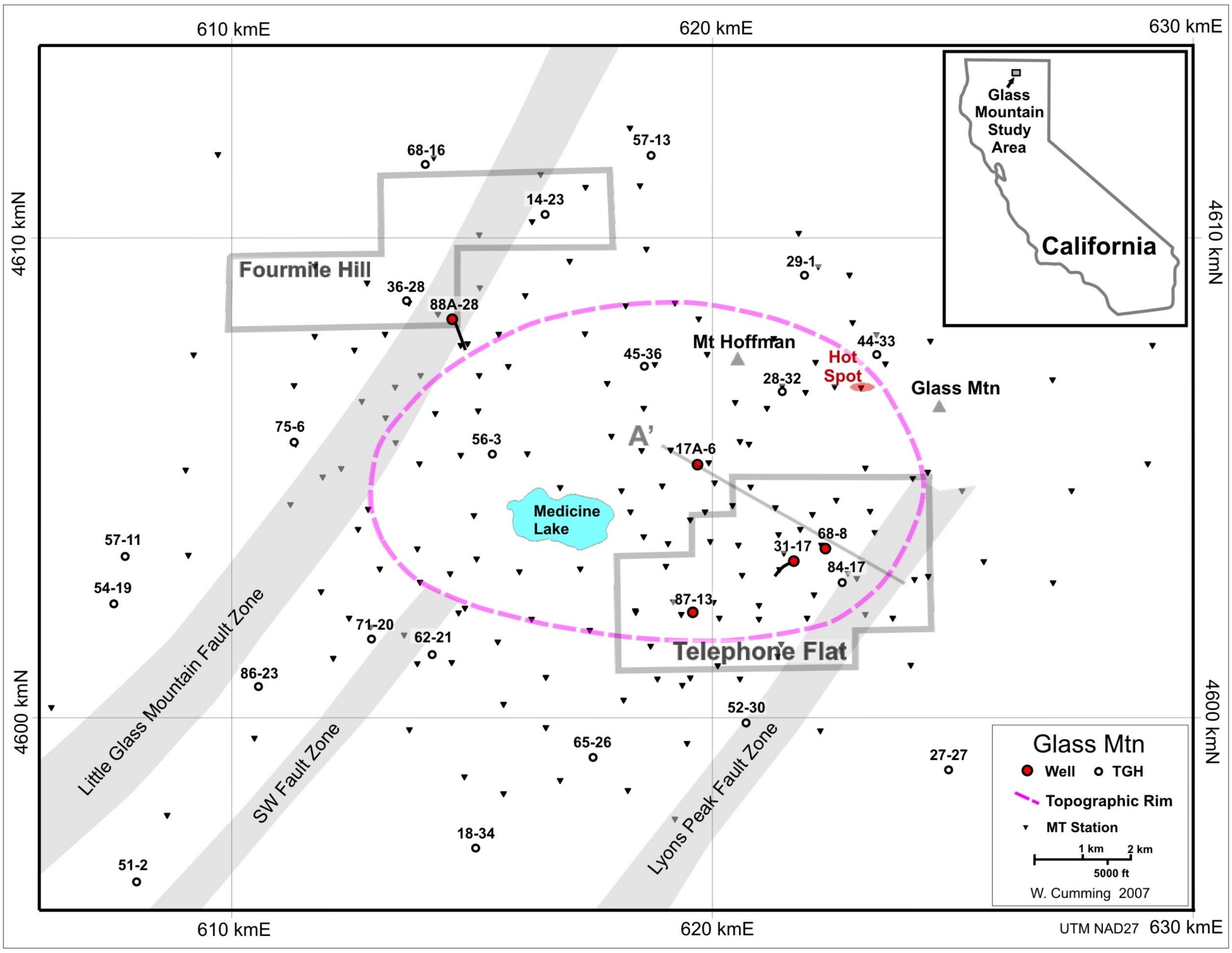

Figure 6. MT station distribution used to image resistivity at Glass Mountain. The gaps south of the Hot Spot and north of Medicine Lake are related to inaccessible rhylolite lava flows, shown in Figure 2.

4. GLASS MOUNTAIN MT INVERSION

The Glass Mountain MT data set includes 91 stations acquired in 2005 and 105 stations recovered from 1980s legacy file formats. Although this data set was relatively large for a geothermal prospect, it was relatively sparse for such a large prospective area. A typical rule-of-thumb is that MT stations should be distributed in a regular grid with spacing closer than the expected depth to the lowest resistivity part of the smectite cap. A follow up survey would include more stations at rapid lateral changes. In this case, the spacing goal was 500 to 1000 m for the known target areas, expanding to 1500 m outside them. As Figure 6 shows, much of the prospect appears to have adequate coverage. However, natural MT signals tend to be weakest near 1 Hz and noise is exacerbated if apparent resistivity is low at that frequency. The clay cap at Glass Mountain is close to the MT depth of investigation of the noisy frequencies 1 Hz, making redundant station spacing desirable. Some gaps were significant, particularly just northeast of the profile A line-of-section where there is a large gap in stations at an inaccessible rhyolite lava flow, one of the areas expected to have very high conductance.

Because 3D MT inversions have many more degrees of freedom than 2D inversions, they require particularly robust stabilizing functions. The stabilizing functions of the 3D MT inversion algorithm that was used for this project, derived from Rodi and Mackie (2001), has been steadily improved so that the inversion is less likely to put many resistivity variations in the model where there is less data; for example, outside the perimeter of the stations or in gaps between stations. However, where 1D and 2D MT inversions are dimensionally valid, they are likely to have higher resolution than a 3D inversion because they are less robustly smoothed.

It is likely that 3D MT inversions, in general, are less forgiving of noisy data and data gaps than 1D and 2D MT inversions and so input data require more careful editing. The much larger number of elements and degrees of freedom in a 3D model that must be constrained by the MT data set implies that there is more opportunity for a 3D inversion to produce unrealistic results if misleading data are included. Early hopes that the use of smoothing and robust statistics would allow the 3D inversion to produce realistic results from lightly edited data are not supported by experience. For example, spatially correlated noise commonly undermines such assumptions because neighboring stations are often biased by noise in a similar way. At Glass Mountain, stations located in trees during a windy week all exhibit a noise bias to lower resistivity at about 0.1 to 0.5 Hz due to magnetometer vibration. If not edited or weighted, the apparent consistency of this response among several stations causes the 3D inversion to produce a zone of unrealistically low resistivity below 3000 m depth. Similar patterns are commonly observed where geothermal power plant facilities create a noisy electrical environment. In fact, operators might consider acquiring additional MT immediately before beginning construction of a first power plant if the additional data is reasonable likely to aid make-up and injection well targeting.

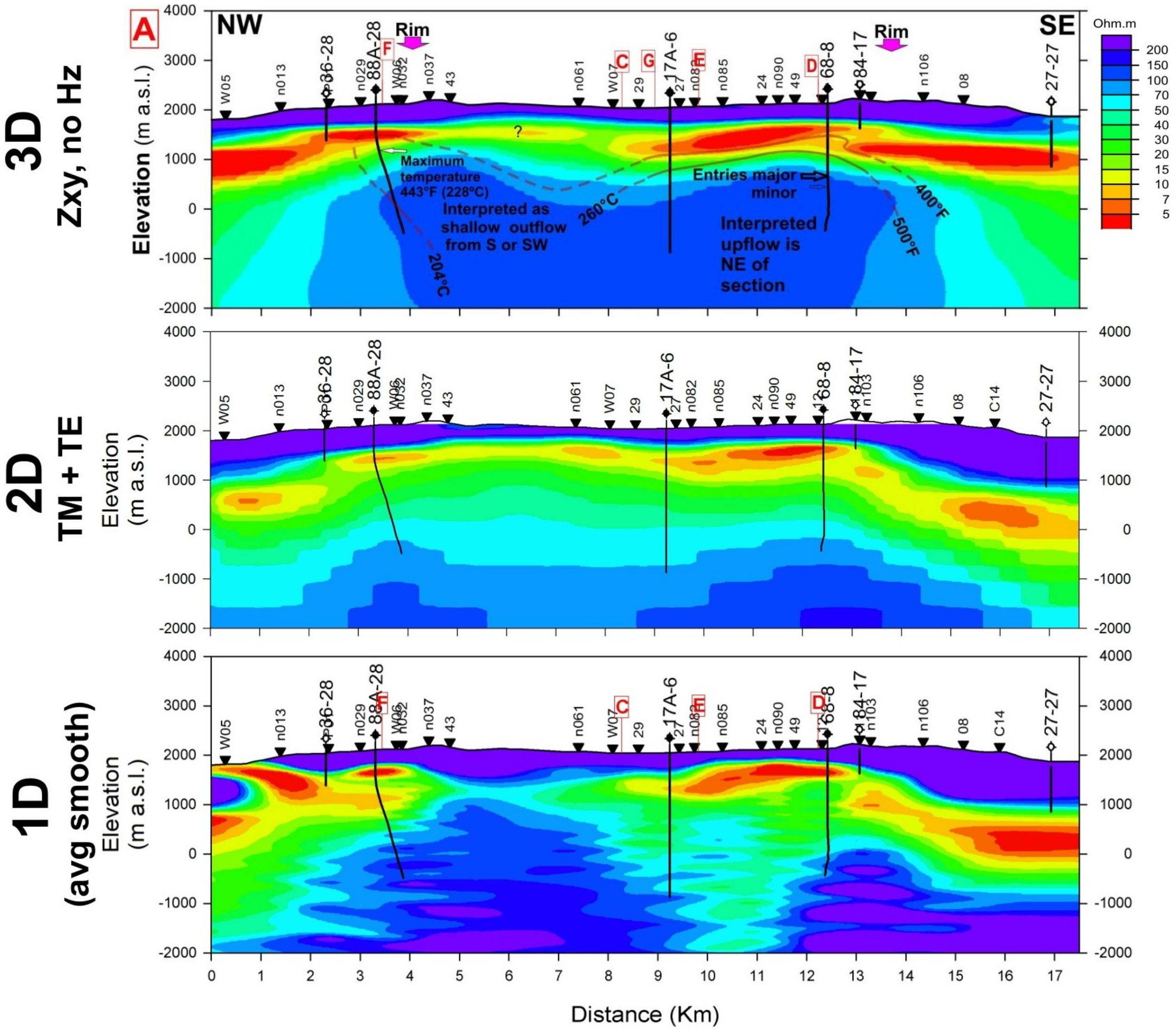

Figure 7. Cross-section A with 1D, 2D and 3D MT resistivity inversions, wells, isotherms and MT stations.

4.1 MT Cross-Section A; 1D, 2D and 3D Inversions

Cross-sections that show natural state isotherms and alteration extrapolated between well control using MT resistivity are commonly used to illustrate geothermal conceptual models. The isotherms are typically hand-contoured to follow the likely path of buoyant thermal flow beneath the low permeability clay cap (Cumming, 2009a).

Cross-section A in Figure 7 includes a few isotherms to illustrate how the resource conceptual model fits the resistivity images. The 260°C isotherm follows the >10 ohm-m resistivity contour at wells 17A-6 and 68-8, just below the <5 ohm-m smectite cap. A geothermal upflow is interpreted northwest of well 68-8 based on well temperatures and the MT resistivity pattern. The 204°C isotherm mimics the overall shape of the deeper >100 ohm-m (blue) contour and shows a slight increase in resistivity where temperatures are lower and smectite alteration reappears near the bottom of the 88A-28 well. This shape might imply an upflow from the southeast; however, the lower intensity of overlying argillic alteration at MT stations n037 and 43 favors the interpretation that the high temperature zone detected by well 88A-28 is more likely to originate from an upflow to the south or southwest. A more detailed correlation of resistivity with Glass Mountain well data is reported in Cumming and Mackie (2008).

4.2 MT 1D Resistivity Inversion

Experience at many geothermal fields indicates that smooth 1D inversions usually work well enough to characterize the overall resistivity geometry of a geothermal clay cap, although not abrupt edges or deep variations. The 1D MT inversions at Glass Mountain were computed from the average of the two MT modes. Although 1D inversions of the MT mode parallel to strike (called TE) sometimes gives a more realistic image, the average is often preferred because it is not affected by changes in the interpretation of strike. The 1D low and high resistivity patterns below sea level in Figure 7 are dominated by inversion artifacts caused primarily by the 2D/3D nature of the data at those depths. The close match of 1D MT inversions to borehole resistivity data through the clay cap (Cumming and Mackie, 2008) suggests that the 1D cross-section is more reliable than the 2D and 3D images above the reservoir, but probably not near the edges.

When plotting maps and cross-sections based on the 1D inversions, data from each station affects the contouring independently, making it easier to identify problems with particular stations. Because 1D inversions can be assembled into cross-sections without regard for 2D strike, it is easy to generate a 1D comparison to any 3D cross-section. Maps of resistivity at a particular depth may be noisier for 1D inversions, making average parameters like conductance over a depth interval a better choice for 1D inversion maps. Providing that the limitations of 1D MT inversion are understood, such as being careful about interpretations below the base of the clay cap or near the boundaries of conductors, 1D MT inversion can support an effective quality assurance and interpretation process.

4.3 MT 2D Inversion

Before 3D inversion became available, the principal advantage of 2D inversion was that it allowed for dimensional distortion that created artifacts in 1D inversion at depth. This is demonstrated by the attenuation of the unlikely 1D resistivity pattern below the low resistivity clay cap (red shading) in Figure 7. With the advent of 3D inversion, 2D inversion will likely retain several advantages. It can be effectively run on a single line or a few lines of stations, provided they are oriented roughly perpendicular to strike, whereas a 3D inversion requires a broader distribution of stations. Because 2D inversion is much faster than 3D MT inversion, it can be quickly rerun to test resolution hypotheses. However, the greater effort required in setting up a reliable 2D inversion will probably make 1D inversion a more effective first pass tool for reviewing data prior to 3D inversion.

Appropriately preparing MT data for 2D inversion can be time consuming and sometimes futile if there is no consistent geological/resistivity strike that is more or less perpendicular to the MT stations available for a cross-section. To complete a 2D inversion, assumptions must be made about how to orient the two MT modes for each station relative to the strike of the profile. If there is no suitable strike, various decomposition approaches have been proposed and routinely used in regional surveys to reduce dimensional complications that are inconsistent with a 2D inversion (Simpson and Bahr, 2005). However, the validity of such approaches for the imaging of geothermal targets has not been extensively demonstrated by model studies or ties to boreholes. It is likely that 3D inversion will replace such methods for distributed arrays of MT stations acquired to address high value decisions.

The most widely used strategy for 2D inversion is to mathematically rotate all of the MT station data along a profile so that Ex is aligned perpendicular to the line-of-section and invert assuming that Ex is parallel to strike. If the MT data actually is 2D with the appropriate strike, this works well. A common remedy if the inversion is unable to fit the data is to fit only the Ey mode data oriented along the line of the section (called the TM mode). This implies that the inversion is incompatible with the 2D assumption, but the result is a useful test of the uncertainty of cross-sections obtained using 1D inversions. As might be expected in such a large area as Glass Mountain, few of the profiles across the prospect that are geologically convenient have a consistent resistivity strike based on patterns of 1D conductance, the polarization of neighboring stations and the goodness of fit of both modes in the 2D inversions.

4.4 MT 3D Inversion

The objective of a 3D MT inversion is to produce a 3D resistivity model consistent with MT data that require it. There are a variety of MT parameters that roughly indicate whether the 3D signal are significant. From a 1D/2D perspective, these signals are distortion. They are seldom significant at geothermal fields above the base of the clay cap, except near lateral discontinuities.

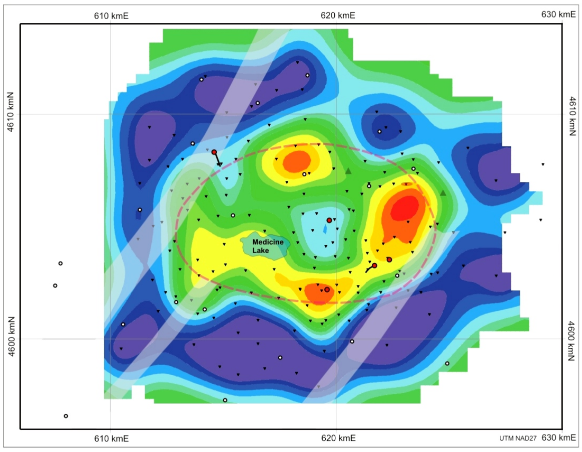

Figure 8. Map of 3D MT resistivity at 1700 masl showing low resistivity clay cap in red near the water table (resistivity scale same as Figure 7).

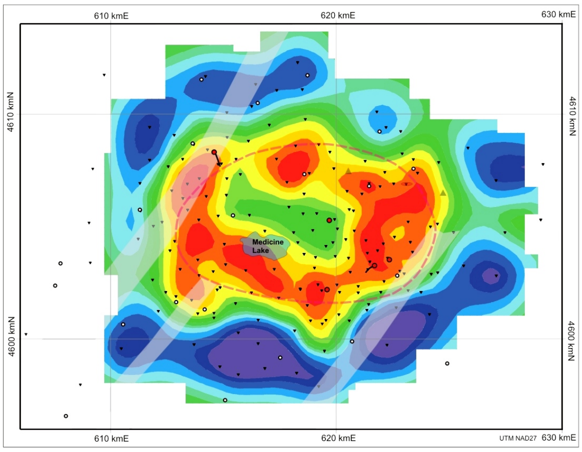

Figure 9. Map of 3D MT resistivity at 1600 masl showing low resistivity clay overlying prospective zones (resistivity scale same as Figure 7).

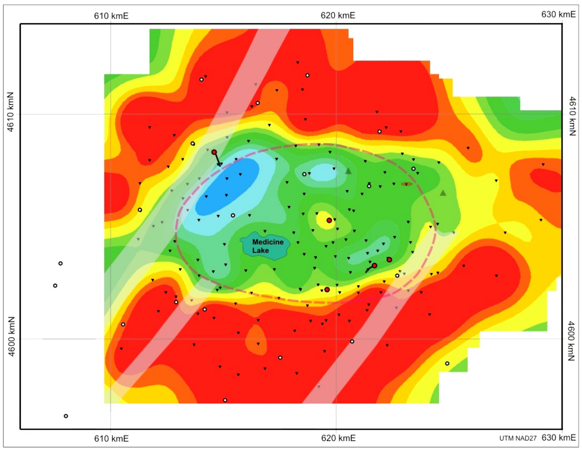

Figure 10. Map of 3D MT resistivity at 1000 masl showing low resistivity clay encasing the volcanic rim (resistivity scale same as Figure 7).

The effective depth of investigation of the 3D inversion is not limited by geometric assumptions as is the case with 1D and 2D inversion. It is, however, limited by the frequency range of the reliable data used in the inversion, the average resistivity of the model, and the width (or aperture) of MT station coverage. At Glass Mountain, resolution was assumed to be limited to 4000 m because frequencies at less than 0.1 Hz were probably distorted by regional power lines. Restricting the 3D inversion to frequencies greater than 0.1 Hz allowed for a greater number of frequencies from 0.1 and 300 Hz to be included in the 3D MT inversion, improving the resolution of finer details in the clay cap and reservoir.

One advantage of 3D MT inversion is that maps prepared at elevation slices through the 3D resistivity model, like those shown in Figures 8, 9 and 10, are easily prepared. Such maps made from 2D MT inversions tend to be misleading because they are likely to have trends aligned with the 2D profiles unless the overall resistivity level is consistent from profile to profile, something difficult to achieve if static shifts are significant. Resistivity maps generated from 1D inversions are more effective than 3D maps for assessing the quality of individual MT stations and, for elevations above the base of the clay cap, they are generally reliable providing that the possibility of distortion near lateral contrasts is appreciated. As in the case for 1D inversions, MT conductance over a depth or elevation interval covering a zone like a geothermal clay cap is, in theory, better resolved than the resistivity at any particular elevation and can be viewed as being roughly analogous to total smectite alteration over that interval.

The map of 3D MT resistivity at 1700 masl in Figure 8 illustrates the resistivity pattern just above the water table at Glass Mountain. Alteration above a water table is consistent with variations in the water table elevation or boiling in the reservoir, as Lutz et al (2000) indicated might be occurring at the top of the reservoir in well 31-17. Any boiling correlated with the resistivity imaging most likely occurred in geologically recent times but it is not necessarily occurring now. Although a lack of thermal manifestations over a currently boiling system is unusual, it is consistent with the very coherent clay cap isolating the reservoir from the surface, as described by Hulen and Lutz (1999).

The map of MT resistivity at 1600 m elevation in Figure 9 illustrates the resistivity pattern just below the water table near the wells. Although many of the lowest values of resistivity are imaged in gaps between stations, the overall pattern is validated by ties to wells which suggest that the <7 ohm-m (red) contour probably corresponds to the clay cap over the geothermal reservoir zones, albeit not necessarily the highest permeability part of such zones.

The map of resistivity at 1000 masl in Figure 10 illustrates the distribution of a thick tabular <7ohm-m (orange-red) layer almost surrounding the rim of the Medicine Lake Volcano. This 500 to 1000 m thick layer consists of porous volcanics that are impermeable due to low resistivity zeolite-smectite and smectite alteration that form a barrier to flow around the volcanic rim.

4.5 Base of the Clay Cap Elevation from 1D and 3D MT

An important part of most geothermal MT interpretations is a map of the elevation of the base of the low resistivity smectite clay zone because this zone typically conforms to the top of the reservoir (Anderson et al., 2000; Cumming et al. 2000). An apex in the top of a geothermal reservoir is associated with a locus of shallow high permeability and this will usually correspond to a high point in the base of the clay cap. However, a high point in the base of the clay cap can have other interpretations, as noted in Figure 1. Two maps of the base of the clay cap are presented, one based on the 3D inversion and the other on a 1D simplified layered model approach that has been widely used in the geothermal industry (Anderson et al. 2000).

The map in Figure 11 is based on using the average of the MT resistivity mode to compute a simple 1D model with a few layers, often just a high-low-high resistivity pattern. The depth to the base of the low resistivity layer roughly corresponds to the base of the smectite alteration zone. When the clay cap becomes less intensely altered and thicker on the margins of the resource, the layered model approach tends to make it appear much thicker, causing some of the high contrast appearance of the map.

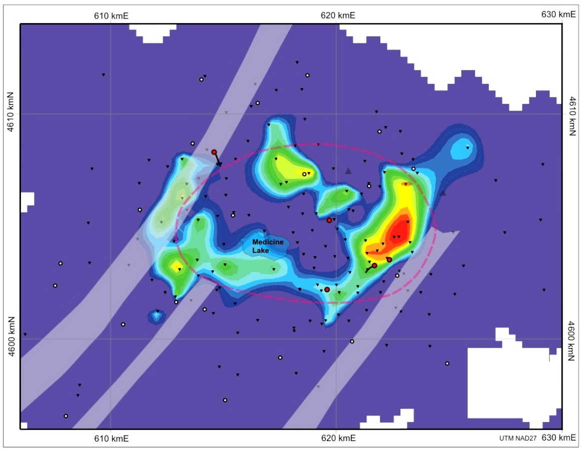

Figure 11. Elevation of the base of the clay cap from MT 1D layered model inversions.

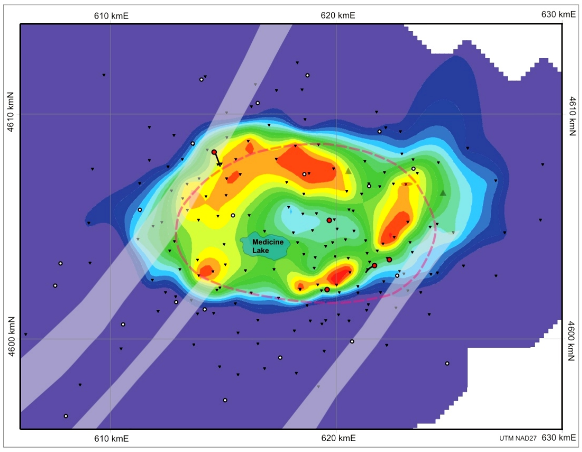

Figure 12. Elevation of the base of the clay cap from MT 3D inversion.

The map of the elevation of the base of the conductive clay cap based on the 3D inversion in Figure 12 is constructed by measuring the elevation at which the 3D model increases to 10 ohm-m below the low resistivity zone. The measurement is made at the MT stations because the 3D inversion is better constrained there. The map shows a rim of high elevation in the base of the clay cap inside the topographic rim of the Medicine Lake Volcano. Four local high areas are highlighted as red and orange zones at elevations of about 1450 to 1550 masl. These correspond to parts of the clay cap that are close to the elevation of the water table. This map does not consider the intensity or quantity of clay alteration, only the elevation of its base. Thus, a comparison to a resistivity map like Figure 8 or 9 highlights the likely importance of each of the high points in the base of the clay cap in terms of its association with hydrothermal alteration and, perhaps, a geothermal upflow. The conceptual implications of this map are best understood by reviewing MT cross-sections.

The differences between the 1D and 3D MT approaches in Figure 11 and 12 reflect the tendency of the 1D MT inversion to exaggerate changes near discontinuities and to displace them because of dimensional distortion while, on the other hand, the stabilization required in the 3D MT inversion tends to produce a smoothed, lower resolution view of the base of the clay cap. The two approaches can be considered to be complementary. In any case, they do not necessarily identify drilling targets; they assist in assembling a conceptual model that would define drilling targets.

4.6 Static Shift Correction Using 2D/3D MT Inversion

Most 2D and some 3D inversion codes have an option to invert for static shift effects based on smoothness of the model, independent of outside data like TDEM. This approach has been effective for 3D MT inversions in sedimentary basins. However, in the volcanic highlands of the Glass Mountain area, the 3D MT inversion with static smoothing caused geological elements important to the interpretation to be overly smoothed.

In areas where TDEM provides effective constraints on MT static shift distortion for 1D inversions, it is feasible to introduce TDEM constraints to 2D and 3D inversions. However, the usual 1D approach where the MT is explicitly shifted to fit the TDEM introduces conceptual inconsistencies to a 2D or 3D inversion that includes topography. If the static shift is caused by topography and topography is adequately represented by the MT inversion model, then the static shift will also be automatically included in the forward computation of the MT response. In this case, the TDEM might be more appropriately included in a joint inversion. In future, it may become possible to mitigate most MT static distortion related to topography by more closely modeling the topography in 3D MT inversions.

5. CONCLUSIONS

By combining a resistivity interpretation of 3D MT inversions with natural state temperature and alteration information from wells, an integrated conceptual model interpretation identified likely drilling targets at the Glass Mountain KGRA despite important gaps in the MT coverage related to poor access.

In areas where thick, resistive rocks cover most of the surface, like at Glass Mountain, TDEM will probably be an ineffective method of correcting MT static shift unless the use of large loops and generators is feasible. If wells will be targeted on the basis of an existing MT interpretation that included TDEM static shift corrections based on portable TDEM stations in areas with thick resistive rocks at the surface, the interpretation should be reviewed and, perhaps, revised. Topographic static effects in the MT will eventually be routinely accommodated by 3D MT inversion, providing that the topography can be cost-effectively represented in the 3D inversion by a sufficiently fine model mesh.

Companies should avoid specifying 3D MT inversion as a sole MT imaging approach and should continue to request initial 1D inversions as a quality assurance check on the 3D inversion results. If no 3D inversion will be run, a 2D inversion should be requested. Cross-sections stitched from Occam 1D inversions of the average of the two MT resistivity modes provide an objective and robust display of the quality of the MT and, for many geothermal fields, it is likely to provide a resistivity image of sufficient quality to propose well targets. However, to assess the uncertainty in well targeting, 3D MT inversion combined with 1D and maybe 2D inversion can test what is reliably resolved that is relevant to an integrated resource conceptual model.

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