Geothermal Prospecting in Utah: A New Thermal Model of the Black Rock Desert

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Keywords

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ABSTRACT

Results from recent geophysical, hydrological, and heat flow projects to assess the geothermal potential of the Black Rock Desert (BRD) in Utah have been combined with historical data to create new 3-dimensional (3D) conductive heat transfer models using a finite-element modeling program (COMSOL Multiphysics 4.3b). The insulating effect of thick (up to 3 km), low-thermal-conductivity sediments along with typical Basin and Range heat-flow values (80 to 90 mW/m^2) in deep basins results in higher temperatures compared to surrounding bedrock geotherms. Preliminary assessments revealed an area of approximately 350 km^2 with temperatures above 150˚C at 3 km depth and an inner 60 km^2 area with temperatures above 200˚C at the same depth. Temperature at depth and surface heat flow are not evenly distributed throughout the BRD. The relatively low observed surface heat flow and temperatures at depth in the southern BRD may be a consequence of local groundwater flushing over the regional background heat flow. A high-heat-flow area situated in the central BRD is thought to be associated with the more recent volcanic activity in the study area. We present new heat transfer models constrained by existing data from known geothermal gradients and material properties to explore the extent and character of geothermal potential in the BRD. New thermal models help characterize and enhance understanding of the dynamics of the BRD and other unconventional geothermal systems in the Great Basin.

Introduction

The study area is a high-heat-flow, approximately 6000 km² basin in the Black Rock Desert (BRD) near the eastern margin of the Basin and Range (Figure 1). A 30 mGal gravity low defines the deepest part of the basin where depth to bedrock is about 3 km (Hardwick and Chapman, 2012). Low-thermal-conductivity basin-fill sediments, confirmed by well data, provide a "thermal blanket" for Upper Cambrian carbonate units at 3–4 km depth. Thrust sheets related to Late Jurassic-early Tertiary Sevier crustal contraction are present in the western part of the basin (Blackett, 2011; Allis and others, 2012). Crustal extension dates to the late Miocene and continues across the region, resulting in numerous north-trending normal faults with minimal displacement (Hintze

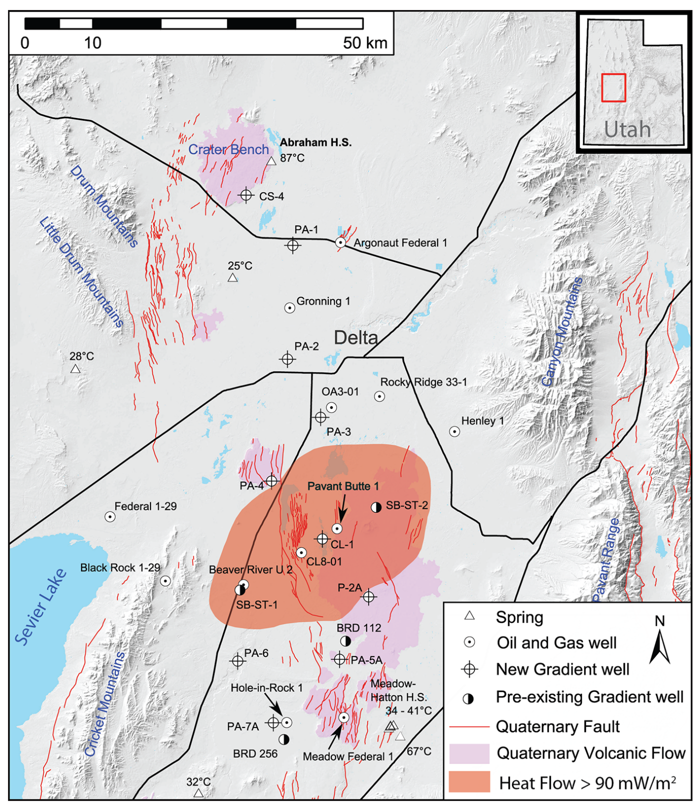

Figure 1. Black Rock Study area showing deep exploration wells, previously drilled thermal gradient wells, recently drilled thermal-gradient wells, spring locations, and the high heat-flow area surrounding Pavant Butte. H.S. = hot spring.

and Davis, 2003). Volcanism in the BRD began in the late Eocene and the latest eruption occurred in the Ice Springs basalt field about 600 years ago (Hintze and Davis, 2003). Volcanism was initially bimodal, but has been almost entirely basaltic in the Quaternary (Hintze and Davis, 2003). Thermal springs with temperatures of 34–87°C are found near the northwest and southeast sections of the basin and several cooler springs (25–32°C) are found near the southern and western margins. Standard geothermometers point to equilibrium temperatures of 86–205°C at Meadow-Hatton and 87–116°C at Abraham Hot Springs (Blackett and Wakefield, 2004). Land ownership is primarily federal, with some state and private parcels. Terrain is generally open and flat with good road networks and extensive power transmission infrastructure.

Background Data and Methods

Thermal data are derived from 12 deep oil exploration and 14 shallow thermal-gradient wells. Cuttings and core were collected from the newly drilled wells to measure thermal conductivity using needle probe and divided bar devices (Gwynn and others, 2013). Thermal conductivity measurements were also performed on archived cuttings from the Pavant Butte 1, Hole-in-Rock 1, and Gronning 1 wells using the divided bar. X-ray Diffraction studies were also conducted on these cuttings and the results suggest that temperatures over 220°C have been present at depths below 2340 m in the Pavant Butte 1 well and below about 3200 m in the Hole-in-Rock 1 well, while temperatures in the Gronning 1 well have likely exceeded 180°C below approximately 2340 m (Jones and Moore, 2012a; 2012b; 2012c). Temperatures in these wells are lower now, suggesting some cooling has occurred over time. Thermal conductivity and gradient data were combined to calculate heat flow in the shallow wells. Since no continuous thermal gradient profiles were available for the deep exploration wells, heat flow in these wells was calculated using geotherm models and applying a "bootstrapping" method. These one-dimensional (1D) models combine measured thermal conductivity values (if available), typical values for the lithology in 100 m intervals, and near-surface values from the recently drilled thermal-gradient wells to develop a temperature-depth curve that is deflected by varying the surface heat flow value until the profile intersects the corrected BHT data (Figure 2).

A total of 371 gravity and 263 magnetotelluric (MT) stations were added to the existing geophysical data set of the area. Two-dimensional models exist for both data sets (Hardwick and Chapman, 2011; 2012) as well as a 3D resistivity model for the MT data (Wannamaker and others, 2013). The primary goals of the geophysical models are to constrain basin depths, delineate structural features and controls of geothermal systems, and to infer the thermal state from MT interpretations.

Thermal Models

We developed a 3D conductive heat transfer model using a finite-element modeling program (COMSOL Multiphysics 4.3b). The model framework (Figure 3) is based on a simplified, regional-scale mesh of cells that are either bedrock or basin fill. Model layers are based on the thickness

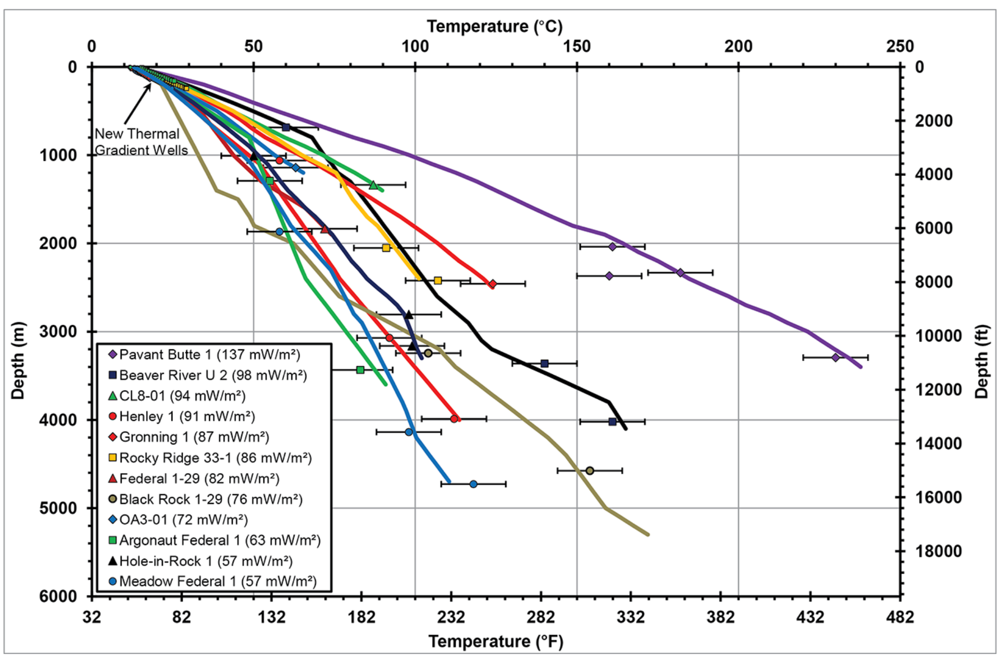

Figure 2. Calculated temperature-depth profiles for 12 deep exploration wells drilled in the Black Rock Desert from 1957-2010. Symbols show corrected bottom-hole temperatures and calculated heat flow for each well is shown in the legend. From Gwynn and others, (2013).

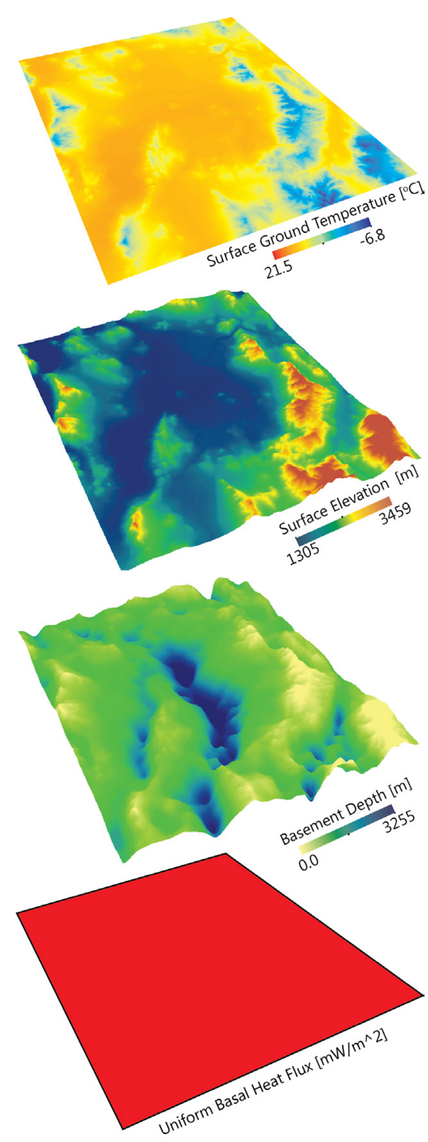

Figure 3. Thermal model framework including upper and lower boundary conditions.

of the basin fill, taken from a regional gravity inversion by Saltus and Jachens (1995) augmented by more recent gravity data (Hardwick and Chapman, 2011; 2012), deep well logs, and a 5-meter digital elevation model (DEM). The grid of basin fill thickness was subtracted from the DEM to create a continuous surface for the basin fill-bedrock contact elevation. In areas where the basin depth was equal to zero the contact between basin fill and bedrock was set at 10 meters below the surface elevation of the 5 meter DEM. This yields a two layer model where both basin fill and bedrock layers are continuous across the entire model area. As a consequence, areas of bedrock exposure are modeled as having a thin layer of basin fill less than 10 meters thick. Model layers were smoothed using algorithms within the COMSOL modeling software to remove overlaps and intersections between basin fill and bedrock layers to simplify the model meshing.

Initial models used simplified, 2-layer volumes that assume a conductive heat-transfer regime in order to bracket the regional background heat-flow values. This approach also allows us to focus on the main parameters controlling temperatures at depth below the basins (thermal conductivity and heat flow) before we start incorporating convective/advective (fluid flow) models. Surface ground temperatures (SGTs), calculated by Edwards (2013) are used as the upper boundary condition. The lower boundary condition, basal heat flow (q_b), is uniform and invariant with respect to time and a range of values from 80 to 100 mW/m^2 are used (5 total). Thermal conductivities for the sedimentary fill layer (k_1) range from1.25 to 2.375 W/mK (7 total) and for the bedrock layer (k_2) range from 2.5 to 4.0 W/mK (9 total). There are 63 models per q_b value giving a total of 315 models created using a parametric sweep schema with COMSOL Multiphysics, a finite element method (FEM) modeling program. A parametric sweep approach is selected in order to determine a best estimate of the background heat flow of the basin in a conductive heat-transfer setting. This will allow us to evaluate convective and advective effects once background values are established.

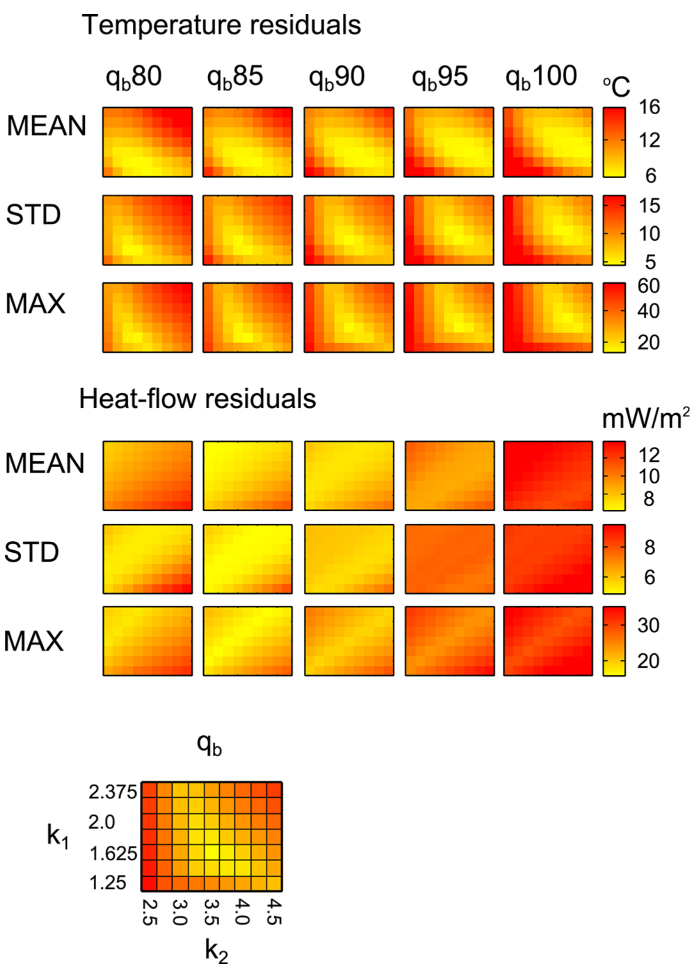

Figure 4. Residuals of model results to observed data for each model parameter set represented as mean, standard deviation, and maximum. Top panel shows temperature residuals and bottom panel shows surface heat-flow residuals.

Results and Discussion

In order to check the validity of the conductive model, we compare the observed temperature and calculated heat-flow data from Gwynn and others (2013) to the model results (Figure 4). Observational data are screened since some of the wells exhibit anomalous values of temperature and/or heat-flow which are not assumed to be representative of the regional thermal signature. The wells excluded from this dataset are Pavant Butte 1, Meadow Federal 1, Hole-in-Rock 1, and Argonaut Federal 1. After screening the observed data, residuals of temperature and heat-flow values in regard to the model results are calculated and are shown in Figure 4.

Residuals shown are mean, standard deviation, and maximum difference. Linear patterns emerge in the residual plot windows (more apparent in heat-flow residuals) since the relationship between heat flow, the temperature gradient, and thermal conductivity is linear. Temperature residuals display a global minimum with a slight trend apparent as an inverse, linear relationship between k_1 and k_2. At the end points of the thermal conductivity ranges, the data residuals increase as expected (indicating a poor fit) since these combinations of k_1 and k_2 are not a good representation of the observed relationships between basin fill and bedrock found within the study area. Heat-flow residuals align in a trough-like feature following a positive, linear relationship between k_1 and k_2. These trends suggest there is a preferential ratio of thermal conductivity that provides a relatively good fit of modeled heat flow to the observed heat-flow data.

When using both the temperature and heat-flow residual results for a given q_b we are able to pick a best estimate for the basin model parameters. The following model parameters were chosen to produce a best representation of the region's background heat flow: q_b=90; k1=1.625; k2=3.5. Residual values of mean, standard deviation and maximum for this model are 6.0, 4.3, 14.1°C for temperature and 8.7, 7.7, 25.6 mW/m^2 for heat flow. Temperature values are within 10°C of the screened observed data, which is a reasonable fit for a background conductive model and within uncertainty estimates of the included temperature BHT data by Gwynn and others (2013). Temperature fields for specified depths from this best model are shown in Figure 5. The significant temperature differences between the model and observed data occur at a depth of approximately 3 km in Hole-in-Rock, Meadow and Pavant Butte 1 wells. The model over predicts temperature at Hole-in-Rock and Meadow by 40°C and 50°C, respectively; the colder

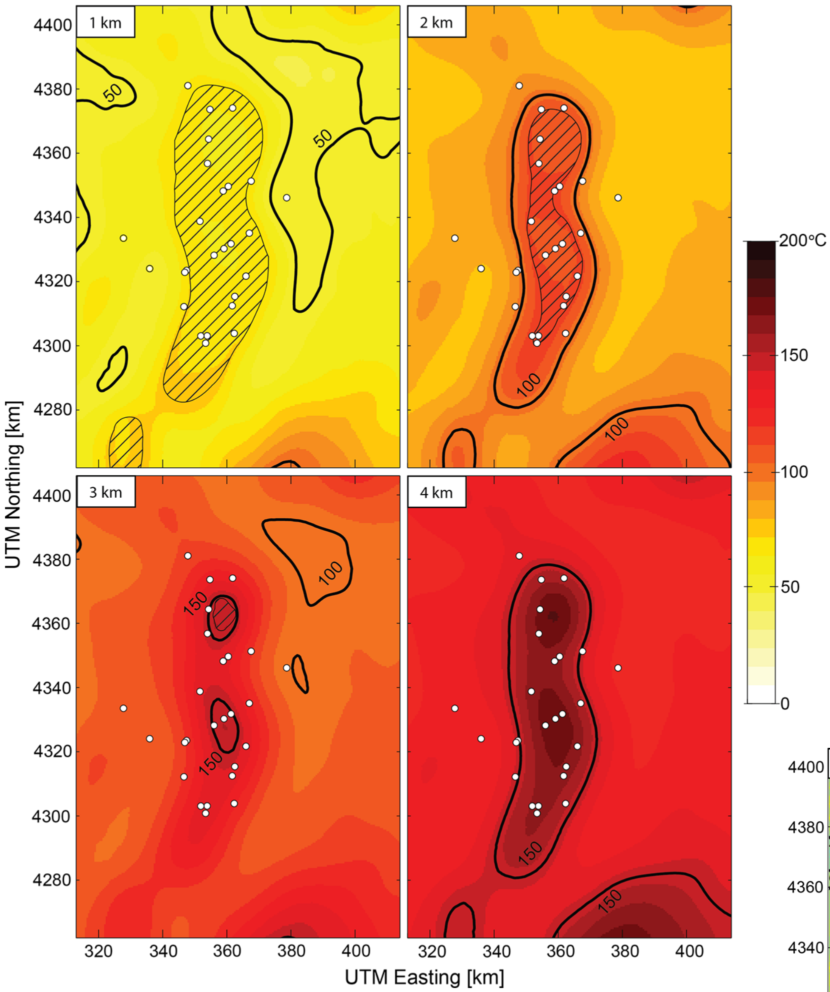

Figure 5. Horizontal slices of temperature from model results at indicated depths. Contours are in 50°C increments, hachured areas indicate location of basin fill at depth, white circles indicate locations of wells from Figure 1.

observed temperature is thought to be caused by groundwater flushing in the southern end of the Black Rock Desert. However, at Pavant Butte 1, the model under predicts temperature by approximately 60°C. This high temperature anomaly could be caused by an extra heat input at depth related to the Pavant Butte volcanics.

Heat-flow plots shown in Figure 6 are generated for 3 horizons: 0 km, 2 km, and 4 km depths. In a purely conductive model, heat will flow along a preferred pathway that has the highest thermal conductivities and least amount of insulative covering. In this model, the preferred flow paths are through the basement along the boundary of the basin fill. The temperature field is continuous whereas heat flow and thermal conductivity are discontinuous across the basin fill/basement boundary. This is referred to as heat-flow refraction. Surface heat flow varies from more than 100 mW/m^2 to less than 80 mW/m^2; highest values are in the ranges surrounding the BRD and lowest are in the center of the basin. When comparing the model to observed surface heat-flow values the area surrounding Pavant Butte is under predicted by 25 to 60 mW/m^2 and the southern part of the BRD is over predicted by about 25 mW/m^2. These differences in heat flow could be explained by the same reasons given for the temperature differences pointed out in the text above (groundwater flushing and extra heat input).

Conclusions

The initial runs of the thermal model are entirely conductive and include no hydrologic data. Comparisons of model-predicted heat flow (Figure 6) with a grid of heat flow based on borehole data (Edwards, 2013) provide a general test of the validity of a purely conductive heat flow. Areas of misfit between model-predicted and measured heat flow could result from additional heat transport processes including advection and convection. Advection may occur in areas where sufficient volumes of groundwater transport heat laterally and alter the expected surface heat flow. Convection may alter heat flow due to thermally driven deep fluid flow and would be most likely to occur in areas of thick, laterally contiguous basin fill.

Future iterations of thermal models for the BRD will use 90 mW/m^2 as a lower boundary condition, representative of the regional background heat flow. Anomalous heat-flow and temperature values in the observed data of the study area indicate that there are other parameters and variables to explore in future models (e.g., porosity effects on conductivity, refined stratographic layers,

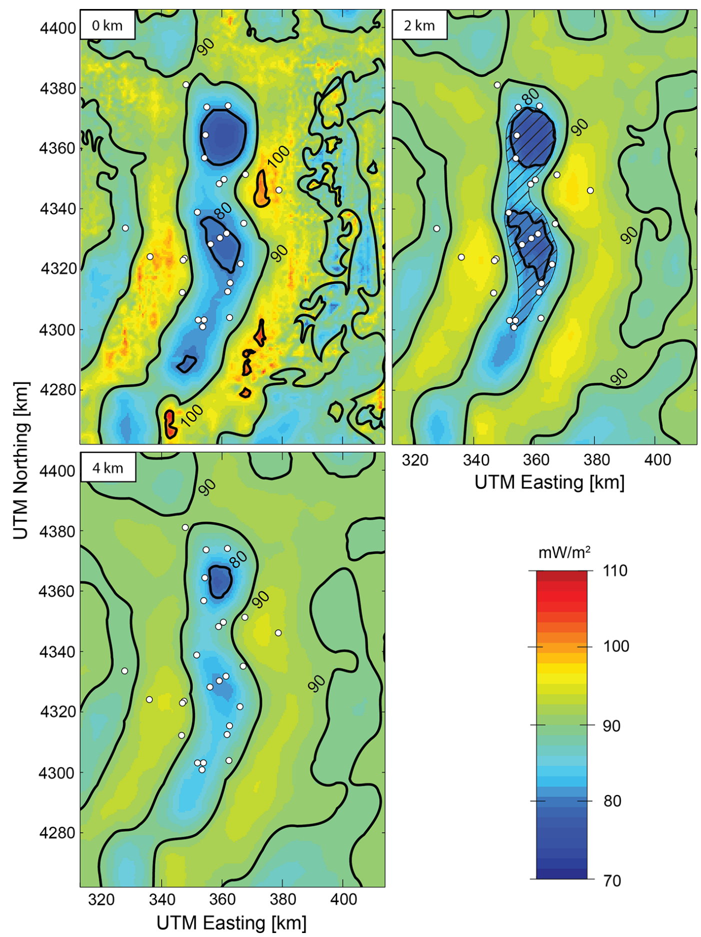

Figure 6. Horizontal slices of heat-flow from best model at indicated depths. Contours are in 10 mW/m^2 increments, hachured areas indicate location of basin fill at depth, white circles indicate locations of wells from Figure 1.

etc.). The main parameters to attend to are 1) a non-uniform distribution of basal heat flux to address excess temperature and heat flow in the area of Pavant Butte and 2) advective/convective heat-flow effects due to the movement of groundwater. Updates to the conductive model will incorporate all observed data and are intended to be used as control points for subsequently refined models. This will allow us to better characterize the subsurface thermal conditions of the BRD and its geothermal potential as a viable resource in a sedimentary basin setting.

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