Crustal Scale Resistivity Structure, Magmatic-Hydrothermal Connections, and Thermal Regionalization of the Great Basin

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ABSTRACT

Wideband MT profiling across the central Great Basin and flanking terrains by the University of Utah/EGI now reaches nearly 1000 km in length and just over 300 stations. Impedance phase tensor analysis indicates a clear north-south dominant trend to deep crustal electrical structure. Two-dimensional inversion of the data reveals an undulatory lower crustal conductor whose depths are greatest under the southern Modoc Plateau and elevated eastern Nevada. Global correlations of depth to top of this conductor with heat flow suggest an isotherm near 500 C. Resistivity thus correlates well with understanding that these regions have been relatively resistant to extension and have a somewhat reduced thermal regime. Particularly shallow reaches of this conductor occur under the Black Rock-Kumiva desert area and western Nevada generally, as well as under western Utah. This in turn is in keeping with enhanced degrees of extension there. Numerous crustal-scale breaks are seen connecting lower crustal magmatic underplating to the near-surface, sometimes to known geothermal systems. Even eastern Nevada exhibits some of these suggesting it may not be devoid of geothermal resources.

Introduction

Geothermal exploration success should increase if prospective districts can be identified within an overall favorable or permissive environment. Attempts to do this within the actively extensional Great Basin province have been based upon heat flow, recent fault traces, young volcanism, alteration, fluid geochemistry, potential fields and geodesy-based extension rates (e.g., Coolbaugh et al., 2005). However, those attempts are based essentially on surface manifestations such that extrapolation of geothermal processes to depth can be difficult or non-unique. Geophysical wave-field methods are applied to image through the third dimension in an attempt to assess fluid sources and pathways, and ultimate heat sources. Surveys of a scale larger than that of individual prospects may reveal controlling structures for resources, prioritize districts for exploration, and clarify the roles of magmatism versus deep circulation in driving a geothermal system.

Magnetotelluric Transect and Model Construction

Imaging the presence of fluids and their controlling structures commonly is attempted using surveys of electrical resistivity (inverse of conductivity). For structure at the scale of geothermal systems and larger, the primary method is magnetotellurics (MT). We have been building up relatively dense MT coverage across

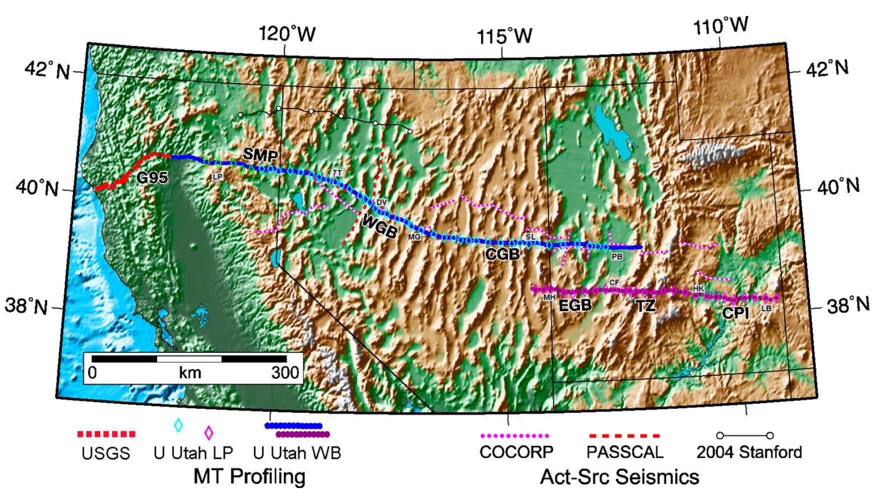

Figure 1. MT transect sites across the Great Basin and surroundings. Physiographic features include Colorado Plateau interior (CPI), transition zone (TZ), eastern, central and western Great Basin (EGB, CGB, WGB), and southern Modoc Plateau (SMP). We discuss wideband (WB) sites of the blue line. Pertinent locations include Lassen Peak volcano (LP), Seven Troughs range (7T), Dixie Valley (DV), McGinniss Hills (MG), Schell Creek range (SL), Pavant Butte (PB), Mountain Home range (MH), Cove Fort geothermal field (CF), Hanksville (HK) and Lisbon Valley (LB).

the entire Great Basin near latitude 40ºN for ~10 years beginning with studies of the context of the high temperature geothermal system at Dixie Valley, Nevada (Wannamaker et al., 2006a,b; 2007). To date, >300 wideband (WB) stations with 3-4 km spacing and wave periods 0.005-400 s have been acquired mainly through private contractor (Figure 1) from unextended terrain near Shasta Dam, CA, to just east of Scipio, UT, in the active eastern Great Basin. This transect forms a complement to the recently published profiling to the southeast across the eastern Great Basin-Colorado Plateau transition in Utah (Wannamaker et al., 2008). Moreover in 2009, 44 long-period (LP) MT soundings (20-10000 s) were appended at regular intervals along the transect to extend depth of resolution through the upper mantle, which is accepted to be the ultimate source of Great Basin rift magmatism. Total period range thus exceeds six decades.

At this writing, data reduction is complete for the WB sites (Figure 2) although the new LP responses have not yet been merged to form a single invertible data set. Impedance trend analysis using the phase tensor method of Caldwell et al., (2004) has been carried out to ascertain deep crustal-scale geoelectric strike corrected for the distortion of upper crustal heterogeneity. This analysis confirmed an average north-south to NNE-SSW deep strike (0.08 – 0.005 Hz frequency range) across the survey area and motivated a 2-D MT inversion analysis. The data pseudosections of Figure 2 show abundant effects over the whole frequency range for the Great Basin of horst-graben sediment resistivity contrasts (strong vertical contours in apparent resistivity). This is not evident for the unextended Modoc Plateau (MDP) and southern Klamath Mountains (SKM). Deep crustal features are more obvious in the impedance phase; a weak phase high at lower frequencies under MDP and SKM denoting subdued low resistivity in the lower crust gives way eastward in the Great Basin to a series of variable but high phase anomalies often extending to much higher frequencies (e.g., 1 Hz). On the whole these denote concentrations of low resistivity in the deep crust.

Moving from qualitative interpretations based on data inspection to a quantitative resistivity model requires a formal data inversion incorporating both apparent resistivity and impedance phase. An inversion using our in-house code (see Wannamaker et al., 2008) that yielded a good data fit was performed on the transverse magnetic (TM, or electric field perpendicular to assumed strike) mode of the entire wideband data set (Figure 3). Starting from a 100 ohm-m half-space, initial nRMS misfit was ~15 and final value was <3 after 10 iterations.

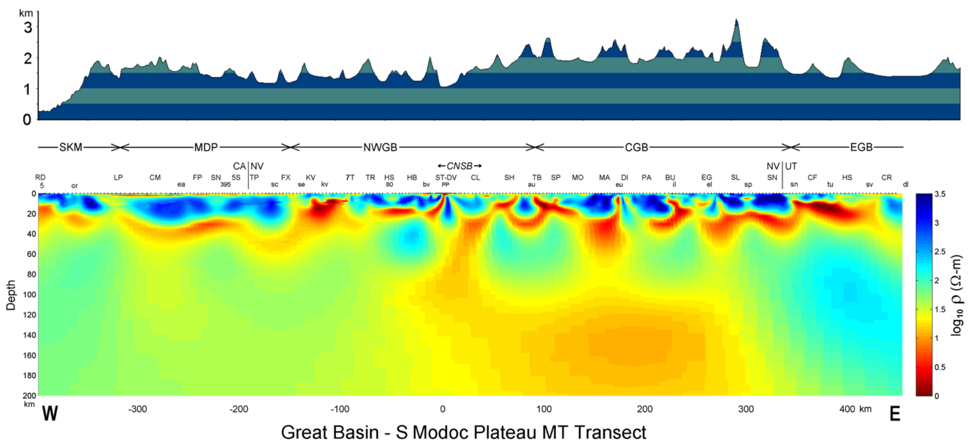

Figure 3. 2-D TM mode inversion section of Great Basin MT transect overlain by elevation profile. Resistivity is represented by ~22,000 inversion pixels. Geographic features defined in Figure 1 and text. SKM is Southern Klamath Mtns and MDP is Modoc Plateau.

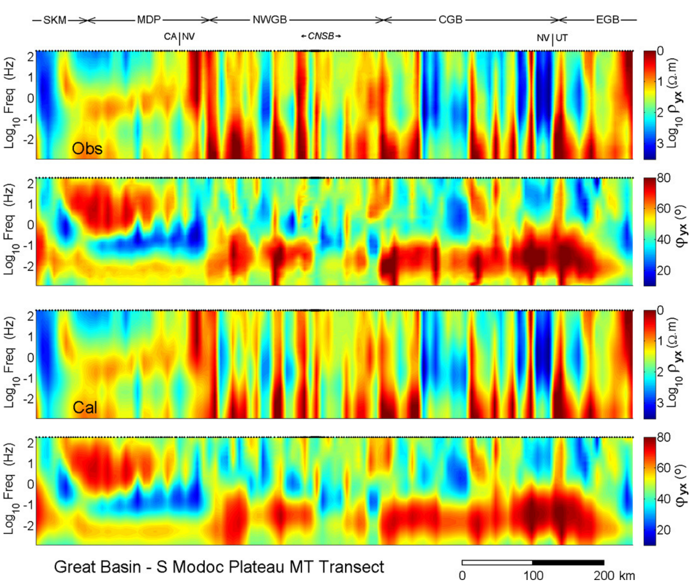

Figure 2. Observed transverse magnetic (TM) mode apparent resistivity and impedance phase pseudosections (upper), and model computed TM mode apparent resistivity and impedance phase pseudosections (lower) for the Great Basin-Modoc Plateau MT transect. SKM is Southern Klamath Mtns and MDP is Modoc Plateau.

Tectonic/Geothermal Correlations with Deep Resistivity

Regional variations in thermal state and extensional activity are apparent in the cross section and on the whole correlate with surface evidence (Figure 3). The section generally shows a resistive upper and middle crust underlain by conductive lower crust of variable depth and intensity. Based on global MT surveying in active environments and our own previous detailed work in the eastern Great Basin-Colorado Plateau transition of Utah (Wannamaker et al., 2008), we recognize the conductors to represent magmatic underplating and hydrothermal fluid release in ductile lower crust based on appropriate temperatures and chemistries. In the west, the non-extended Southern Klamath Mtns and Modoc Plateau exhibit a resistive upper and middle crust to depths beyond 20 km with the exception of a conductive axis under the Cascades volcanic chain just north of Lassen Peak. This deep high resistivity includes the basement to Smoke Creek desert (sc) but ends suddenly at the San Emidio desert (se).

At that point a marked upwelling and increase of crustal scale conductivity to ~5 km depth occurs and may be correlated with the Black Rock-Kumiva desert geothermal trend. Henceforth eastward for ~200 km, one sees numerous resistive crustal zones separated by conductors in the 12-25 km depth range such as that underlying Buena Vista valley (bv) and the Humboldt Mtns (HB). This particular feature correlates with a zone of high seismic P-wave attenuation and reflectivity and a high V_P Moho 'pillow' in the Cocorp and Passcal surveys, supportive of recent magmatic underplating (Wannamaker et al., 2006a,b). A steep conductive segment projects upward from its east end reaching the base of Dixie Valley (DV) and its geothermal system. Elevated He^3 concentrations in production well fluids (Kennedy and van Soest, 2007) point to a mantle component, suggesting that the steep conductor is a fault zone connecting lower crustal, magma-sourced fluids with the meteoric regime. Along the presumed NNE-SSW strike of this steep conductive trend also lie the hypocenters of the central Nevada seismic belt (CNSB) and the major historic earthquakes of Dixie Valley area (Smith et al., 1989; Hammond, 2005). The west end of the Toiyabe-Simpson Park ranges (TB-SP) conductor shows a similar steep branch coming near surface just east of the town of Austin (au). This coincides precisely with the newly developing McGinnis Hills geothermal system. Additional, lesser instances of these structures can be seen also along this interval.

From San Emidio desert to McGinnis Hills are seen on average the shallowest manifestations of the lower crustal conductors in the Nevada Great Basin (Figure 3). Global compilations and our own studies suggest that the tops of widespread, elevated conductivity in the lower crust due to thermal processes lie near 500 C (Wannamaker et al., 2008). Thus the relatively shallow disposition of deep crustal conductors in western Nevada is in keeping with higher heat flow and greater numbers of geothermal prospects. It also is expected from the greater rate of crustal extension inferred on abundance of young faults and GPS geodetic estimates (e.g., Hammond and Thatcher, 2004). However, the deep crustal conductivity here is by no means layerlike; we suggest intermediate scale rheological contrasts such as between thick dominantly sedimentary sections and plutonic bodies may control local degrees of extension and the loci of magmatic underplating and intrusion.

East of the McGinnis Hills occurrence across eastern Nevada, the thickness and amplitude of upper to middle crustal resistive bodies increase again and appear comparable to that of the Modoc Plateau if not quite as thick (Figure 3). From this we infer reduced crustal-scale temperatures at depth compared to the northwestern Great Basin (NWGB) and that features such as the Eureka heat flow low are not necessarily the result mainly of meteorological hydrology disturbances (Lachenbruch and Sass, 1977). The region corresponds to a relatively undeforming subdomain of the central Great Basin (CGB) as evident in GPS geodetic vectors (Hammond and Thatcher, 2004). Its western boundary coincides approximately to the $Sr^{87}/Sr^{86} = 0.708$ contour of Farmer (1988) interpreted to denote the transition eastward to predominantly early Proterozoic metaigneous deep-crustal source rocks for plutons of the Great Basin. This is distinct from the 0.706 contour traditionally cited as the ultimate western limit to early Proterozoic basement; that line lies closer to Dixie Valley (Farmer, 1988). From an electrical standpoint at least, we place the NWGB-CGB transition near the McGinnis Hills crustal break (Figures 2 and 3).

Nevertheless, the resistive middle to upper crust in eastern Nevada also is broken up by subvertical conductors reaching the near surface similar to the western Great Basin. For instance, one at Eureka could project northward along strike to an elevated He^3 anomaly at the west side of Diamond Valley (DI) reported by Kennedy and van Soest (2007). GPS geodetic transients have been correlated with high seismic reflectivity under the Schell Creek range (SL) and interpreted as a possible magma injection area by Wernicke et al. (2008). Further study is needed to explain the prominent conductor under the Butte range (BU) near Illipah summit (il).

Just inside Utah below Snake Valley (sn), the deep crustal conductor elevates abruptly and increases in amplitude, extending east at least into the Sevier desert (sv) near where our coverage ends. This is in keeping with the greater extensional activity of the eastern Great Basin. The reality of its attenuation under the Cricket range (CR) needs to be established after we integrate the latest 30 stations at the eastern end of the profile. Correlation of upper mantle properties with lower crustal state probably is better left until the long period data are integrated. However, the conductive upwelling under the central Great Basin is suggestive of melt in the upper mantle which may provide buoyant support for eastern Nevada's higher elevations. These are recognized as requiring a mantle component of uplift (Sonder and Jones, 1999). Resolution at these depths however, is best left to inversion after integration of the long period data.

Conclusions

Regionalization in the characteristics of crustal scale electrical resistivity correlates reasonably well with surface indicators such as heat flow, extension rate, and geothermal prospect occurrences. Transitions between tectonic provinces and even subprovinces can be abrupt and are expected to be influenced by rheological contrasts ranging from plutonic complexes to the ancestral Precambrian-Phanerozoic margin. The MT resistivity model is striking for the numerous crustal scale fault zones imaged that are interpreted to connect active magmatic underplating and fluid release in the lower crust with surface geothermal systems many of which exhibit independent geochemical evidence for mantle components.

Acknowledgements

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