

**Project Final Report, to:
U.S. Department of Energy
Office of Geothermal Technologies
University Program**

Title: Structural controls, alteration, permeability and thermal regime of Dixie Valley from new-generation MT/galvanic array profiling

Award No.: DE- FG07-02ID14416

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Project Start Date: 10/01/2002

Project End Date: 08/31/2007

Total Funding: \$165,808

Executive Summary: 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 range-front 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.

Objectives and Accomplishments

A new-generation MT/DC array resistivity measurement system was applied at the Dixie Valley thermal area. Basic goals of the survey are 1), resolve a fundamental structural ambiguity at the Dixie Valley thermal area (single range-front fault versus shallower, stepped

pediment; 2), delineate fault zones which have experienced fluid flux as indicated by low resistivity; 3), image the disposition of resistive, possible reservoir formations in the subsurface; and 4), from a generic standpoint, investigate the capability of fully sampled electrical data for resolving subsurface structure. Broader project objectives include increasing the number of states with geothermal electric power facilities, reduced the levelized cost of generating power, and increase the power/heat energy supply for homes and businesses by improving exploration technology.

We view these goals as having been well met in this project. The style of faulting at the range front has been distinguished (multiply faulted pediment), deeper feeder fault zones supplying high temperature fluids to the system identified, and zones of resistive basement rocks imaged below the pediment area. Fine scale faulting and altered fluid pathways were resolved with the contiguous bipole approach which otherwise likely would have been overlooked. The project demonstrated the benefit of integration of contiguous bipole data with existing MT transect data involving widely spaced sites. Together these identified probably magmatic fluid input to the Dixie Valley system, conceptually greatly increasing the size of the resource.

Project Activities and Results

Background/Approach: 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 applied a new-generation array magnetotelluric/galvanic (MT/DC) system in a contiguous bipole deployment over three profiles at the Dixie Valley thermal area. This well-sampled data set was being analysed using an in-house inversion algorithm for resistivity image construction based on stabilization using a-priori constraints. A specific goal of the survey is to resolve a fundamental structural ambiguity at the Dixie Valley thermal area (single range front fault vs stepped pediment) (Blackwell et al., 1999; Smith et al., 2001, GRC Trans.; Blackwell et al., 2006, SGP Proc.). Data were obtained in years 1 and 2, analysis has taken place throughout project lifetime.

Data Acquisition: MT/DC surveying was carried out on three, 4-6 mile long profiles totalling 14 line miles, each crossing the Stillwater fault zone approximately at right angles (Wannamaker, 2003, GRC Trans.) (Figure 1). The acquisition was by contract to Quantec Geoscience, Inc., who recently developed the system for exploration problems in the mining industry. The frequency range of the MT data is ~10 kHz to 0.03 Hz. These lines cross the Senator Fumaroles area, the Cottonwood Creek and main producing area, and the low-permeability region through the section 10-15 area. With array MT data, complete lateral sampling of the response is achieved through contiguous bipole deployment (Torres-Verdin and Bostick, 1992, Geophysics). In such a deployment, near-surface “static” distortions do not require qualitative correction but instead are included directly in the inversion process. Added to the profiles on their SE ends have been stand-alone five-channel MT stations to span and allow imaging of the boundaries of the conductive Dixie Valley. The MT data of all three profiles received final editing and assembly, and merging with added stand-alone five-channel MT sites in order to completely span Dixie Valley, to gain control on the effects of the sedimentary body upon responses near the production areas. The galvanic

(DC) data unfortunately were not of good quality for the most part due to extremely dry soil conditions at the time of the survey.

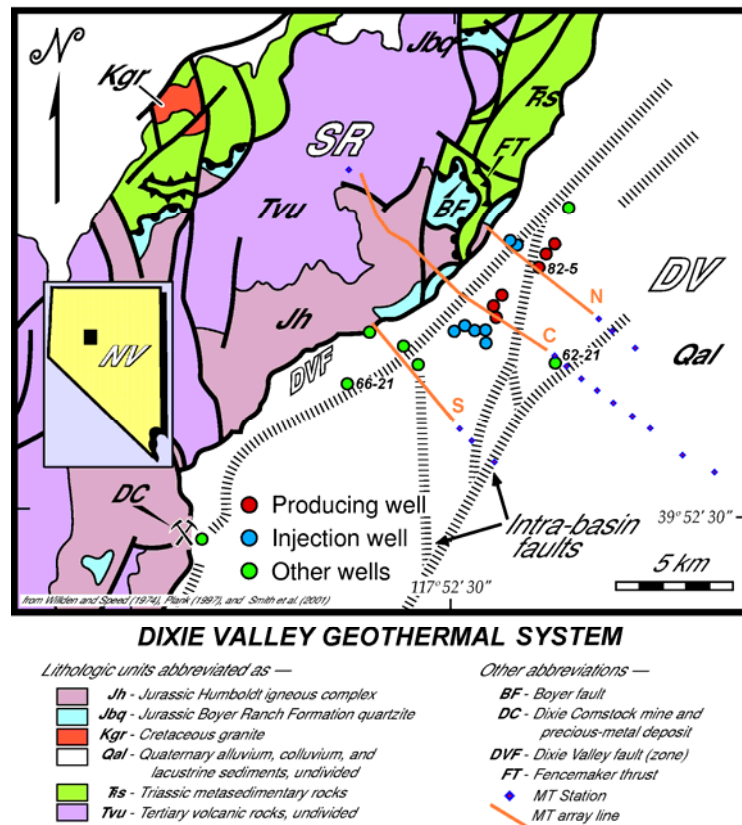


Figure 1. Simplified geological map of the Dixie Valley (DV)-Stillwater Range (SR) area surrounding the Dixie Valley thermal field. Orange-brown lines show acquired contiguous MT/DC profiling through the system and adjacent fumarole fields. Lines are labeled N (north), C (central) and S (southern). Blue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

Northern Array Profile: First is shown the inversion model for the northern line N reaching Senator Fumaroles (Figure 2). 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, Geophysics), 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.

The inversion to this point suggests that shallow basement rocks extend for a considerable distance to the southeast 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., 1999, 2000, Proc. WGC). However, the structural interpretation remains somewhat non-unique: although 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 range-front fault here to complicate the structural framework (Johnson and Hulen, 2002, GRC Trans.). 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.

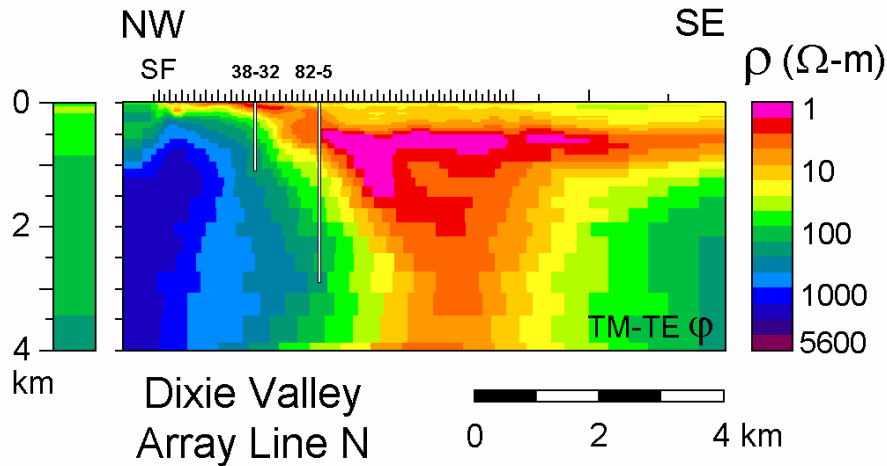


Figure 2. Electrical resistivity section for the northern (N) profile across Senator fumaroles derived from 60 array MT sites taken with contiguous, 100 m long electric field bipoles, plus three stand-alone MT sites at SE end. Tick marks are located at bipole centers. Bedrock-alluvium interface is interpreted to lie near the 70-100 ohm-m “contour”. Senator Fumaroles are denoted SF, and wells 38-32 and 82-5 are projected onto section.

Central Array Profile: The data of the long central profile C were inverted and are shown in Figure 3, 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/alterd 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., GRC Trans., 2006). The latter is interpreted to be a zone of active magmatic underplating, indicating together with enhanced He-3 levels sampled in the Dixie Valley field by Mack Kennedy that there is magmatic input to Dixie Valley. Deep well 62-21 (Figure 3) 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. This feeder zone appears also in the inversion section of Figure 2 though we ended that section at 4 km depth.

Producing well 41-22 enters more resistive material at a depth of around 2 km, which according to sections in Plank (1992, Ph.D. thesis, UNR) 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 the alteration of White Rock Canyon. In contrast to the Senator Fumaroles line, there is scant evidence of shallow bedrock persisting valleyward but rather a steady dip near 40 degrees with some steepening about 1.5 km SE of the topographic scarp.

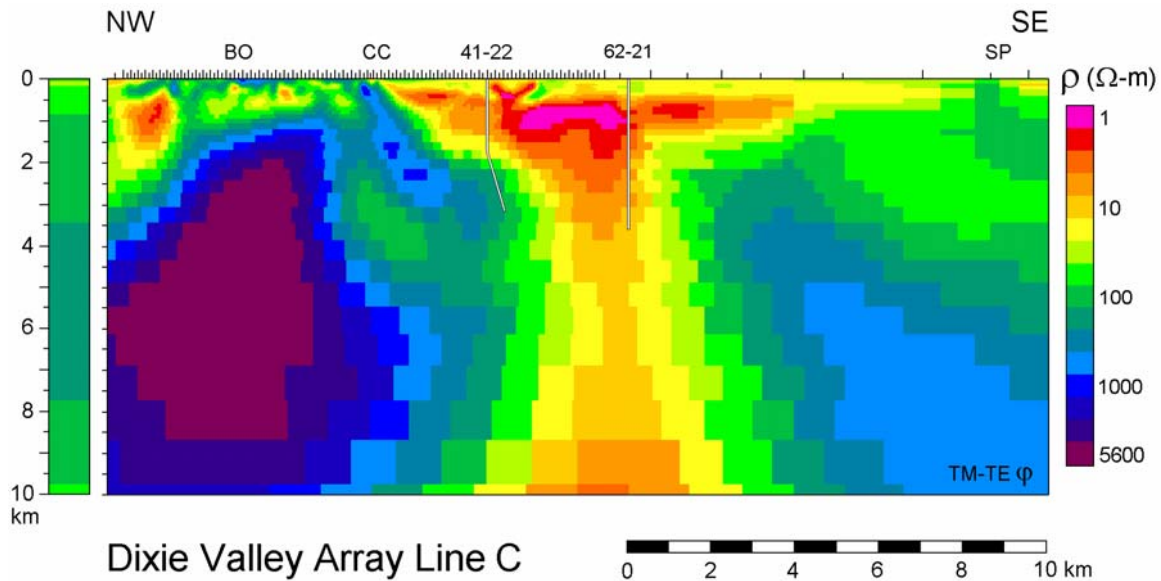


Figure 3. Resistivity inversion section across the Dixie Valley power producing field from dense MT array measurements and appended wideband MT soundings derived from 120 array MT sites (tick marks denote bipole centers) plus 13 standalone soundings on SE end. Other landmarks are Cottonwood Creek mouth (CC), Bolivia mine (BO), and two deep wells 41-22 and 62-21, and Shoshone Point (SP).

Southern Array Profile: Finally, the inversion section for the southerly line S reaching the Section 10 Fumaroles is shown in Figure 4. Again 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. Wells near the line project into fairly resistive material, probably plutonics, and the area is described as being hot but with poor permeability. The deep feeder zone projecting from the lower crust is visible again, though of great width than under the other two MT array 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. On the other hand, the models for the three lines do not unequivocally support either the multi-fault or the single fault model as the rule for the Dixie Valley thermal area. Senator Fumaroles appears to exemplify shallow basement persisting well

under the alluvium toward the valley, but a more steady dip is observed for the other two lines.

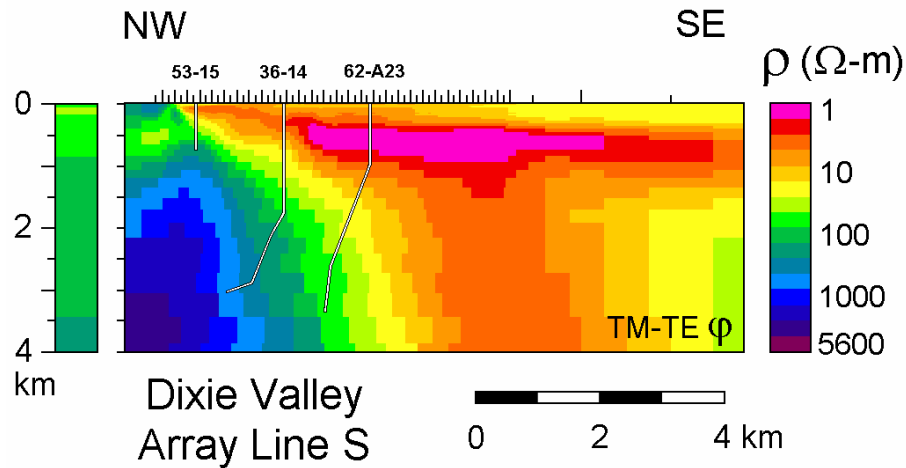


Figure 4. Resistivity inversion section across the Section 10-15 area for the dense MT array line S plus three stand-alone MT sites to the SE. Nearby wells appear to intersect relatively resistive basement rocks of the footwall.

Developed Products

Wannamaker, P. E., D. P. Hasterok, and W. M. Doerner, 2006, Possible magmatic input to the Dixie Valley geothermal field, and implications for district-scale resource exploration, inferred from magnetotelluric (MT) resistivity surveying, GRC Trans., v. 30, 471-475.

Wannamaker, P. E., W. M. Doerner, and D. P. Hasterok, 2007, Integrated dense array and transect MT surveying at Dixie Valley geothermal area, Nevada; structural controls, hydrothermal alteration, and deep fluid sources, Proc 32nd Workshop on Geothermal Reservoir Engineering, Stanford Univ., Jan. 22-24, SGP-TR-183, in prep.

An ascii listing of the rectilinear inversion parameter resistivity values and geometries is available from the P.I. upon request.