INTERSECTING FAULT TRENDS AND CRUSTAL-SCALE FLUID PATHWAYS
BELOW THE DIXIE VALLEY GEOThERMAL AREA, NEVADA,
INFERRED FROM 3D MAGNETOTELLURIC SURVEYING

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ABSTRACT
Geothermal systems may occur in zones of structural dilatancy which create the crustal plumbing that allows concentration of high-temperature fluids from surrounding volumes. While structural orientations of the U.S. Great Basin are dominated visually by the NNE-oriented horst-graben morphology, other alignments are apparent, perhaps principally a NNW-trending grain related to early-stage Great Basin extension. As part of an integrative research project to establish Engineered Geothermal Systems (EGS) methodology at district scales for high-enthalpy extensional systems, a 3D magnetotelluric (MT) resistivity survey of 94 tensor stations was acquired over the Dixie Valley geothermal system and has undergone 3D inversion analysis. Part of the motivation for the MT study was the observation in earlier 2D MT transect data of a large-scale, low-resistivity (conductive), presumably fluidized crustal fault zone connecting interpreted deep magmatic upwelling nearby to the west under Buena Vista Valley with the Dixie Valley geothermal system, consistent with helium isotope studies. The 3D inversion model largely confirms the 2D structure, albeit not surprisingly with a more complicated geometry. Primarily, the 3D model exhibits an intersection of NNE graben fill and range-bounding conductive trends with deeper, NNW conductors. These conductors are believed to represent zones of saline fluids whose collection is promoted by opening of these structural trends with the ongoing extension of the Great Basin through this area. The collection of intersections as a group equates to the previously identified 2D crustal break and plunge steeply west beneath the Stillwater Range. Visually, these structural conduits coalesce toward the lower crust and dip westward toward Buena Vista valley and the deep magmatic activity.

INTRODUCTION
The magnetotelluric (MT) method measures the scattering within the Earth of naturally occurring, vertically-incident, planar electromagnetic (EM) waves as a means of producing images of subsurface electrical resistivity (e.g., Vozoff, 1991; Chave et al., 2011). At typical geothermal conditions, electrical resistivity in turn is controlled primarily by (1) the quantity, salinity and efficiency of long-range interconnection of aqueous fluids in pores and fractures, and (2) the presence of hydrothermal alteration mineralogy with appreciable cation exchange capacity (Palacky, 1987; Ussher, 2000; Kulenkampff, 2005). Secondary controls on the resistivity of host rock lithologies include minor variations in porosity and clay content, most of which may predate geothermal activity of interest. Geothermal production hinges upon fluid recovery from open fractures, and such fractures in turn are promoted by conditions of structural dilatency (Faulds et al., 2011). Dilatency can occur with diverse structural styles, including the intersection of faults of differing orientations under a generally extensional stress regime. At Dixie Valley we have been recognizing that the generally northeast trend of horst-graben morphology has been superimposed on a slightly older set trending nearly north or even a bit west of north (Waibel, 1987; Zoback et al., 1994).

In 2012, 70 new tensor MT stations were taken and merged with 24 existing (baseline) soundings for a total of 94 sites (Figure 1) over the Dixie Valley geothermal system (DVGS), the largest and hottest of the geothermal systems in the northern Basin and Range (Great Basin) believed to be sourced by deep circulation (Blackwell et al., 2007). This is part of research lead by AltaRock Energy Inc. to establish a method to evaluate engineered geothermal systems (EGS) exploration methodology in the Great Basin through
an integrated geoscience analysis using the DVGS as a calibration site (Iovenitti et al. 2012). The resultant 3D resistivity model is to be analyzed together with physical property, structure and state models arising from new passive seismic, potential fields, mapping, downhole stress and temperature in an attempt to provide a calibration of EGS favorability against observables. The new MT soundings were acquired by Quantec Geoscience Inc. (Quantec) using their standard L-array with steel plate electrodes, high-moment induction coils, and GPS timing (Spartan survey system) (Figure 2). Data quality was high given generally low noise conditions and use of a remote reference site near Austin, Nevada, as exemplified in Figure 3 and discussed later. High frequencies (e.g., 100 Hz) penetrate to a depth on the order of 100m, while frequencies of <0.01 Hz penetrate to near the base of the crust (>20 km).

while the northern and southern lines crossed the Senator fumaroles and Dixie Valley Power Producers section 14 areas, respectively. Although achieving finer lateral sampling along each profile (~100 m) than the 3D survey discussed here, the analysis of these older profiles was restricted to being essentially 2D whereas Dixie Valley possesses substantial departures from that simple geometry. However, we did utilize selected soundings from the baseline arraying profiling to fill in the overall 3D coverage.

Figure 1: MT site distribution over the Dixie Valley thermal area for analysis through 3D inversion. The Dixie Valley geothermal wellfield, a calibration area for this methodology study, is outlined in red.

Figure 2: Schematic MT system layout in L-array mode as implemented by Quantec Geoscience Inc. Typically four-six such setups are laid out during the day and record over night.

Figure 3: Two example soundings from the Dixie Valley field with apparent resistivity on the left and impedance phase on the right exemplifying data quality in the field. The useful frequency range for this study is from 10 to 0.02 Hz.

PRIOR MT RESULTS AT DIXIE VALLEY

The results of analyzing the 3D data set can be compared to models from more localized profiling acquired in 2002 that acquired three lines of MT stations oriented northwest-southeast across the field (Wannamaker et al., 2006, 2007). These baseline survey lines consisted of dense MT array profiles using the Quantec Titan-24 multi-channel system located primarily up against the range-front, plus discrete five-channel sites with the predecessor of their Spartan system appended to one or both ends to increase aperture. The central longest line ran through the main geothermal power producing area,
In Figure 4 we present a multi-scale inversion image combining the results of the dense MT array profiling and more standard site deployment (2-3 km spacing) over a span of order 100 km. These sections were presented separately in Wannamaker et al (2006; 2007) but are useful to compare here with the 3D models. The lower regional section was derived first and shows a broad, quasi-horizontal conductor in the deep crust beneath Buena Vista Valley and the Humboldt Range. It is coincident with an anomalous active-source seismic area of high P-wave attenuation, high reflectivity, and a high Vp underplate (Catchings and Mooney, 1991). These are all suggestive of recent magmatic underplating to which we ascribe the low-resistivity feature. At the conductor’s east end occurs a steep upward branch joining into the base of Dixie Valley. A higher-resolution view of this feature appears in the dense array MT profile inversion of the upper panel. The steep conductor is viewed as a fluidized fault zone bringing mantle-derived (magmatic?) fluid components from the deep western underplate toward the DVGS as reflected e.g. in 3He isotope samples (Kennedy and van Soest, 2006; 2007). A role for deep magmatism in EGS potential is under assessment.

Figure 4. Two-dimensional resistivity inversion sections derived from transect MT stations (below) and from dense MT array profiling (top) across the Dixie Valley geothermal system, Nevada (Wannamaker et al., 2006; 2007).

ANALYSIS OF NEW MT DATA COVERAGE

One concern in models such as Figure 4 is the validity of the 2D assumption for resistivity structure. While we took care to emphasize the data subsets most robust against finite strike extent, complications exist including diverse structural trends and complex intrusives. To provide a more confident and representative picture of the resistivity structure below the DVGS, the early transect data was augmented to provide the 3D coverage of Figure 1.

Inversion Model Mechanics

In Figure 2, the upward directed electric bipole is typically assigned to the x-axis of MT measurement while the right directed bipole is along the y-axis. In turn, x normally is geographic north and y is east. The coordinate conventions are somewhat arbitrary and usually meant to standardize field procedure; after the time series data are transformed to the frequency domain and the four tensor impedance quantities \((Z_{xx}, Z_{xy}, Z_{yx}, Z_{yy})\) formed, those quantities can be rotated to any other user-desired coordinate orientation through application of a simple 2x2 rotation matrix (e.g., Vozoff, 1991). Given the visual trend of the Stillwater Range front and Dixie Valley, and inferred Dixie Valley fault zone (DVFZ) (Johnson and Hulen, 2003), we selected a N040E coordinate system for input to the inversion imaging algorithm discussed below. However, we are aware that other resistivity structural trends may emerge in the inversion model, such as N-S aligned features. In principle, apart from unescapable issues such as lateral sampling, the coordinate system chosen should be immaterial as all calculations internal to the inversion code would be consistently rotated as well and we invert all four impedance tensor elements.
The soundings exemplified in Figure 3 have ~135 individual frequency data points over the range of data collected, and thus are highly oversampled in frequency, a consequence of a typically long time series acquired over ~16hrs at 1000 samples per second. While it was important to collect this amount of data for quality purposes, we require only a much reduced data set for our analysis herein. For computational efficiency, we bin the sounding samples into a coarser set of four per decade in frequency using a Gaussian weighting procedure that causes no overall error inflation or deflation following general statistical principles such as in Bevington (1969). We thus selected soundings with 12 data points over the frequency range 10Hz to 0.02Hz to cover the depth range a few 100m to >20km. Furthermore, given the length of the typical time series data relative to the frequencies of interest, the processing error bars on the data points are often much smaller than the apparent scatter in the data over frequencies especially toward the higher frequencies. This is pervasive with MT data and it has become standard to apply an error floor to the data points more typical of the scatter; in our case this is 5% of the impedance determinant magnitude. This floor still is much small than the overall or broad-scale variation of the soundings over the whole frequency range and is not a detriment to resolution of resistivity structure to the extent feasible with a diffusive EM wave technique like MT.

The four complex elements of the multi-frequency impedance at each MT sounding were input to a non-linear (iterative), regularized inversion program to produce a 3D model of electrical resistivity under the Dixie Valley region with particular detail in the central Dixie Valley geothermal wellfield, or EGS favorability calibration area (Figure 1). The algorithm used is based on that described by Sasaki (2004), loaned to Wannamaker for research for about 10 years. We have significantly modified the program by replacing the parameter step solver after Tarantola (1987), using a modified Cholesky parameter matrix solver, and parallelizing the code on multi-core linux workstations to improve speed (Maris and Wannamaker, 2010). Such inversion algorithms function by representing the earth domain probed by the MT fields as a large series of prismatic parameters or ‘bricks’ (Figure 5). The code uses finite difference (FD) approximations to Maxwell’s equations to simulate the MT response of the 3D earth and the sensitivities of the response to incremental changes in the resistivity of each parameter (i.e., the jacobians; deGroot-Hedlin and Constable, 1990; Sasaki, 2004).

**Figure 5.** Central region of the parameter or ‘brick’ ensemble representing 3D resistivity variations in the earth that fit or simulate the observed MT response at DVGS. Each brick in plan view is made up of 2x2 FD cells, while in section view only the top layer of bricks is two FD cells thick with the remainder below being one FD cell thick.
The bricks are made so small that the individual geometries are essentially immaterial but instead serve essentially as sample points in 3D space. A parameter step equation is defined that jointly minimizes, in a least-squares sense, the misfit of the computed MT 3D model response to the data plus the roughness of the 3D model. Roughness is defined in the sense of the first spatial derivative or slope of the model in 3D space (deGroot-Hedlin and Constable, 1990; Sasaki, 2004). This is a widely accepted means of suppressing small-scale artifacts in the model not demanded by the data which can result from attempting to resolve subsurface structure using a diffusive wavefield that provides finite data with scatter or noise (e.g., deGroot-Hedlin and Constable, 1990). The model grid in Figure 5 is comprised of $79 \times 65 \times 28 = 143,780$ parameters with the upper layer being 200m thick and deeper layers thickening gradually but geometrically according to resolution of diffusive EM. This lies within a FD grid of $153 \times 125 \times 43$ nodes in x, y, and z directions. In the calibration area, typical parameter (brick) widths are 400m, which is 1/4 to 1/5 typical station spacing there. The mesh extends to just over 20km in depth, well below levels of geothermal prospectively but still interesting from the standpoint of deep heat sources and the possible role of magmatism.

The program was run on a modern linux workstation with 24 cores and 0.5 Tb RAM using the Lahey Fortran compiler parallelized under the OpenMP protocol (Maris and Wannamaker, 2010). The Dixie Valley MT data set is unusually demanding of parameters for 94 sites because a portion of the sites are concentrated in the calibration area with the remainder having a much larger station spacing over the greater project area. Model run times were on the order of one week. Misfit in a normalized root-mean-square (nRMS) started at ~36 for the starting 20 ohm-m half-space and converged to ~3.4, which is considered reasonable and typical for such inversion runs in the sense that it is spread fairly evenly over the data set, and an ideal nRMS value of unity is rarely achieved.

**Model Presentation: Plan and Section Views**

Various section and plan views through the 3D model are depicted in Figures 6-11. The model brick distribution of values is sampled every 200m x-y-z and plotted using the Voxler graphics platform of Golden Software Inc.

The first view is at a depth of only 500m (Figure 6). Here is apparent the NE-SW trend of conductive sediments of the shallow Dixie Valley against the Stillwater Range to its northwest. Stillwater rocks near surface are quite heterogeneous in resistivity at small scales. The geothermal significance of that is unclear and much could represent conductive shales and clastics in the late Paleozoic/early Mesozoic host rocks. Apparent though less clearly defined is Buena Vista Valley further northwest.

![Figure 6. Vertical plan view of the 3D resistivity model from non-linear inversion for a depth slice at 500m below the surface. Inversion assumes a flat earth. Small black squares denote MT station locations while white circles are geothermal wells.](image)

The next view (Figure 7) is at the greater depth of 2000m which begins to reveal basement features. For one, resistive pediment rocks at shallow depths between the Stillwater topographic scarp (the Dixie Valley range-front fault segment of the DVFZ (Blackwell et al., 2005; Iovenitti et al. 2012) and the main graben bounding fault (the piedmont fault segment of the DVFZ) into which the production and injection wells are drilled are clear as the dark blue band hugging the wells on their northwest side. Local resistive ‘fingers’ which we take to be protrusions of shallow bedrock further into the valley seem to ap-
pear southwest of the power plant area wells and more weakly in the neighborhood of Senator fumaroles (e.g., wells 38-32, 45-33). Second, there is a suggestion of NW-aligned conductive bands toward the southeast margins of the MT site coverage, although the MT station spacing is coarse there.

The plan view at 3500m depth (Figure 8) reaches depths which are below the unconsolidated Dixie Valley basin fill and yet pronounced low resistivity is still quite evident in the central valley areas, especially east and south of well 45-14. This is confirmed even by a plan view at 5000m below ground surface (Figure 9). In the latter view, one sees some coalescing and rotation of the conductive elements under Dixie Valley to start to suggest a somewhat northerly orientation. This becomes even more apparent in the perspective view of Figure 10 at a depth of 6500m below the surface.

Interpretively, in Figure 10 we have drawn three grey arrows which we suggest highlight conductive lineaments with a N-S component of orientation. Since renewed structural study following early observations of Waibel (1987), there has emerged the possibility that the intersection of older N-S fault zones with modern NE-SW extensional fault zones may be important in creation of dilatency and deep geothermal conduits in the DVGS (Iovenitti et al. 2011; 2012). In any event, particular low resistivity zones in the upper middle crust appear to be associated with shallower geothermal manifestations around wells 45-14, 66-21 and the main power producing area. These could be more firmly defined with MT station densification to the southeast in the valley and western Clan Alpine Range. The fence section in Figure 10 roughly corresponds to the original transect of Wannamaker et al. (2007).

Finally, we present a series of fence diagrams in Figure 11 to provide a view of the relation between upper and deep crustal low resistivity structure in the project area. The fences correspond to the transect of Wannamaker et al (2006) plus two others ~6 and ~13 km further SW developed in this study. The main purpose is to illuminate the 3D equivalent of the crustal scale low-resistivity break in the earlier 2D model that extended from base of Dixie Valley steeply westward under the Stillwater Range to join the near sub-horizontal low resistivity zone under Buena Vista.
Valley and the East Humboldt Range (Figure 4). In Figure 11, one sees that a similar albeit strike-varying conductive zone projects from under Dixie Valley westward to the deep crust. Precisely under the fence of the original transect (northeastern section in Figure 11), the deep conductive zone appears double lobed as it descends from the valley whereas only a single zone was seen in the original 2D model. The 3D structure here portrays the convergence of NE-SW and N-S conductors discussed in Figures 9 and 10. A short distance further northeast, these structures essentially join.

![Figure 11. Perspective view from the south of 3D resistivity model in three fence diagrams extending to a depth of ~20km below the surface. The wells are not color coded by temperature here. The MT site symbols are at zero elevation.](image)

The original transect can be said to have passed through at a fortunate position; if it had gone much further north, evidence for the large scale, steep conductor joining deep crustal magmatism to the west with the Dixie Valley thermal field might have been missed. Nevertheless this experience confirms early theoretical simulations (Wannamaker et al., 1984; Wannamaker, 1999) that fixed-axis, TM mode modeling of data in many 3D situations can yield fundamentally significant information about the earth section below (or nearby below) an MT profile.

**DISCUSSION AND CONCLUSIONS**

The 3D data coverage and inversion reveal intersection of NE-SW, nearly N-S and perhaps NW-SE low resistivity trends in the DVGS. Concentrations of low resistivity appear to occur at the geothermal manifestations associated with wells 45-14, 66-21 and the main power production area. These concentrations may be promoted by intersection of NE-SW and N-S structural trends at upper middle crustal levels. Strong resistivity structures in the upper 5 km such as these are not characteristic within the Stillwater Range, although very limited MT stations are present in the range. The 3D model appears to confirm the presence inferred from a previous MT transect through the producing area of a crustal-scale conductive break dipping steeply under the Stillwater Range and connecting with a previously suspected zone of deep crustal magmatic underplating and fluid release to the west under Buena Vista Valley. However, this data set highlights the value of full 3D coverage to pinpoint geothermal concentrations associated with intersection of varying trends.

For EGS prospectively, identification of suitable reservoir rocks which can support brittle fracturing and are at high temperatures is crucial. Candidate reservoir rocks include the Jurassic mafic/ultramafic Humboldt Fm and the Cretaceous granodioritic New York Canyon intrusives. At this point it is considered unlikely that hot (up to ~300 °C) dry rocks can be distinguished from cold dry rocks based on bulk electrical resistivity. At fixed salinity, pore fluid resistivity will reduce by a factor of ~5 from room temperature to 300 °C (Nesbitt, 1991). Thus, for example, a tight granitic rock with a resistivity of 5000 ohm-m at room temperature would exhibit a resistivity of 1000 ohm-m at 300 °C. Using typical Archie’s Law mixing relations (Grant and West, 1965), one also could cause such a resistivity reduction through increasing the porosity by a factor of 2-5 at fixed salinity and temperature depending upon whether conduction was predominantly through tortuous pores or straight fractures. Furthermore, values of 5000 and 1000 ohm-m would both be considered resistive and difficult to resolve from MT data that are imaged via smoothing-stabilized inversion such as we have employed in the face of burial and proximity to other lithologies. Perhaps it would be more fruitful to establish the location of generally resistive lithologies from the inversion, and then examine whether other structures may be responsible for bringing heat into the area and increasing the temperature of potential reservoir rocks. Candidates for that might include the conductive linear features in the 5-6.5 km depth range discussed above.

The values of the lowest resistivities at depths of several km can be quite small, of order 1 ohm-m. Expected temperatures should be well over 200 °C and probably more like 300 °C based on encountered well temperatures (Blackwell et al., 2007). Thus we do not expect presence of high cation exchangeable clays such as smectite to exist and contribute to lowering resistivity. The root cause is expected to be presence of saline aqueous fluids interconnected over distances comparable to the size of the resolved structures. Highly saline (20+ wt %), deep crustal fluids such as are exsolved during magmatic crystallization are perhaps suitable as they have resistivity around 0.002 ohm-m at such temperatures (Nesbitt, 1993). In a medium of aligned fractures, the necessary porosity to achieve 1 ohm-m is only ~0.5 vol % assuming...
ideal interconnection. However, such saline fluids are not characteristic of the wells and would imply disconnection of such deep fluids from the production domain. This in turn may relate to the ambiguity of evidence for direct magmatic input to the geothermal field. The concentrations of $^3$He in the field fluids at face value imply that magmatic fluid proportions should be within 10% of the total; together with the lack of nearby young volcanic outcrop this has lead to deep fluid circulation and heat mining as the preferred system driver (Kennedy and van Soest, 2006; 2007; Blackwell et al., 2007). On the other hand, to date steady-state deep circulation models have not explained temperatures as high as 285 C in DVGS wells, calling instead upon transient models tied to an earthquake cycle (McKenna and Blackwell, 2004). Perhaps lower crustal magmatism nearby to the west implied by the MT data over time has effecte some (unquantified) subregional-scale, additional heating of Stillwater Range crustal rocks that subsequently can be mined by deep circulating water. The true nature of heat and fluid sources for the DVGS remains an area of further study.

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