Importance of Understanding Bottom-Up Control when Characterizing Geothermal Systems

Jared R. Peacock[1] and Paul A. Bedrosian[2]

[1]U.S. Geological Survey, Geology, Minerals, Energy, and Geophysics Science Center, Moffett Field, CA, 94035

[2]U.S. Geological Survey, Geology, Geophysics, and Geochemistry Science Center, Denver Federal Center, CO, 80225

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ABSTRACT

Methods designed to identify favorable areas for geothermal resources have traditionally been focused on near-surface information, namely data that can be compiled into a 2D map. However, these methods fail to account for the third dimension: depth. As a result, they do not incorporate deep crustal and mantle features like heat sources. Geophysical methods with multi-scale capabilities, such as magnetotellurics (MT), provide tools to image deeper structures and bottom-up control on location of near surface hydrothermal systems in 3D. This study briefly demonstrates the advantage of understanding bottom-up control on hydrothermal systems to aid assessment and characterization. A regional 3D electrical resistivity model of the Great Basin is developed from MT data that image the near surface down to the mantle. From the 3D model, electrical conductance (depth integrated electrical conductivity) maps are created at logical depth intervals to identify anomalies. The conductance maps image discrete zones of high conductance between 15-20 km depth indicative of fluid collection at the brittle-ductile transition; high-conductance zones around Moho depths (30-50 km) suggestive of partial melt; high-conductance zones in the upper mantle indicative of higher temperature and larger melt fraction, and low-conductance zones indicative of lithospheric material descending in the mantle. One anomalous zone of low conductance in the mantle is under north central Nevada, suggesting vertical mantle flow transport of heat to the crust related to sinking lithospheric material.

1. Introduction

Play fairway analysis is the process of assimilating various geologic data into a database and producing favorability models of specific targets. This type of analysis has been used in the petroleum industry and, in the last decade, has been a topic of research to identify areas of interest for geothermal resources (e.g. Siler et al., 2017, Ito et al., 2017, Smith et al., (2021, 2023), Faulds et al., 2021). The most common approach with non-continuous data is to interpolate onto a common 2D map for correlation and statistical analysis. The types of data sets commonly include near surface data: geologic maps, digital elevation models, heat flow, gravity and magnetic data, and fault information (e.g. Smith et al., 2023). Data are then weighted and combined to identify areas of interest. Weighting is often assigned by experts (e.g. Siler et al., 2017, Ito et al., 2017, Faulds et al., 2021) but more recently, machine learning methods have been incorporated to help optimize anomaly detection (e.g. Smith et al. (2021, 2023), Mordensky et al. 2023). As the input data sets and resulting prediction maps are 2D surfaces representing 3D processes, 3D information is important but not innately included. Multi-scale geophysical data, like MT and seismic tomography, offer the opportunity to improve existing models by including depth information. This would help constrain bottom-up control on how heat travels from the lower crust to the near surface.

Imaging the subsurface at various scales to understand both top-down and bottom-up control on location of hydrothermal systems in the Great Basin was a key contribution of Phil Wannamaker from the University of Utah. In numerous studies, Wannamaker demonstrated the power of imaging the subsurface in 3D using MT and jointly interpreting with other geophysical data to characterize hydrothermal systems at various scales (Wannamaker et al. [2004, 2008, 2010, 2013, 2015, 2017, 2019, 2020, 2021], Newman et al., 2008, Meqbel et al., 2014, Hardwick et al., 2015). Wannamaker et al. (2019) conducted a comprehensive multi-scale multi-disciplinary study to identify potential areas of interest for geothermal resources. Their study suggested that areas of interest are commonly found at the confluence of zones under local dilation, with elevated ^{3}He and R/Ra values, elevated CO_2 flux, and near-surface low electrical conductivity zones proximal to the faults connected to mid- to lower-crustal, low-electrical zones. This pattern suggests a deep crustal magmatic heat source connected to the upper crust through deep faults that can transport fluids, heat, and gas to the near surface and support an active hydrothermal system. In a similar study, Peacock and Siler (2021) demonstrated that joint interpretation of geologic and MT modeling can constrain bottom-up and top-down control on hydrothermal systems.

Herein, an electrical resistivity model of the Great Basin will be discussed by estimating electrical conductance for different depth intervals. These are then compared with seismic tomography models and a recent heat flow map. A conceptual model of the Great Basin is discussed and finally suggestions on how regional 3D data can be used for play fairway analysis.

2. 3D Electrical Resistivity Model

Available MT data collected from various projects are assimilated into a single data set (Figure 1) and interpolated onto a single period map for modeling. The impedance and induction vectors are inverted in 3D using ModEM (Kelbert et al., 2014) on the U.S. Geological Survey (USGS) high performance computer (USGS, 2015). The model grid includes cells of 7 x 7 km in the horizontal direction within the station area and geometrically increases with depth starting from a top layer of 50 m. The global normalized root-mean-square error (nRMS) is reduced from 46 to 2.1 using error floors of 0.03 times the geometric mean for the impedance elements and 0.02 for the induction vectors. Average iteration time of the inversion was around two hours, and the inversion ran for 146 iterations for a total compute time of about 12 days. ModEM is a deterministic inversion and therefore provides one out of an infinite number of models (Kelbert et al., 2014).

The model presented is a preferred model and should be interpreted with caution understanding that station distribution and model parameters can cause artifacts.

MT is sensitive to where fluids are or have been, and often appear as high conductivity zones (e.g. Wannamaker et al., 2008). These fluids can be aqueous or magmatic, and can originate from meteoric, connate, magmatic, or metamorphic sources. Electrical conductance is the depth integrated electrical conductivity and is a useful parameter for assessing zones of high or low conductance. Electrical conductance is estimated for the near surface (2 – 12 km), middle crust (12 – 20 km), lower crust (20 – 50 km), upper mantle (50 – 90 km), and mantle (90 – 200 km) (Peacock and Bedrosian, 2022).

Figure 1: Map of MT stations used to develop a 3D electrical resistivity model of the Great Basin. The study area is from GBCGE, NBMG, UNR (2022). Map image is the intellectual property of Esri and is used herein under license. Copyright © 2020 Esri and its licensors. All rights reserved.

3. Analysis

Comparing the electrical conductance layers to other geophysical data provides insights into what anomalous zones of conductance represent (Figure 2). The upper crust layer identifies shallow zones of high conductance potentially related to hydrothermal systems and possible connections to deeper heat sources (Figure 2a). Because the model cells have horizontal dimensions of 7 x 7 km, near-surface features and features smaller than 7 km are not well resolved. Nevertheless, the conductance suggests areas where fluids may accumulate to transport heat to near surface hydrothermal systems.

The middle crust layer identifies areas of fluid collection at the brittle-ductile transition. As suggested in Wannamaker et al. (2008), the brittle-ductile transition occurs at around 15 km depth throughout the Great Basin (Figure 2b) and represents the isotherm of about 500 ^{o}C. This acts as a boundary where fluids get trapped and accumulate often in topographic highs of the brittle-ductile transition (Peacock and Siler, 2021). These highs are commonly associated with deep crustal faults which episodically dilate and act as pathways of relatively high permeability, allowing hot fluids to ascend into the crust transporting heat (Sibson 1990).

The lower crust layer identifies areas of enhanced partial melt near the Moho (Figure 2c). Similarly, the mantle layers identify areas of elevated fractions of partial melt in the mantle (Figure 2d, e). Mantle heat distribution and fluid content influences the percent of partial melt of mafic underplating near the Moho. For example, one key feature in the mantle layers are zones of low conductance, high p-wave velocity (Roth et al., 2008), and an SKS shear wave splitting anomaly (Walpole et al., 2014). The low p-wave velocity zone has been attributed to lithospheric drip (West et al., 2009) causing toroidal mantle flow (Zandt and Humphreys, 2008) as evidenced from the SKS shear wave splitting estimations (Zandt and Humphreys, 2008, Walpole et al., 2014) and mantle xenoliths (Dygert et al., 2019). The toroidal flow forces vertical mantle transported heat into the crust around the edges of the downwelling lithosphere which matches well with heat flow (DeAngelo et al., 2022). Discrepancies in delineating boundaries of the downwelling lithosphere appear between the p-wave and conductance models. This may be caused by a skew in depth- the conductance is a depth-integrated calculation whereas seismic p-wave velocity is a single depth slice. The downwelling lithosphere is imaged to be dipping to the east and therefore may be further east than the seismic depth slice in the upper lithospheric mantle. Regardless, the correlation with heat flow at the surface indicates the importance of understanding structures at depth and how they provide bottom-up control on surface features.

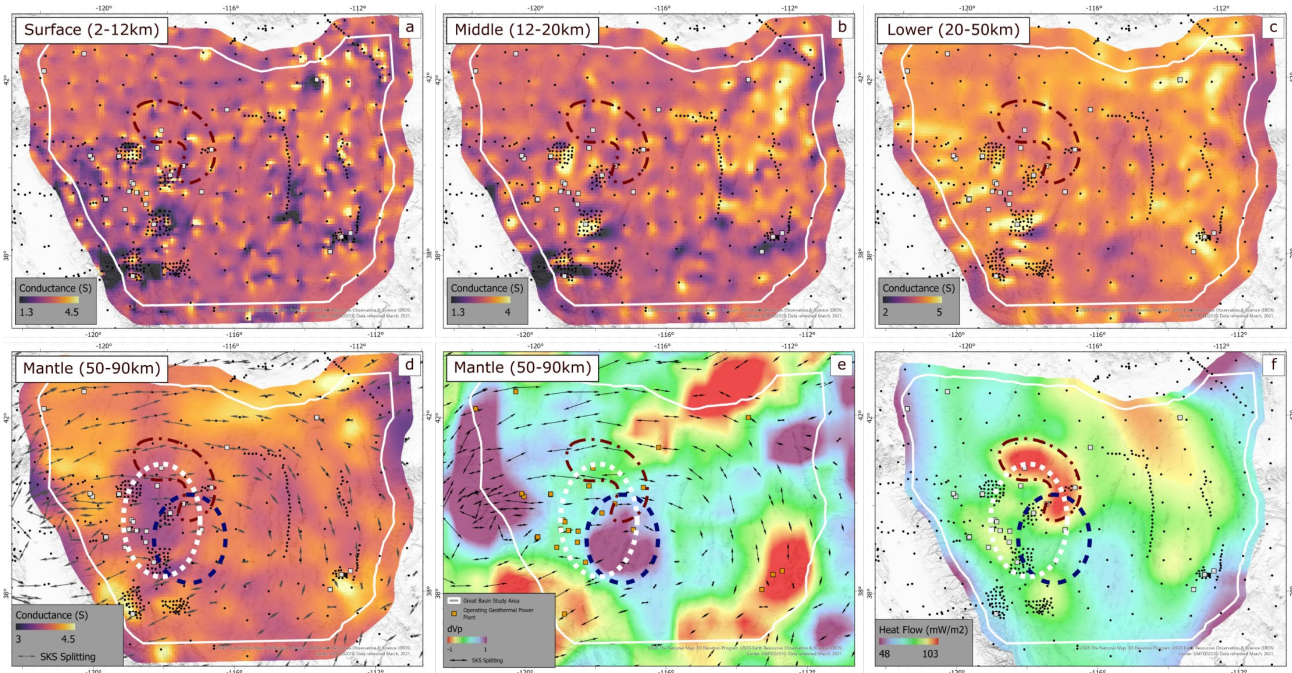

Figure 2: Maps of electrical conductance for various selected depth sections (a-d), difference in p-wave seismic velocity (dVp) from a starting model (e; Roth et al., 2008), and heat flow (f; DeAngelo et al., 2022). Mantle layers have fast SKS shear wave splitting directions plotted as black arrows (Walpole et al. 2014). Same symbols as Figure 1. Blue dashed line: seismically interpreted lithosphere sinking into the mantle; white dotted line: downwelling lithosphere interpreted from electrical conductance; red dot-dashed line: the Battle Mountain high heat flow area. Background map image is the intellectual property of Esri and is used herein under license. Copyright © 2020 Esri and its licensors. All rights reserved.

4. Conceptual Model

From the many studies in the Great Basin, a conceptual model of full crustal control on hydrothermal systems can be developed (Figure 3). Bottom-up control begins in the mantle where anomalous mantle flow transports heat into the lithosphere. Vertical heat transport can be generated by downwelling lithosphere caused by Rayleigh-Taylor instabilities (lithospheric drip). As the lithospheric block descends, toroidal flow is generated, and heat is transported vertically around the sinking block (Zandt and Humphreys, 2008; West et al., 2009). This heat is transported into the lithosphere causing melting and increasing partial melt percentage in the existing melt related to extension induced underplating (Wannamaker et al., 2008). This melt stalls near the Moho and as it cools, it releases aqueous fluids into the lower crust. The aqueous fluid transports heat and stalls at the brittle-ductile transition, collecting in topographic highs within the brittle-ductile transition (Wannamaker et al., 2008). These highs are often found near deep crustal faults and are imaged in electrical resistivity models as conductive zones and are associated with earthquakes (Peacock and Siler, 2021). Episodic earthquakes related to fault dilation allow fluids to be transported into the middle and upper crust, transporting heat. These are not the working fluids of shallow hydrothermal systems as the faults are often self-annealing in the depth range of 5 km, when temperatures drop enough for scaling to occur. Transported heat can support shallow hydrothermal systems where faults and basins allow meteoric water to penetrate deep enough to create convection.

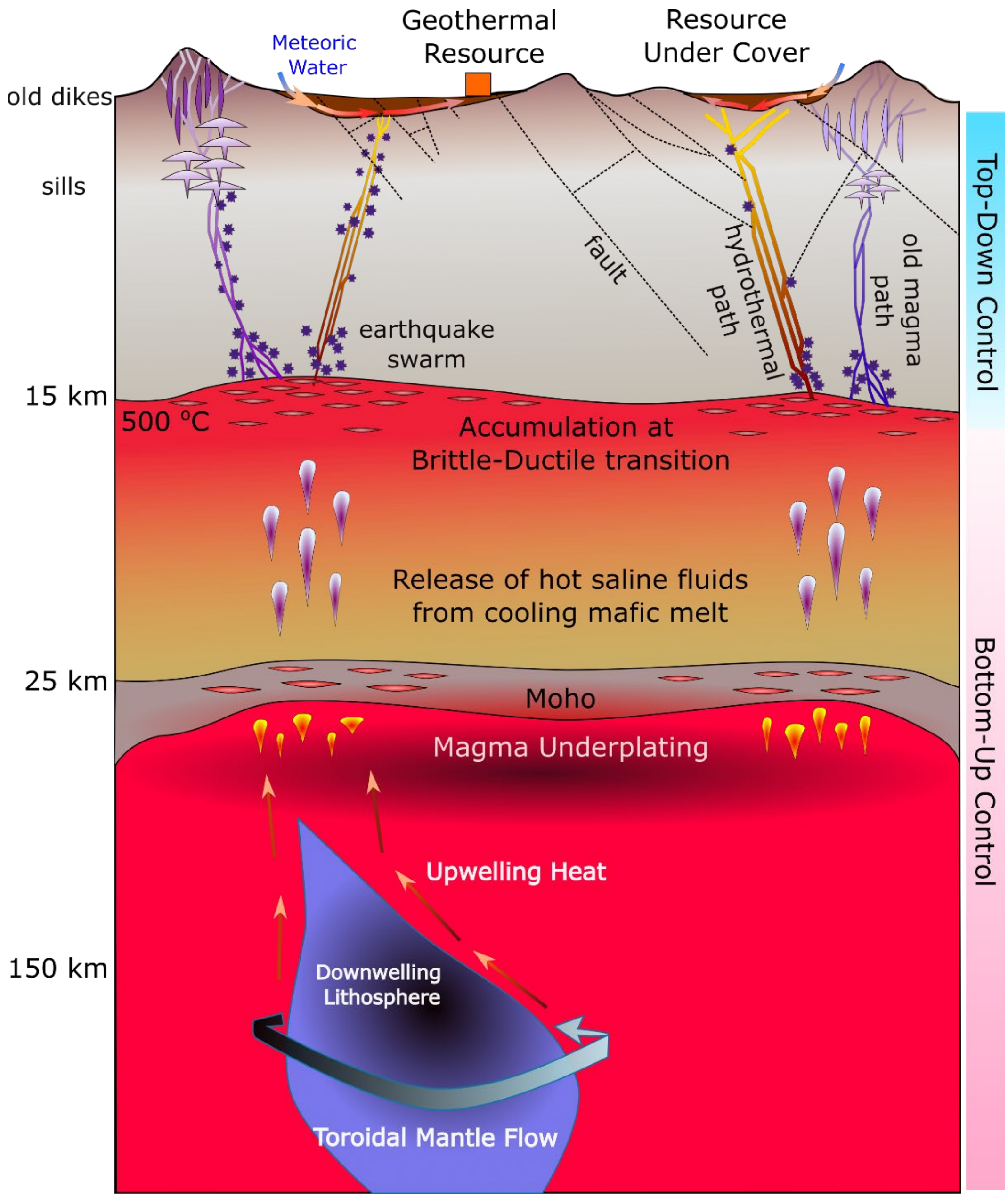

Figure 3: Conceptual model of full crustal control on near-surface hydrothermal systems adapted from Peacock and Siler (2021). See Section 4 for more details.

5. Discussion

Most play fairway analyses use geophysical data that relate to a top-down control often representing conditions within the top 5 km of the crust where exploitable geothermal resources exist. However, knowing why hydrothermal systems exist and details about their heat source can be of equal importance. For example, if an area has ideal fault or basin geometry, it would be advantageous to know if a deeper heat source can support a hydrothermal system.

Relative to 3D models, 2D maps are simpler for correlating multiple data sets and, therefore, adding a third dimension brings complexity. Instead of developing a full-scale 3D favorability model, a few 2D layers could be added to the play fairway analysis that represent depth slices or intervals from the mantle to the upper crust that identify zones of favorability (Figure 4). In the spirit of play fairway analysis, this would provide constraints on anomalies in the near surface and identify if they have deeper connections to possible heat sources.

The mantle layer could include electrical conductance, seismic velocity (p- and s-wave), and SKS shear wave splitting (indicative of mantle flow). A zone of favorability could be the outside of low-conductance zones collocated with high-velocity zones and circular patterns in SKS splitting directions. This pattern would indicate downwelling lithosphere and upwelling mantle heat.

The next layer up could be near the Moho (about 30 km deep across the Basin and Range). This layer could include electrical conductance, seismic velocity (p- and s-wave), and gravity data. A zone of favorability would be a high-conductance zone collocated with low-velocity and low-density. This pattern would identify elevated partial melt.

The mid-crustal layer could be in the range of the brittle-ductile transition (around 12-15 km). Data would include electrical conductance, seismicity, and fault geometry. Depth slices from 3D gravity and magnetic models could also be useful at this depth range and could be jointly inverted with MT data (Moorkamp, 2022). The pattern for favorability would then be a zone of high conductance collocated with high earthquake density. Knowing fault geometry would identify where heat is transported into the crust.

Another layer could be added in the upper crust (5 – 10 km depth) that includes electrical conductance, depth slices from 3D gravity and magnetic models, seismicity, and fault and structural geometry. A zone of favorability could be thin electrical conductance anomalies that connect the mid-crust to the upper crust collocated with low-density, low-magnetic susceptibility zones, and high earthquake density. A different favorability target could be where high gradients exist in the physical property models--for instance, where high conductance is juxtaposed to low conductance, or high density juxtaposed to low density--because these would identify potential permeable boundaries. Another favorability target could be identifying density highs collocated with conductance lows and magnetic highs suggestive of competent rock that could conduct heat.

Joint 3D inversion to develop coherent and related 3D models through physical properties (e.g. Moorkamp, 2022) could be used to constrain anomalous zones. Existing play fairway methods should account for depth information from these joint or individual geophysical models like electrical resistivity, density, magnetic susceptibility, and structural geology. Moreover, as machine learning play fairway analysis research progresses, training data could include information from 3D geophysical models to help understand how bottom-up control and top-down control interact and how that interaction relates to near surface anomalies.

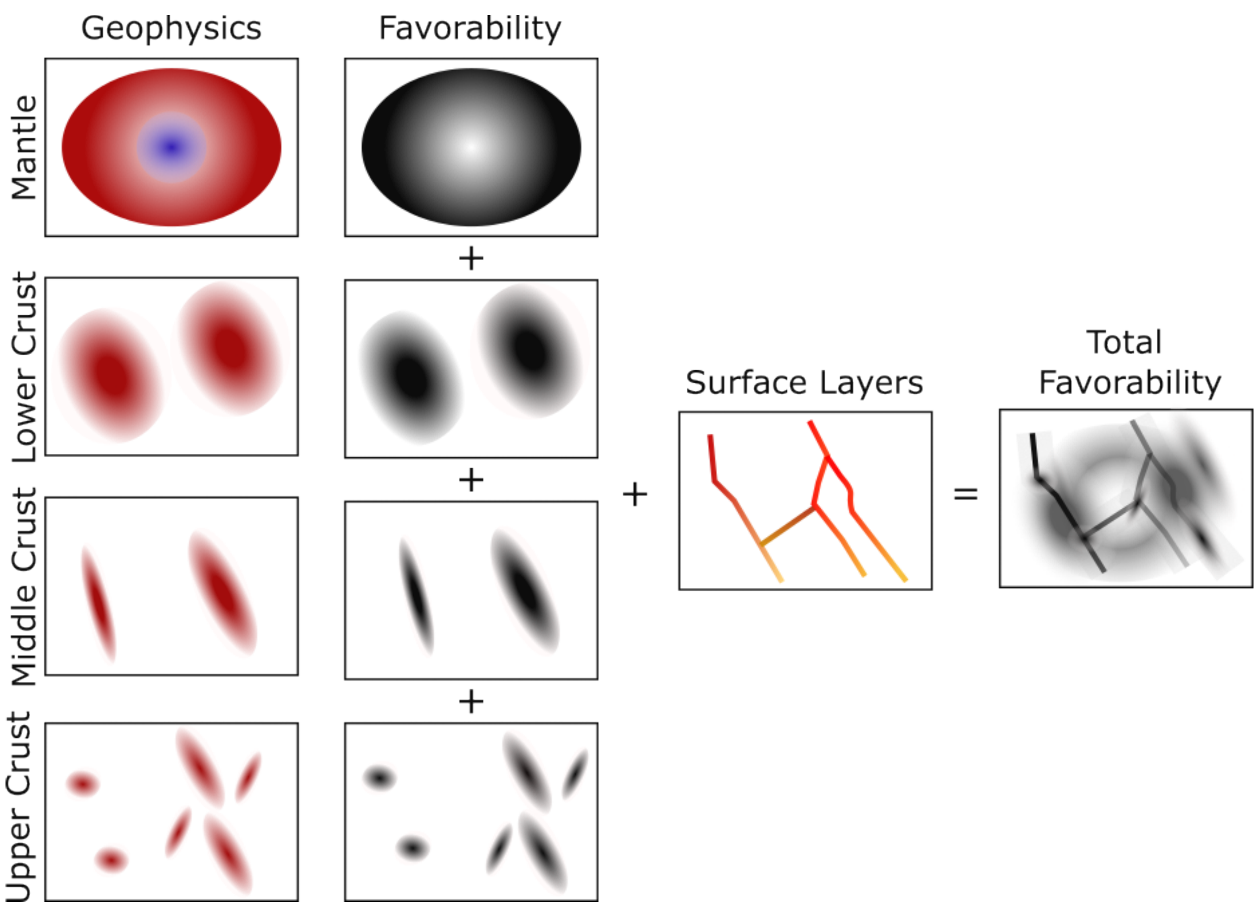

Figure 4: Example of adding depth information into a play fairway analysis. Far left are examples of geophysics depth slices or intervals at different levels of the lithosphere, this could be electrical conductance (reds). Examples of favorability are colored in a gray scale with black = 1 and white = 0, which could be logically weighted depending on confidence in the layer and influence on the overall favorability. These layers could be added to the existing play fairway layers to come up with a more informed favorability model.

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