Possible Magmatic Input to the Dixie Valley Geothermal Field, and Implications for District-Scale Resource Exploration, Inferred from Magnetotelluric (MT) Resistivity Surveying

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ABSTRACT

Magnetotelluric (MT) profiling in northwestern Nevada is used to test hypotheses on the main sources of heat and hydrothermal fluid for the Dixie Valley-Central Nevada Seismic Belt area. The transect reveals families of resistivity structures commonly dominated by steeply-dipping features, some of which may be of key geothermal significance. Most notably, 2-D inversion of these data has resolved a high-angle, conductive fault zone-like structure extending from the base of Dixie Valley to a broad, deep crustal conductor beneath the Stillwater-Humboldt Range area. The deep conductor is coincident with the Buena Vista anomalous seismic area, and such conductors are generally correlated with magmatic underplating and fluid exsolution. This deeply extending, steep fault zone may be the means for deep transport of fluids upward to provide high temperatures at the Dixie Valley field, including a component of magmatic fluids consistent with recent He isotope studies and the existence of hot springs manifestations in the center of the valley. Decomposed impedance axis analysis suggests the overall trend of this break is nearly N-S. However, other important conductivity structures imaged in the transect include possible large-scale sedimentary folds in the Phanerozoic continental shelf section, and overthrusting near the margin with the Sierra Nevada plutonic province. This experience highlights the need to bring external constraints when interpreting resistivity in the Great Basin.

Introduction

The Dixie Valley power producing thermal area is a classic, high temperature extensional geothermal system of the Great Basin. However, it lacks nearby young volcanic rocks, and thus is argued to be controlled by large-scale convective fluid flow mining ambient heat from the rock (Benoit, 1999; Blackwell et al., 2000). This is not inconsistent with the area being one of active extension and large historic earthquakes (e.g., Hammond and Thatcher, 2005), but if so, circulation scales must extend to the middle crust at least in order to achieve measured wellbore temperatures ~280 C in the upper 3 km with typical geothermal gradients (McKenna and Blackwell, 2004; Wisian and Blackwell, 2004). In detail however, such circulation models so far have yielded shallow temperatures only around half the observed. Moreover, seismic and geochemical evidence we will review suggest that cryptic magmatic activity in the

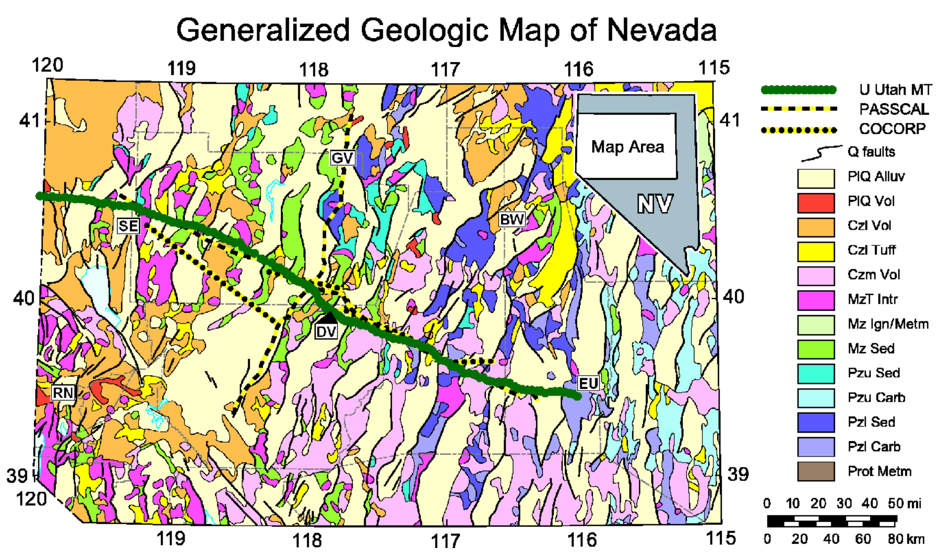

Figure 1. Generalized geological map of northwestern Nevada showing MT station transect and active source seismic profiles of the COCORP effort and the 1986 PASSCAL experiment. Locations include Dixie Valley (DV), Reno (RN), Grass Valley (GV), San Emidio (SE), Beowawe(BW) and Eureka (EU).

crust may not be distant and could influence the hydrothermal regime. In this work, we attempt to trace the reaches of high-T fluid pathways and their sources in the Dixie Valley region and northwestern Great Basin through their influence on electrical resistivity based on a detailed magnetotelluric (MT) profile (Figure 1).

MT Data Collection and Modeling

Our MT transect of ~140 soundings is centered on Dixie Valley and oriented WNW-ESE approximately normal to the average trend of horst-graben morphology from the California border in the Smoke Creek area to near the town of Eureka in central Nevada. In the Dixie Valley area, the line passes through Cottonwood Canyon and the power producing area. About 20 of the five-channel tensor sites were acquired with the University of Utah system, while the remainder were contracted to Quantec Geoscience Inc. Most of the latter were recorded using Reftek data loggers with incorporated in-house electric field preamps and analog signals from EMI Inc. BF4 and BF7 magnetic induction coils. Cross-site remote referencing was standard and, in the western part of the survey, H-fields of the Parkfield California MT observatory were used as references to counteract the Bonneville Power Authority interstate DC power transmission line as it passes through this area (Wannamaker et al., 2004).

Pseudosections of the observed MT responses were presented by Wannamaker et al (2006) and will not be repeated here. However, key features worth noting include alternating high and low apparent resistivity (ρ_a) contours indicative of individual horsts and grabens, and a series of semi-regional highs in the impedance phase (φ) over the 10-100 s band. The latter, particularly evident in the Seven Troughs Range area, from I-80 to Buena Vista Valley, and from the Simpson Park Range to Eureka, will be shown to represent enhanced electrical conductivity in the lower crust. Some of the lateral transitions in the transverse magnetic (TM) mode phase are quite abrupt even though they occur at relatively long periods. The most notable example of these was below central Dixie Valley itself. As reviewed by Wannamaker et al (2006), these abrupt changes are typically associated with steep, crustal scale conducting elements like fault zones connecting electrical currents induced in conductive upper crustal heterogeneity, with large-scale conductors in the deep crust.

A non-linear 2-D inversion was carried out of the TM mode apparent resistivity and impedance phase, and including the TE vertical magnetic field; these data subsets have been shown to be relatively robust to finite strike (3-D) effects (Wannamaker, 1999; Ledo et al., 2005). We used the University of Utah/EGI in-house finite element algorithm implementing an explicit Gauss-Newton parameter step (Wannamaker et al., 1987; DeLugao and Wannamaker, 1996: Tarantola, 1987) (Figure 2). This program seeks to fit the data as well as possible, subject to stabilization by adherence to an a-priori model in either an absolute or first spatial derivative sense. The 1-D starting and a-priori model is shown as a column to the left of the sections and was derived by integrating the TM mode impedance along the transect (Wannamaker et al., 1997). Improvements over the model of Wannamaker et al. (2006) include significantly more precise auxiliary field and jacobian calculations, and use of an integrated impedance starting model specific to the data of this transect. Error floors of 1.5 $\log_{10}$ % in ρ_a, 1° in φ, and 0.015 in vertical H-field were set and final RMS misfit was ~3.6, an improvement over the previous model fit.

Numerous heterogeneous features have formed in the model section from the 1-D initial guess (Figure 2). Large low resistivity zones in the lower crust are seen under the Humboldt-Stillwater Range corridor, and under the Simpson Park

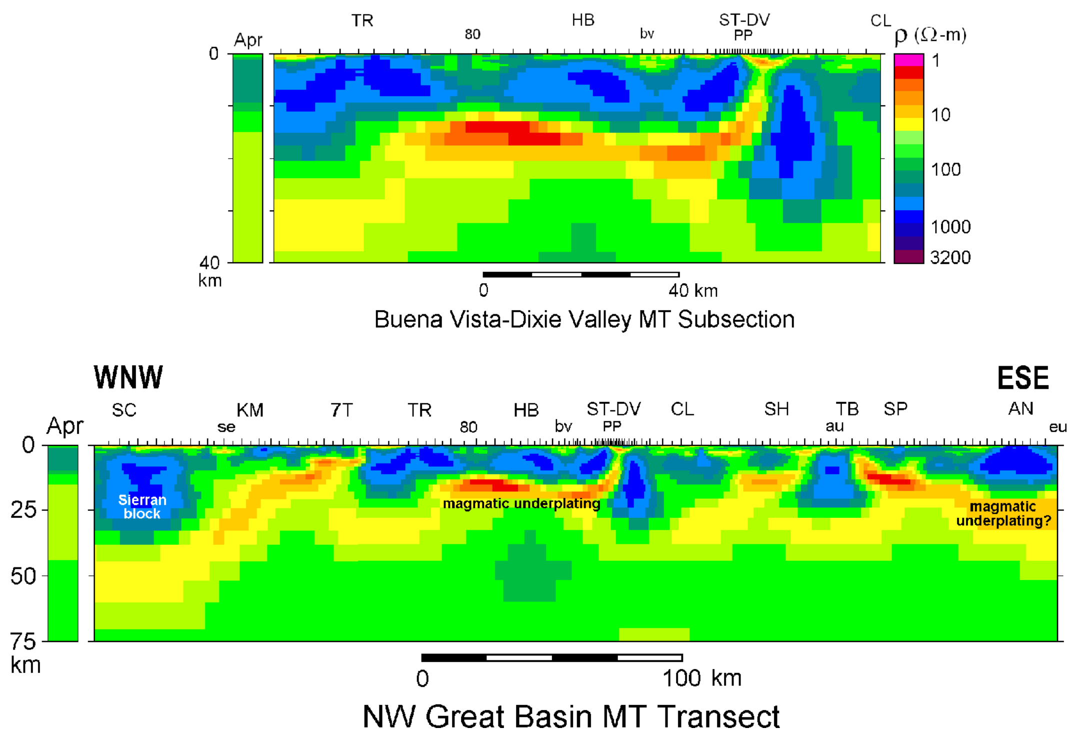

Figure 2. Non-linear 2-D inversion of TM mode apparent resistivity and impedance phase plus vertical magnetic field element Kzy data of MT transect. Starting and a-priori model for inversion is shown as a column on left hand side. Blow-up of section across Dixie Valley and the Buena Vista anomalous seismic area is shown toward top. Landmarks include Smoke Creek (SC), San Emidio hot springs, (se), Kumiva Peak (KM), Seven Troughs Range (7T), Trinity Range (TR), I-80, Humboldt Range (HB), Buena Vista Valley (bv), Stillwater Range-Dixie Valley system (ST-DV), power plant (PP), Clan Alpine Range (CL), Shoshone Range (SH), town of Austin (au), Toiyabe Range (TB), Simpson Park Range (SP), Antelope Range (AN), and town of Eureka. Points A-A' and P-P' denote approximate projections of geological sections of Speed (1988) and seismic section of Catchings and Mooney (1991).

to Antelope Range area, with lesser ones under the Kumiva-Seven Troughs Ranges and the Clan Alpine-Shoshone Ranges. At the east end of the Stillwater deep conductor, a slablike low resistivity zone dips steeply upward to connect to the bottom of Dixie Valley. Its presence allows simulation of the abrupt change in impedance phase across the center of the valley in the 10-300 s period range and is a robust feature. It does not attach near the rangefront but rather the center of the valley, where the data break actually occurs (Wannamaker et al., 2006). Additional prominent mid-crustal conductors include one dipping west under the Seven Troughs Range, and other concave-up conductors under the Shoshone and Simpson Park Ranges. Note however, that several mid-crustal zones of resistivity much higher than the starting model also exist. The lower crustal conductive zones which generally lie in the 15-35 km depth range under most of the line are replaced at the far northwest end by a weaker conductor in the 45-65 km range consistent with a lesser, longer period TM mode phase response. Resistivity variations elsewhere in the uppermost mantle are weak, but this is reaching the limits of penetration of the data in the measured period range.

An attempt is made to estimate the strike of the prominent fault-like feature connecting Dixie Valley to the Humboldt-Stillwater deep conductor by the properties of the long period (10-400 s) impedance phase of the 22 soundings over a 25 km stretch centered on this area. Using the ~250 individual impedance values therein, the phase tensor ellipse axes (Caldwell et al., 2004) and the coordinate axial directions which equalize the phases of the impedance tensor columns (Bahr, 1988) are binned into rose histogram plots, and the average principal axes and standard deviations computed (Figure 3). With either method, a rather clear N-S dominant trend appears, suggesting that deep structural controls do not strictly parallel the surface horst-graben morphology. Nevertheless, it is difficult to define just how 'local' this deep strike is, in other words, how far to the north and south to extrapolate. Whether, for example, this crustal break relates to the north more closely with the Beowawe system, or the Grass Valley system, or others in between, would best be settled by parallel profiles of new soundings.

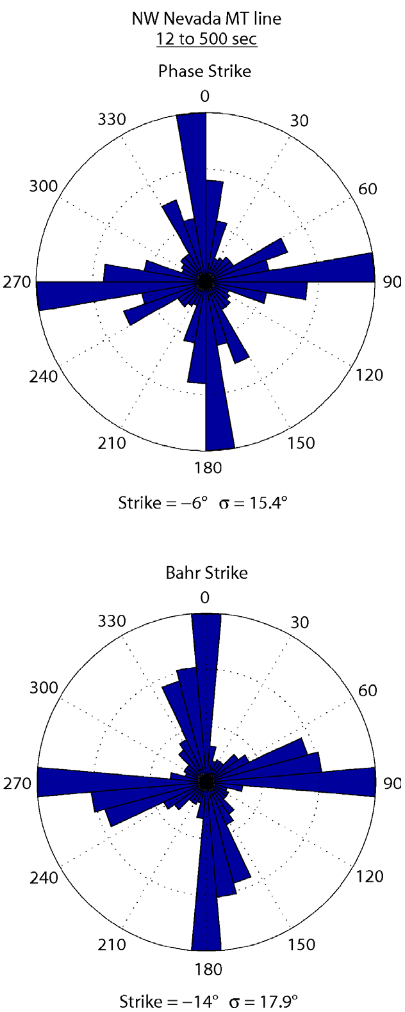

Figure 3. Long period principal impedance directions estimated by axes of the phase tensor ellipse (left) or by column phase equalization (right) for 22 soundings centered over the Dixie Valley production area.

Physical Significance of Model Resistivity Structure

The concentrated low resistivity zones of the lower crust of Figure 2, in light of the probable average geotherm of Great Basin crust (Lachenbruch and Sass, 1978), most likely represent partial melts near the Moho (~900 C near 35 km depth) and high-temperature hypersaline brines (presumably exsolved from said magmas) near their tops (~500 C near 20 km depth) (Wannamaker et al., 1997; Wannamaker, 2000). The most pronounced zone is that extending from the Stillwater Range northwestward nearly to the Trinity Range. It shallows to as little as 15 km below the western Humboldt Range and Interstate Highway 80. The low resistivity zone is roughly coincident with the region of highest seismic reflectivity, the greatest thickness of high Vp (7.4-7.5 km/s) lower crust, and high P-wave amplitude attenuation in the 1986 Nevada PASSCAL wide-angle seismic experiment, all characteristics which have been correlated with magmatic underplating (Catchings and Mooney, 1991). Moreover, the area from Dixie Valley westward is one of enhanced active extension based on modern GPS geodesy (Hammond and Thatcher, 2005), a process known to induce mantle upwelling and partial melting.

A minor additional low resistivity zone in the deep crust lies between the Clan Alpine and Shoshone Ranges, but a surprisingly substantial one is seen under the easternmost end of the line toward Eureka (Figure 2). If this is an area of magmatic underplating also, it implies substantial decoupling between upper mantle processes and those of the crust above in this otherwise stable block (Lowry and Smith, 2000). It would be interesting to follow this conductor to the east to see if its closes, or instead joins with even higher degrees of conductivity in the lower crust of the active eastern Great Basin (Wannamaker et al., 1997). At the west end of the line, the drop in depth of the conductor to 50 km signifies crossing onto rigid, undeformed thick crust of Sierra Nevada affinity, in keeping with the composition of outcrop (e.g., Stewart and Carlson, 1978), but in contrast to the inferred delaminated mantle lid and thinned state of the crust in the southern Sierra Nevada (Ducea, 2001; Park and Wernicke, 2003). The lower crustal conductor is punctured several times along the profile by restricted areas of high resistivity, such as below the Toiyabe Range and deep below Dixie Valley. We suggest that these are competent bodies of Late Mesozoic or Middle Cenozoic plutonics, mechanically resistant to modern magmatic penetration, based on following the resistors to outcrop.

The slablike low resistivity zone dipping steeply upward to connect to the bottom of Dixie Valley from the east end of the Stillwater deep conductor is suggested to be a deep conduit for high temperature fluids exploited at the Dixie Valley system. These fluids appear to intersect the valley at its center, and then ascend along the rangefront faulting on the valley's west side. This geometry helps explain the presence of thermal occurences in the valley center such as Hyder hot springs (Benoit, 1999; Blackwell et al., 2000). We point out that this deep hydrothermal process has 'lit up' Dixie Valley from a low resistivity standpoint in a unique fashion relative to other valleys on the transect, first observed in the dense array surveying of Wannamaker (2003). The proposed conduit connecting the Dixie Valley system with active magmatic underplating nearby to the west could explain the observed elevated He^3 values in Dixie Valley thermal waters (Kennedy and van Soest, 2006). These are generally taken to imply a mantle magmatic component to the waters even though Dixie Valley has been argued to be a deep circulation rather than a magmatic system (McKenna and Blackwell, 2004; Wisian and Blackwell, 2004). Our imaged geometry provides a means of injecting lower crustal, very high temperature fluids to shallow levels to mix with deep circulation waters.

The large earthquakes of the Central Nevada Seismic Belt (CNSB) (Wesnousky et al., 2005) lie 10-30 km off profile but project near the east transition of the conductive break to localized high resistivity, inferred plutonics. Worldwide, active earthquakes commonly are seen at transitions between conductive and resistive rock, or somewhat within the latter. Such locations are interpreted to allow stress buildup to significant levels before failure, possibly aided by fluid infiltration from the nearby good conductors (reviewed by Wannamaker et al., 2006). At larger scales, this low resistivity crustal break, the major earthquakes, and the CNSB overall coincide with the transition between cratonic Proterozoic North American basement and the Paleozoic accreted terranes under western Nevada (Speed et al., 1988; Burchfiel et al., 1992).

The two concave-up conductors under the Shoshone and Simpson Park Ranges (Figure 2) may reflect processes other than geothermal ones. They roughly flank the Toiyabe uplift, a plutonic-cored N-S trending axis of high metamorphic grade rocks arising in Late Mesozoic-Middle Cenozoic time (Speed, 1988; Stockli, 1999), and may represent deformed, graphite-bearing conductive strata deep in the Phanerozoic continental shelf section which has been downwarped along the uplift flanks. On the other hand, it is possible that these conductors too represent large-scale, fluidized normal faults of crustal scale. The west-dipping conductive zone starting on the east flank of the Seven Troughs Range (Figure 2) may bear some relation to the middle Miocene epithermal gold deposits there (Hudson et al., 2005), but the dip also is suggestive of control by the mega-scale Late Mesozoic overthrusting of Sierran rocks conjectured to have occurred in the westernmost Great Basin area (Ducea, 2001). The San Emidio geothermal system appears to lie at the junction of the thick Sierran block with the extending Great Basin crust. Hammond and Hatcher (2005) argue for a diffuse axis of enhanced extension in this area, 75-100 km NW of the CNSB, based on GPS geodetic data.

Conclusions

We see two main contributions from collection and interpretation of the transect data in this paper. First, a particular electrical structure has been identified which possibly represents a deep hydrothermal source for the Dixie Valley system. It is interpreted to connect to active extension and magmatic underplating in the lower crust. Magmatic underplating is variably concentrated in space in the western Great Basin, and on occasion the related lower crustal conductor seems completely absent in possibly resistant lithologies. Second, long transects such as this provide an opportunity to recognize the breadth of possibilities for creating enhanced conductivity in the crust. This important information underscores the value of external constraints for resistivity models in order to identify the structures which most likely pertain to geothermal processes. It would be interesting to pursue additional profiling parallel to this transect (though of shorter length possibly) in order to trace the Dixie Valley source structure to the northeast or southwest. Further insights could be expected from lengthening the main profile somewhat to increase confidence in the identification of resistivity structural causes and to test for coupling between ultimate deep magmatic sources and upper crustal extension.

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