

## **INTEGRATED DENSE ARRAY AND TRANSECT MT SURVEYING AT DIXIE VALLEY GEOHERMAL AREA, NEVADA; STRUCTURAL CONTROLS, HYDROTHERMAL ALTERATION AND DEEP FLUID SOURCES**

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### **ABSTRACT**

State-of-the-art MT array measurements in contiguous bipole deployments across the Dixie Valley thermal area have been integrated with regional MT transect data and other evidence to address several basic geothermal goals. These include 1), resolve a fundamental structural ambiguity at the Dixie Valley thermal area (single rangefront fault versus shallower, stepped pediment); 2), delineate fault zones which have experienced fluid flux as indicated by low resistivity; 3), infer ultimate heat and fluid sources for the thermal area; and 4), from a generic technique standpoint, investigate the capability of well-sampled electrical data for resolving subsurface structure. Three dense lines cross the Senator Fumaroles area, the Cottonwood Creek and main producing area, and the low-permeability region through the section 10-15 area, and have stand-alone MT soundings appended at one or both ends for local background control. Regularized 2-D inversion implies that shallow pediment basement rocks extend for a considerable distance (1-2 km) southeastward from the topographic scarp of the Stillwater Range under all three dense profiles, but especially for the Senator Fumaroles line. This result is similar to gravity interpretations in the area, but with the intrinsic depth resolution possible from EM wave propagation. Low resistivity zones flank the interpreted main offsetting fault especially toward the north end of the field which may be due to alteration from geothermal fluid outflow and upflow. The appended MT soundings help to substantiate a deep, subvertical conductor intersecting the base of Dixie Valley from the middle crust, which appears to be a hydrothermal conduit feeding from deep crustal magmatic underplating. This may supply at least part of the high temperature fluids and explain enhanced He-3 levels in those fluids.

### **INTRODUCTION**

Predictive capability for subsurface resource location is an important aspect of a geothermal exploration tool. Geophysical methods have long received attention for this purpose due to their ability to provide structural images of the underground from data taken at the surface. Of the various physical properties of the earth, electrical resistivity is one which can be strongly affected by geothermal processes. Since an increased fluid content due to fracturing, and the development of more conductive alteration minerals (clays, etc.), can give rise to an electrical resistivity contrast, electromagnetic (EM) methods of probing have been investigated and applied for many years. The reliable mapping of electrical resistivity should increase chances of discovering blind geothermal resources, in defining the extent of geothermal reservoirs, in imaging controlling structures for geothermal systems, and in locating and characterizing permeable fracture zones.

However, images of subsurface resistivity have suffered in resolution due to limited data type, inadequate data sampling, and non-optimal inversion approaches translating data to models. We have applied a new-generation array magnetotelluric (MT) system in a contiguous bipole deployment over three profiles at the Dixie Valley thermal area (Figure 1). This well-sampled data set is analysed using an in-house inversion algorithm for MT image construction based on stabilization using a-priori constraints and spatial smoothing. One of our overall goals is to provide better tools, methods and data for resource identification and characterization using the MT method. A specific goal of the survey is to resolve a fundamental structural ambiguity at the Dixie Valley thermal area (single rangefront fault versus shallower, stepped pediment). Furthermore, we attempt to illuminate deep heat and fluid sources for the geothermal system.

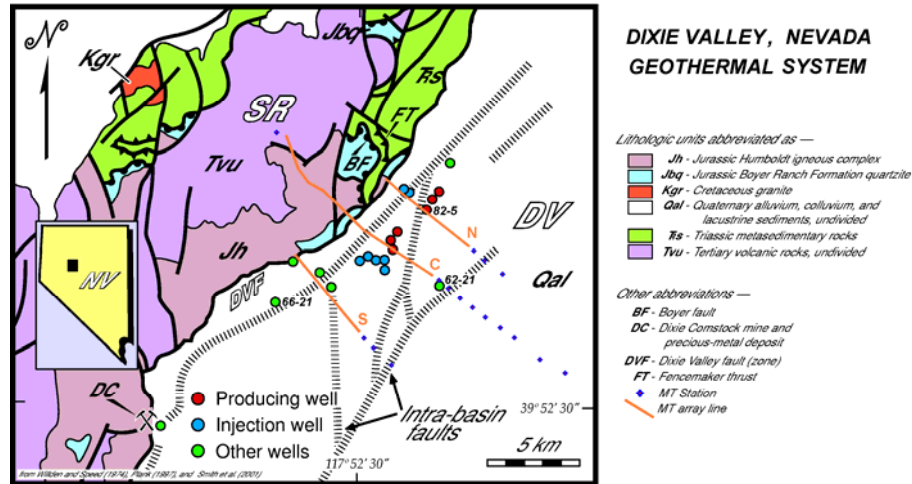


Figure 1. Simplified geological map of the Dixie Valley (DV)-Stillwater Range (SR) area surrounding the Dixie Valley thermal field. Orange-brown lines show acquired contiguous MT profiling through the system and adjacent fumarole fields. Lines are labeled N (north), C (central) and S (southern). Blue diamonds are five-channel MT stations added to extend profiles across the valley. Original figure courtesy of Jeff Hulen.

## GEOLOGICAL BACKGROUND

The Dixie Valley geothermal field lies in a highly extended area of northwestern Nevada within the Battle Mountain heat flow high and fields of Late Cenozoic volcanism (Blakely, 1988; Christiansen and Yeats, 1992). Modern cumulative extension rate in the western Great Basin is nearly 1 cm/yr, with a concentration of such in the Central Nevada Seismic Belt within which Dixie Valley lies (Hammond et al., 2005). The Dixie Valley field has been considered a classic rangefront fault system with production mainly from brittle igneous units represented by Oligocene silicic volcanics, Cretaceous granodiorite, or Jurassic mafic rocks (spilite or ophiolite) (Okaya and Thompson, 1985; Waibel, 1987; Dilek and Moores, 1995), possibly promoted by favorable stress regimes and fault orientations (Barton et al., 1998; Hickman et al., 1998). The thermal anomaly is interpreted in terms of deep circulation and background heat mining by Wisian and Blackwell (2004) due to lack of nearby young volcanics. However, enhanced levels of mantle-derived He-3 are observed at Dixie Valley (Kennedy and van Soest, 2006) and deep MT structure suggests a connection with the Buena Vista deep crustal geophysical anomaly (Wannamaker et al., 2006a,b).

Controversy has arisen regarding the basic structural controls for the Dixie Valley system, as summarized in Figure 2. The traditional model has been one of a single normal fault dipping  $\sim 55^\circ$  to the southeast connecting from the range/valley topographic contact through the producing wells (Benoit, 1999). However, recent drilling, gravity and thermal

modeling indicates a more complicated structural setting with the range-valley contact being a series of step-down faults under the pediment (Blackwell et al., 2000). Numerous normal faults are mapped in the Stillwater Range itself (Plank, 1999), some of which must provide controls on fluid flow for alteration and fumarole activity near the rangefront. Smith et al. (2001) also interpret Dixie Valley to be a nested graben structure with a relatively narrow, deep central section. Resolving this structural ambiguity is a principal goal of the project.

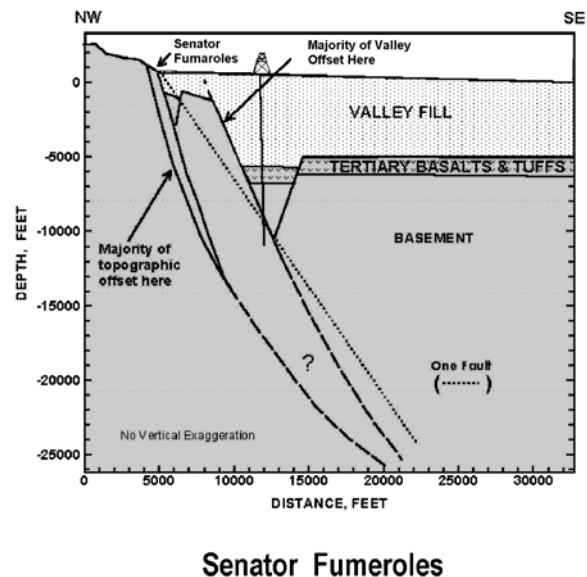


Figure 2. Fault splay model of the Dixie Valley/Stillwater Range bounding structure compared with the single fault model (Blackwell et al., 1999).

## **FIELD ACQUISITION AND PROCESSING**

With array MT data, complete lateral sampling of the response is achieved through contiguous bipole deployment (Torres-Verdin and Bostick, 1992). The system currently being fielded possesses 60 recording channels, two-thirds of which typically are assigned to the electric field component across assumed strike (transverse magnetic or TM mode), one-third to the E-field along strike (transverse electric or TE mode), and a pair of magnetic field coils near the center of the deployment. In such a deployment, near-surface “static” distortions do not require qualitative correction (e.g., Pellerin and Hohmann, 1990) but instead are included directly in the inversion process. It is anticipated that the 2-D assumption is expected to hold reasonably well at least for the upper few km of the study area, aided by experience in understanding relative effects of finite strike upon the various tensor data subsets (summarized in Wannamaker, 1999). In addition to the contiguous array data, however, we appended some traditional five-channel MT soundings to the southeast end of each profile in order to span the bulk of the Dixie Valley sediments and constrain their influence on the responses near the range front.

MT signals are small in amplitude and require careful processing to achieve accurate response functions. Some EM interference is generated by the existing power facility, but a distant remote reference synchronized by GPS timing was emplaced to suppress this through unbiased stacking. The overall time series processing consisted of three main steps, similar to the description by Larsen et al. (1996). First, the entire series is Fourier transformed to allow ultra-narrow band removal of spectral outliers such as 60 Hz and its harmonics. Second, the remaining time series is subdivided into short time segments with spectral estimates of each made using cascade decimation. Multiple coherence of spectral estimates between the base readings and the remote reference were made and low coherence time series segments rejected. Finally, the surviving spectral cross products undergo robust outlier removal following Egbert and Booker (1986). The frequency range of the MT data is ~10 kHz to 0.03 Hz.

Our approach to the inversion of array MT data to yield resistivity cross sections is based on the a-priori, maximum likelihood estimates of Tarantola (1987) and utilizes the finite element platform of DeLugao and Wannamaker (1996). The approach applies stabilization through a weighted sum of a-priori model adherence and spatial smoothing in terms of model slope (cf., DeGroot-Hedlin and Constable, 1990; Rodi and Mackie, 2001). The a-priori damping factor is updated each iteration to achieve stabilization in terms of fundamental

parameter correlations characteristic of the physics of diffusive EM (e.g., conductivity-dimension). Also, the parameters defining the image grow both laterally and vertically with depth, thereby preserving the influence of individual parameters at the surface according to basic EM scaling, and thus stabilizing the parameter step matrix and increasing depth of exploration.

## **OBSERVED MT DATA AND INVERSION CROSS SECTIONS**

Our presentation of results begins with the northeasterly Senator fumaroles line and works toward the southwest (Figure 3). The starting model in all cases is consistent with an integrated sounding from regional MT surveying in the tectonically active western Great Basin (Wannamaker et al., 2006a,b), with a smooth variation ~100 ohm-m down to 3 km depth, reaching 300 ohm-m near 10 km, and finally dropping to ~10 ohm-m below 20 km. Since the interpretation is taking place within a two-dimensional framework, inaccuracies from possible 3-D effects were reduced by emphasizing inversion of the TM mode over the whole frequency range, and the TE mode down to 3 Hz where the resistive basement becomes influential (Wannamaker, 1999).

In the first model, high resistivities (~1000 ohm-m) are seen under the Stillwater Range below 400 m depth and extending to the southeast under the pediment. Moderately high values (~100 ohm-m) persist at rather shallow depths (~400 m) from the topographic scarp where Senator fumaroles are located, to a distance of about 1.5 km southeast just past well 38-32. Values of 100 ohm-m are more consistent with rock than alluvium (e.g., Ward et al., 1978), although some alteration of the rock is a possibility. The alluvium of the main part of Dixie Valley is moderately conductive (10-25 ohm-m) in the upper 500 m, and quite conductive in the 500-1000 m depth range (< 3 ohm-m). A low resistivity limb dips upward from ~1 km depth to the near-surface under well 38-32 near the west flank of Dixie Valley. Senator Fumaroles itself does not exhibit a strong resistivity expression.

This inversion suggests that shallow basement rocks extend for a considerable distance to the SE before plunging steeply down the main range front fault. It thus is more supportive of the multi-fault basement model than that of the single main fault (Blackwell et al., 2000). This is supported by the drilling results and interpretive geological cross section described by Johnson and Hulen (2002). However, that interpretation remains non-unique: while Stillwater Range lithologies were intersected at a depth of ~400 m in well 38-32, near where the step in resistivity to values of 100 ohm-m or more occurs, an unknown amount of slide block material may exist over the

main Dixie Valley rangefront fault here to complicate the structural framework (op. cit.). A particularly low resistivity zone flanks the interpreted main offsetting fault and may be due to alteration from geothermal fluid outflow and upflow. There also is a near-surface concentration of such intersected by well 38-32. Finally, low resistivity persists below the valley floor beyond depths of 4 km in Figure 3. This is viewed as reflecting a deep thermal fluid feeder zone, more about which will be discussed with the model of the central line.

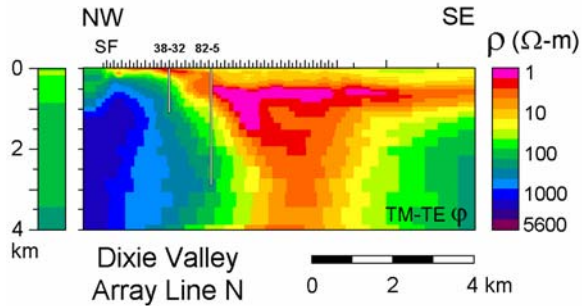


Figure 3. Electrical resistivity section for the northern (N) profile across Senator fumaroles derived from 60 array MT sites taken with contiguous E-field bipoles, plus three stand-alone MT sites at the SE end. Tick marks are located at bipole centers. Senator fumaroles are denoted SF, and wells 38-32 and 82-5 are projected onto the section.

The data of the long central profile C were inverted and the results are shown in Figure 4, this time to 10 km depth due to the greater length of the profile. The inversion section reveals the valley basement faulting profile across the main power producing area, small-scale fluidized/alterated graben structure within the valley, and a large thermal feeder zone entering the bottom of the valley. The latter is a more finely resolved analog of the high-angle conductive zone connecting the Buena Vista-Humboldt Range low resistivity bright spot to the bottom of Dixie Valley as imaged in regional MT transect data (Wannamaker et al., 2006a,b). It emerges in the images as a result of the strong and abrupt transition in TM mode impedance phases across Dixie Valley, behavior which is uniquely prominent here relative to elsewhere on the regional transect (op. cit.). The deep crustal low resistivity is interpreted to be a zone of active magmatic underplating, indicating together with enhanced He-3 levels sampled in the Dixie Valley field (Kennedy and van Soest, 2006) that there is magmatic input to Dixie Valley. Deep well 62-21 (Figure 4) in fact shows the highest mantle He-3 levels of any of the water samples at Dixie Valley, corroborating that the steep conductor corresponds to a magmatic fluid pathway. Nearly coincident seismic reflection profiling confirms a pronounced but fairly compact zone of downdropping of valley basement rocks in the vicinity of this deep vertical conductor (Blackwell and Smith, 2006). The feeder zone appears also in the inversion section of Figure 3 though we ended that section at 4 km depth.

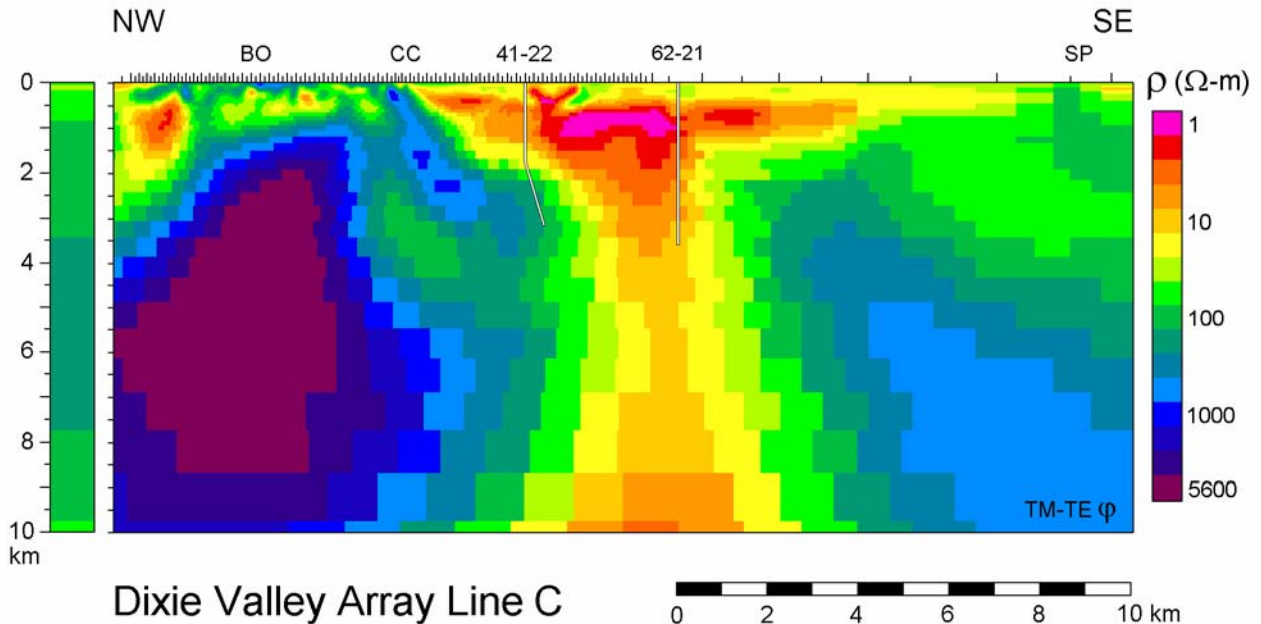


Figure 4. Resistivity inversion section across the Dixie Valley power producing field from 120 dense MT array measurements and 13 appended wideband MT soundings (tick marks denote bipole centers). Other landmarks are Cottonwood Creek mouth (CC), Bolivia mine (BO), and deep wells 41-22 and 62-21, and Shoshone Point (SP).

Producing well 41-22 enters more resistive material at a depth of around 2 km, which according to sections in Plank (1999) are mid-Tertiary to Mesozoic rocks of the range front fault hanging wall. The large resistor toward the west is interpreted to be part of the Cretaceous New York Canyon batholith. A steep, lower resistivity thick curvi-planar zone in the eastern part of this resistor dips upward to near the surface NW of the mouth of Cottonwood Canyon and may represent a modest fluid pathway feeding surface alteration noted here (Blackwell et al., 2000). In contrast to the Senator Fumaroles line, there is weaker evidence of shallow bedrock persisting valleyward, but the undulatory nature of the transition to high resistivity suggests multiple basement faults anyway.

Finally, the inversion section for the southerly line S reaching the Section 10 fumaroles is shown in Figure 5. We do not observe basement rocks as shallow as those of the northerly line from Senator fumaroles extending toward the valley, but rather a more steady dip to the SE. Nevertheless, this is a rather shallow dip for a single fault plane so we entertain the possibility of this being a stepdown zone across several steep faults of limited throw. Wells near the line project into fairly resistive material, probably plutonic rocks, and the area is described as being hot but with poor permeability (e.g., Blackwell et al, 2000). The deep feeder zone projecting from the lower crust is visible again, though of greater width than under the other two MT profiles. However, we view these results as significant in establishing continuity along a NE-SW strike of the deep feeder zone in the Dixie Valley area. The models for the three lines tend to support the multi-fault as a rule for the Dixie Valley thermal area, especially for Senator fumaroles, although it is somewhat more interpretive for the other two profiles.

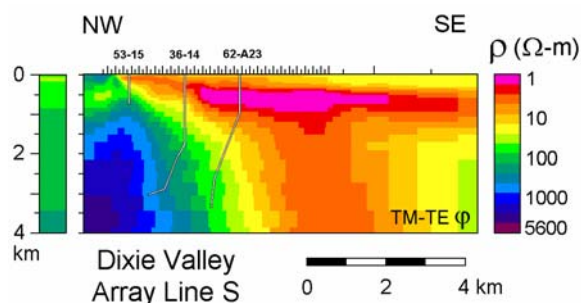


Figure 5. Resistivity inversion section across the Section 10-15 area for the dense MT array line S plus three stand-alone MT sites to the SE. Nearby wells appear to intersect relatively resistive basement rocks of the footwall.

## CONCLUSIONS

Lateral sampling uncertainties in MT are greatly reduced by contiguous bipole deployment, which helps to maximize the resolution of resistivity structure. Remote referencing and robust processing have generally yielded very high quality data even in a field where power production has already been established. Inversion cross sections show numerous interesting resistivity structures and help resolve a long-standing structural ambiguity in the area. In particular, a structural model of multiple fault steps toward central Dixie Valley appears more consistent with the MT data than a single range front fault. The transition from low to high resistivity (>100 ohm-m) appears to represent basement interface based on drilling results. All three inverted profiles, with appended five-channel soundings for improved aperture, show a potential deep feeder zone for high temperature fluids rising into central Dixie Valley at its most downdropped location. This is the same feeder zone as imaged in regional MT transect inversion which appears to connect to a pronounced low resistivity zone in the deep crust under Buena Vista Valley and the Humboldt Range to the northwest. It is a means of providing a magmatic component to the fluids of Dixie Valley as reflected in enhanced He-3 concentrations in the field.

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