CRYPTIC FAULTING AND MULTI-SCALE GEOTHERMAL FLUID CONNECTIONS IN THE DIXIE VALLEY-CENTRAL NEVADA SEISMIC BELT AREA; IMPLICATIONS FROM MT RESISTIVITY SURVEYING

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ABSTRACT

Extended magnetotelluric (MT) profiling results over the Dixie Valley-Central Nevada Seismic Belt area were recently completed to explore the hypothesis that fluid circulation to depths of 10 km or more is generating well temperatures in the field >280 C. This transect has revealed families of resistivity structures commonly dominated by high-angle 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. 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. West of San Emidio hot springs, we appear to encounter relatively rigid, resistive Sierran basement. This experience highlights the need to bring external constraints when interpreting resistivity in the Great Basin. Apart from possible deep vestiges of Mesozoic or younger batholithic volumes, the lower electrical crust at least in this region of the Great Basin is primarily a modern feature.

INTRODUCTION

In the extensional Great Basin province of the southwestern U.S., common models for rift basin faulting and hydrothermal systems hosted therein based e.g. on reflection seismology data show dominant displacement along steep master faults roughly coincident with the main topographic scarp and potentially soling to the brittle-ductile transition in the middle crust (Okaya and Thompson, 1985; Benoit, 1999). On the other hand, complementary data such as drilling, earthquake focal mechanisms, regional volcanic occurrences, and trace indicators such as helium isotopes suggest that there are diverse geometries and scales of crustal faulting and material transport in this province. Firmer conclusions about the nature of fundamental crustal breaks, the role of prior heterogeneity in deformation, the scales of geothermal fluid circulation, and the ultimate sources of such fluids in extensional regimes may be advanced through development and application of geophysical imaging techniques which are responsive to relevant petrophysical properties. This includes concern about competing causes of low resistivity that may obscure geothermal exploration.

The Dixie Valley power producing thermal area and surroundings may be nearly ideal for studying such issues. It is a high temperature system lacking nearby young volcanic rocks, and thus is argued to be controlled by large-scale convective fluid flow mining ambient heat from the rock (Blackwell et al., 2000). This is not inconsistent with the area being one of active extension and large historic earthquakes (e.g., Hammond, 2005). 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 review suggest that cryptic magmatic activity in the crust may not be that 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 using magnetotellurics (MT).
OBSERVED MT RESULTS

We collected an MT transect of nearly 140 soundings centered on Dixie Valley including some dense array profiling near the producing system (Figure 1). It is 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 Quanotec Geosience 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 the Parkfield MT observatory H-fields 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).

A standard summary representation for the MT response along a transect is as pseudosections, where station location is the abscissa and log$_{10}$ period is the ordinate for contour plots of various functions (Figure 2). Here we plot the TM mode (current flow normal to presume NNE strike) log$_{10}$ apparent resistivity and impedance phase, TE mode (current flow along strike) impedance phase, TE mode vertical magnetic field, and ‘TM’ mode vertical magnetic field (sensitive to structural variations along strike) for x = N25E. This is a large and complex data set, and we will emphasize a few key features.

The upper two panels are the TM (yx) results and these are emphasized typically in an interpretation because they have been shown to be more robust to a 2-D assumption (Wannamaker, 1999; Ledo et al., 2005). Even if the profile passes across the edge of a conductor, TM mode imaging still can yield a reasonably accurate depiction of the cross section. The vertically elongated apparent resistivity contours with alternating low and high valued areas represent mainly the individual Great Basin grabens and horsts. Their effects are more period band-limited in the impedance phase whose main features are a series of semi-regional highs in the 10-100 s band. Particular highs are seen in the Seven Troughs range area, from I-80 to Buena Vista valley, and from the Simpson Park range to Eureka. These will be shown to represent enhanced electrical conductivity in the lower crust. A significant area with a lower phase peak restricted to the 100-300 s range lies at the far northwest end in the Smoke Creek area.

There is some correlation between the prior TM phase behavior and that of the TE (xy), but to the extent it is lacking then 3-D features may be at play. The TE mode has gained a reputation for being more prone to these effects, and for being sensitive to the rotation angle chosen, especially as it is typically the weaker quantity in the Great Basin (Wannamaker, 1999). The TE mode vertical magnetic field (zy) commonly shows the expected sign reversals as one cross major bodies of conductive graben fill (op. cit.). Non-zero behavior of the ‘TM’ vertical field (zx) is associated with e.g. variations in graben width below the transect, but these generally are less than zy. Only limited change in pseudosection appearance results from coordinate rotation of +/- 15 degrees.
Some of the lateral transitions in the TM mode phase are quite abrupt even though they occur at relatively long periods. Examples include that below the Seven Troughs range, below central Dixie Valley especially, and below the Toiyabe Range. 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 (Figure 3). They have shown up in numerous prior MT surveys (e.g. Park et al., 1991; Wannamaker et al., 1997a, 2002).

MODEL RESISTIVITY CROSS SECTION

A non-linear 2-D inversion of the TM mode apparent resistivity and impedance phase, and including the TE vertical magnetic field, was carried out using 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 4). 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. Error floors of 1.5 log 10 % in apparent resistivity, 1 degree phase, and 0.015 in vertical H-field were set and final RMS misfit was ~4.5, reasonable for actual field data. 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. This suppresses the effects of heterogeneity narrower than this scale and is roughly equivalent to laying one long E-field bipole the entire length of the transect (Torres-Verdin and Bostick, 1992; Wannamaker et al., 1997b). The run took about 15 hours on a Pentium-4 processor running at 3 GHz and required 1.7 Gbyte RAM.
Numerous heterogeneous features have formed in the model section from the 1-D initial guess (Figure 4). Large low resistivity zones in the lower crust are seen under the I-80 to Stillwater range corridor, and under the Simpson Park 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. Additional prominent mid-crustal conductors include the one dipping west under the Seven Troughs range, and the concave-up ones 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 20-35 km depth range under most of the line are replaced at the far northwest end by a weaker conductor in the 50-80 km range consistent with the weaker, longer period TM mode phase response described there earlier. 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.

**PHYSICAL SIGNIFICANCE OF MODEL RESISTIVITY STRUCTURE**

The concentrated low resistivity zones of the lower crust of Figure 4 in light of the probable average geotherm of Great Basin crust (Lachenbruch and Sass, 1978) almost undoubtedly are represented by 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) (Frost et al., 1989; Wannamaker et al., 1997b; Wannamaker, 2000). Magmatic products imply that the lower crust probably is too oxidizing overall for graphite to be stable for T > ~500 C (Wannamaker et al., 2001; Christiansen, 2005). 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 near its west end. 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 as described by Catchings and Mooney (1991), all characteristics which have been correlated with magmatic underplating (op. cit.). Moreover, the area from Dixie Valley westward is one of enhanced active extension based on modern GPS geodesy (Hammond, 2005), a process known to induced mantle upwelling and partial melting.

An additional minor low resistivity zone in the deep crust may be observed between the Clan Alpine and Shoshone ranges, but a surprisingly substantial one is seen in the model to the east from below the Simpson Park range to at least the east end of the line at Eureka (Figure 4). This is curious because geodesy and potential fields imply that this area lies in a stable interior block to the Great Basin without current active extension (Wannamaker et al., 1997b; Lowry et al., 2000; Hammond, 2005). If this is an area of magmatic underplating also, it implies substantial decoupling between upper mantle processes and those of the crust above. 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., 1997a,b).

A minor low resistivity zone in the lower crust beneath the Kumiva range is observed. However, for points further west, the drop in depth of the conductor to 50 km or more is taken to signify crossing onto rigid, undeformed thick crust of Sierra Nevada affinity, in keeping with the composition of outcrop (e.g., Stewart and Carlson, 1978). The thick nature of the Sierran crust here is in contrast to the inferred delaminated mantle lid and thinned state of the crust in the southern Sierra Nevada as reflected in both seismic and electrical structure (Duca, 2001; Park and Wernicke, 2003). It would also be interesting to extend the profiling to the west to see whether this is an isolated block or is attached to the Sierran province as a whole.

The concentrations of low resistivity in the lower crust are punctuated by some restricted areas of high resistivity where the conductor is essentially absent, such as below the Toiyabe range and deep below Dixie Valley. Such resistive regions visible elsewhere on the profile commonly project to near surface where copious plutons of Late Mesozoic or Middle Cenozoic age are mapped, such as in the Antelope, western Stillwater, Humboldt and Trinity ranges. We thus suggest that the deep crustal resistors are similarly competent bodies of plutonics which are mechanically resistant to further magmatic penetration. Apart from these possible vestiges, the lower electrical crust at least in this region of the Great Basin is primarily a modern feature.

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 Dixiewater deep conductor system. These fluids appear to intersect the valley at its center, and then ascend along the rangefront faulting on the valley’s west side. However, this position of intersection helps explain the presence of thermal occurrences 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 any other valley on the transect. The low resistivities at depth in the valley fill were initially observed by Wannamaker (2003) from shallow level array MT profiling. It was suggested then that they could in part represent low resistivity lacustrine clays from Pleistocene Lake Lahontan. While the lake did barely reach this far north in Dixie Valley (Caskey and Ramelli, 2004), its presence was far more extensive in other valleys to the northwest which do not exhibit such low resistivities.

The proposed conduit connecting the Dixie Valley system with active magmatic underplating nearby to the west could explain the observed elevated He³ values in Dixie Valley thermal waters (Kennedy and van Soest, 2005). 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). Agreed, our image is consistent with lack of a high-level, discrete magma chamber such as has been associated with standard magmatic systems such as the Roosevelt (Robinson and Iyer, 1981) and Coso Hot Springs (Monastero et al., 2005), but at least a second order magmatic connection is suggested. Moreover, current deep circulation models (McKenna and Blackwell, 2004; Wisian and Blackwell, 2004) only achieve temperatures at depths of 3 km that are ~1/2 the observed maxima near 285 C. Our imaged geometry provides a means of injecting lower crustal, very high temperature fluids to shallow levels to mix with deep circulation waters.

This major crustal break below Dixie Valley and the Stillwater range parallels the NNE trending Central Nevada Seismic Belt (CNSB) including several large historic earthquakes (M=7, Wesnousky et al., 2005; Gourmelen and Amelung, 2005; Hammond, 2005). All the large quakes 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
intercepted to allow stress buildup to significant levels before failure possibly aided by fluid infiltration from the nearby good conductors (e.g., Bedrosian et al., 2004; Ogawa and Honkura, 2004; Tank et al., 2005). 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). However, further to the northeast the CNSB may either die out or become so laterally diffuse as to be hard to distinguish from background (Wensoulsky et al., 2005); it thus would be interesting to follow the deep conductive break along strike to test continuity.

The two concave-up conductors under the Shoshone and Simpson Park ranges (Figure 4) may not primarily reflect geothermal processes. They roughly flank the area of the Toiyabe uplift, a plutonic-cored N-S trending axis arising in Late Mesozoic-Middle Cenozoic time (Speed, 1988; Stockli, 1999), and may represent a deformed conductive stratum deep in the Phanerozoic continental shelf section which has been downwarped along the uplift flanks. Candidates for the conductor could include the lower Cambrian Pioche shale or perhaps Late Proterozoic shales of the McCoy group (Stewart, 1980), the former at least being reported as locally graphitized and was interpreted at similar depths to the northeast in the Ruby Mountains area (Wannamaker and Doerner, 2002). Conduction due to graphite may be enhanced by metamorphism and fluid remobilization (Wannamaker, 2000). Extension of the profile further east over the less disturbed sedimentary section of eastern Nevada would help to corroborate this. Although these synclinal conductors sit above areas of enhanced conductivity in the lower crust, there is not the clear electrical connection exhibited with the Dixie Valley conductor and thus their positions may be coincidental.

The west-dipping conductive zone starting on the east flank of the Seven Troughs range (Figure 4) 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). An electrical connection with the San Emidio geothermal system is more obscure, but the system is about 10 miles south of the transect so continuity of structure along strike may be an issue. It does, however, appear to lie at the junction of the thick Sierran block with the extending Great Basin crust. There is building evidence that the primary extension of northwestern Nevada commenced at a distinctly later time (6-8 Ma) relative to the rest of the Great Basin (Colgan et al., 2004). Hammond and Hatcher (2005) argue for a diffuse axis of enhanced extension in this area, 75-100 km NW of the CNSB, based on new 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, though no discrete high-level magma chamber is identified. 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, and to confirm global models of the relation between earthquake sources and resistivity structure. 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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