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NEW GEOTHERMAL RESOURCE DELINEATED BENEATH BLACK ROCK DESERT, UTAH

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ABSTRACT

The Utah Geological Survey recently completed the drilling of ten temperature gradient wells in the Black Rock Desert of western Utah. Seven of these wells and four others drilled in the 1970s delineate a geothermal resource where temperatures of more than 150°C cover an area of about 350 km² at a depth of 3 km. This coincides with the axis of an actively extending basin containing Late Tertiary-Recent sediments up to 3 km thick overlying Mid-Late Cambrian carbonate bedrock. An area of approximately 60 km² has temperatures above 200°C at 3 km depth. An abandoned oil exploration well confirms temperatures of 230°C at 3.3 km depth in the center of this thermal anomaly. At this well, the near-surface temperature gradient is 105°C/km, and the heat flow is 125 mW/m². This thermal anomaly may be associated with a cooling intrusion in the upper crust beneath Pavant Butte volcano, which last erupted about 15,000 years ago. Potential geothermal reservoirs likely exist in the near-horizontal carbonate strata between 3 and 4 km deep in the Black Rock Desert. These same units are exposed in the adjacent Cricket Mountains west of the Black Rock Desert. If these carbonate bedrock formations are sufficiently permeable, a substantial deep geothermal resource may exist in the Black Rock Desert.

INTRODUCTION

Twelve oil and gas exploration wells were drilled in the Black Rock Desert (BRD) study area between 1957 and 2010, all of which were eventually plugged and abandoned. Most bottom-hole temperature (BHT) data, obtained from well logs and corrected to minimize depressed temperatures caused by the drilling, typically revealed geothermal gradients around 30-45°C/km. However, the Pavant Butte 1 well, drilled to 3,290 m by Arco Oil and Gas Co. in 1981, revealed a corrected BHT of 230±10°C, equating to a geothermal gradient of about 66°C/km. The Pavant Butte 1 well is located 3.5 km west of Pavant Butte, a volcano that last erupted about 15,000 years ago, and is roughly centered in the basin containing the BRD (Blackett and Wakefield, 2004; Figure 1). The anomalously high BHT and gradient at Pavant Butte 1 became the impetus for further study in the area, ultimately leading to the drilling of 10 thermal-gradient wells in 2011-2012.

GEOLOGIC SETTING

The BRD is located in a 6,000 km² basin at the northern end of what is informally known as the Sevier thermal anomaly along the eastern boundary of the Great Basin (Mabey and Budding, 1987; Allis et al., 2012). The basin is subdivided into the Black Rock Desert to the south and the Sevier Desert to the north, but as there is no distinct bounding feature, the name Black Rock Desert will be used to refer to the basin as a whole. The basin is bounded by the Simpson and Sheeprock Mountains to the north, the Pavant Range and Canyon Mountains to the east, the Twin Peaks in the south and the Cricket and Drum Mountains to the west (Figure 1).

The north-south elongated basin measures about 100 km by 60 km. Hardwick and Chapman (2012) reported a north-trending gravity low of about -30 mGal (relative to the regional anomaly) that defines the deepest section of the basin. Within this gravity low, the maximum depth to basement is about 3 km and depths are 2 km or greater in a roughly 15-km-wide zone along the axis. Their interpretation is reinforced by reinterpreted logging data from the Pavant Butte 1 and Hole-in-Rock 1 wells, both drilled by Arco in 1981, which show that 2.8-3.0 km of Paleogene to Recent sediments lie above lower Paleozoic bedrock (Allis et al., 2012).

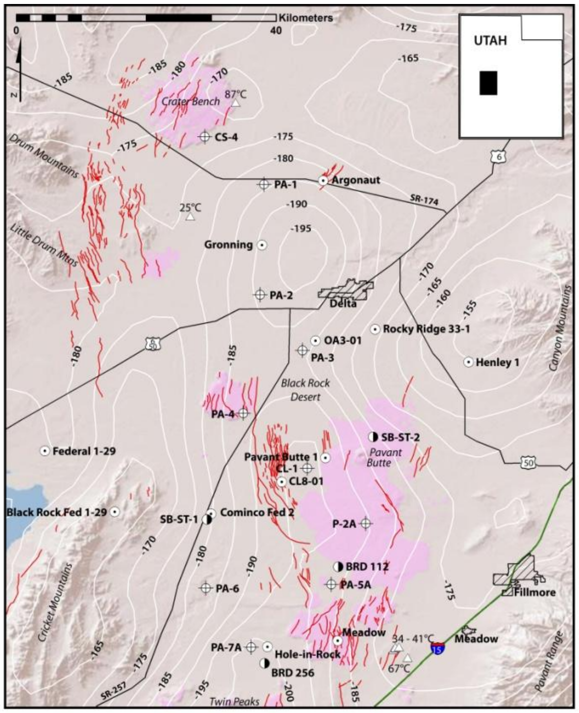

Figure 1. Location of the Black Rock Desert study area. Deep oil exploration wells (circle and a dot), pre-existing shallow thermal gradient wells (divided circle), and newly drilled shallow thermal gradient wells (circle and cross) have downhole temperature profiles shown in Figures 2-4 respectively. Pink areas show the extent of Quaternary volcanism. Thermal springs (triangles) and Quaternary faults (red lines) are from Utah Geological Survey databases. White contours define the Bouguer gravity anomaly (5 mGal intervals).

The Pavant Butte 1 well penetrated about 400 m of shale, limestone, and quartzite beneath the Sevier Desert Reflector at a depth of about 3,000 m (Allis et al., 2012). The reflector was encountered at about 2,800 m in the Hole-in-Rock 1 well, about 30 km south of Pavant Butte 1, before approximately 580 m of often fractured to highly fractured limestone and dolostone was drilled (Allis et al., 2012). Seismic reflection profiles show that the Sevier Desert Reflector dips to the west at about 11° and covers an area of about 7,000 km² (Anders and Christie-Blick, 1994). The origin of the reflector is controversial and thought by some to represent the glide surface of a thrust or low-angle normal fault while others consider it to simply be an unconformity (Hintze and Davis, 2003). Thrust sheets related to Sevier crustal contraction from the Late Jurassic though the early Tertiary are present in the western portion of the basin (Blackett, 2011; Allis et al., 2012). Regardless of its origin, the reflector separates the Cenozoic basin fill sediments from underlying Paleozoic and Precambrian strata.

North-trending normal faults with minimal displacement are common in the BRD. Some faults have offset the abundant Pleistocene to Recent lavas found across the area and may have acted as structural controls for many of the eruptive centers (Hintze and Davis, 2003). Although volcanism has been bimodal through time, with the exception of a single, small rhyolitic event, Quaternary flows have been of basaltic composition (Hintze and Davis, 2003) and it is the preponderance of basalt that gives rise to the Black Rock Desert's name.

The Meadow-Hatton geothermal area in the southeastern portion of the BRD hosts a number of thermal springs ranging in temperature from about 22 to 67°C. Several other springs with temperatures of about 25-28°C are present on the south and western sides of the basin. Abraham Hot Springs is located in the northwestern section of the basin and exhibits temperatures as high as 87°C. 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).

OIL AND GAS EXPLORATION WELLS

The 12 deep exploration wells drilled in the BRD range in depth from 1,143 m (OA3-01, United Oil and Minerals) to 5,326 m (Black Rock Federal 1, Chevron USA, Inc.). No continuous temperature logs were run in any of the wells, so BHT data from well log headers were used to determine deep subsurface temperatures. The BHTs were corrected using the methods of Henrikson (2000), and in cases where header data was insufficient to apply his correction techniques, in situ temperatures were estimated by adding 5°C for each kilometer of depth to the BHT.

Due to the lack of continuous temperature-depth profiles, geotherm models were constructed for each well using a spreadsheet (Figure 2). The geotherms were calculated using published lithologic data (Hintze and Davis, 2003; Allis et al., 2012) and lithologic data from available well logs, combined with the characteristic thermal conductivity data of Lappin (1980), Sass and Mase (1980), Robertson

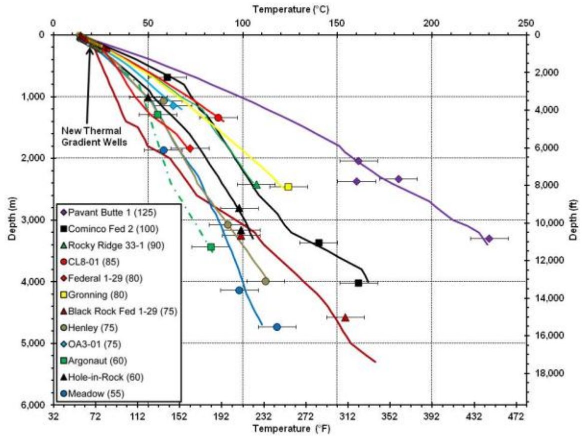

Figure 2. Calculated temperature-depth profiles of deep oil exploration wells in the Black Rock Desert. Symbols show corrected bottom-hole temperatures with ± 10°C error bars for each well. Numbers in parentheses are the calculated heat flow in mW/m. Well locations are identified in Figure 1.

(1988), Sass et al. (1999), Beardsmore and Cull (2001), Gosnold et al. (2012), and the near-surface conductivity data obtained from the recent drilling program. Once the characteristic thermal conductivity values were matched to the lithologies present in the well bores, heat-flow values (the mathematical product of thermal gradient and thermal conductivity) were then adjusted until the profiles intersected the corrected BHT data. The resulting temperature-depth profile therefore approximates the curve that would result if precision temperature logs were acquired after the formation had returned to pre-drilling temperatures (thermal equilibrium).

EARLIER THERMAL-GRADIENT WELLS

Over 80 shallow thermal-gradient wells have been drilled near the southern and west-central margins of the BRD and in the adjacent ranges as part of previous geothermal exploration programs. These wells range in depth from 32 to 522 m, but about 80% are less than 100 m deep. The temperature profiles in many of these wells, from all depths, appear to be disturbed or convective and gradients fluctuate widely. Because the data in many of these wells are questionable and many of them are in the ranges surrounding the BRD rather than in the basin, only four wells, all located within the basin, were used in this study. However, some of the excluded wells will be included in an ongoing research project regarding regional heat flow.

The more reliable wells are BRD 112 (68 m), BRD 256 (95 m), SB-ST-1 (474 m), and SB-ST-2 (522 m) in the southern third of the BRD (Figure 1). The first two were drilled by Amax Geothermal, Inc. in the 1970s and the others were drilled by Phillips Petroleum Co. in 1976. The temperature-depth data from these wells yield gradients of 47-67°C/km (Figure 3). Thermal conductivity data from the nearest newly-drilled wells were used to calculate heat flow in the Amax wells. Because compaction of the sediments in the much deeper Phillips wells would cause the thermal conductivity to increase, a slightly higher value of 1.50 W/m·K was used to calculate heat flow in these wells.

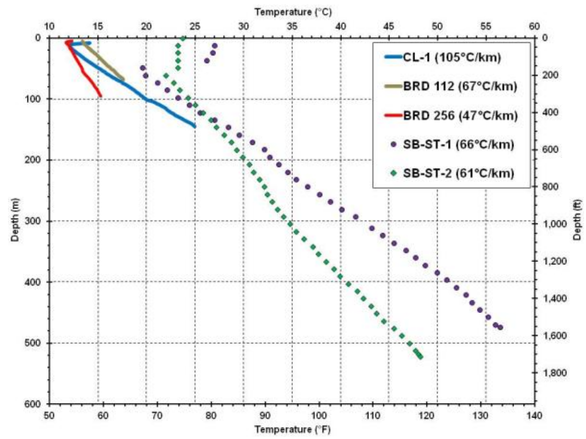

Figure 3. Temperature-depth profiles for four shallow thermal gradient wells located in the Black Rock Desert completed in the 1970s. High-gradient CL-1 well drilled in 2011 is shown for comparison.

NEW THERMAL-GRADIENT WELLS

Sites for the new wells were selected based on several criteria. The first was to drill across a broad area that would allow refinement of the thermal regime suggested by existing oil and gas wells along with several existing shallow thermal-gradient wells. The second was to drill in the deeper parts of the basin where up to 3.0 km of sedimentary basin fill is present. In such a basin, the relatively low thermal conductivity of the basin fill compared to bedrock provides an "insulating blanket" that results in higher temperatures at shallower depths, as discussed by Allis et al. (2011, 2012). Gravity data were used to define the basin geometry and depth. Lastly, the sites, which were all on land owned by the Utah School and Institutional Trust Lands Administration, required good access for the drill rig and related heavy equipment.

The new thermal gradient wells were drilled between December 2010 and September 2012. These wells range in depth from 145 to 244 m and were completed with a string of 2-in PVC pipe, sealed at the bottom and filled with fresh water, to facilitate making precision temperature surveys once drilling-induced temperature perturbations had attenuated.

The first well, Clear Lake-1 (CL-1), was drilled as a groundwater supply test well for the Utah Division of Wildlife Resources in the Clear Lake Wildlife Management Area. The well was drilled to a total depth of 420 m, but permeability was insufficient for water supply. Rather than simply plugging and abandoning the well, it was completed as a thermal-gradient well. Unfortunately, caving within the well bore prevented the PVC string from being inserted below 145 m. The remaining thermal-gradient wells, Crater Springs-4 (CS-4), Pavant-2A (P-2A), and Pavant Area-1 to Pavant Area-7A (PA-1 to PA-7A), were drilled in 2011-2012 by the U.S. Geological Survey's (USGS) Western Region Research Drilling Program using mud-rotary and direct-air techniques (P-2A only). The CL-1 well is approximately 2.7 km southwest of the Pavant Butte 1 oil well and exhibited the highest geothermal gradient, 105°C/km, of all ten thermal-gradient wells drilled during this investigation.

Samples of drill cuttings were collected over 3 m intervals in all nine of the USGS-drilled wells. The samples were rinsed in fresh water to remove as much drilling mud as possible and, with the exception of the CS-4 well, were then sealed in plastic bags to preserve the moisture content of the clay. The CS-4 and CL-1 samples were inadequately preserved and could not be used for thermal conductivity measurements. Samples from the remaining eight wells were well preserved for thermal conductivity, X-ray diffraction, and other studies. Samples from all 10 of the wells are predominantly hydrated clays with minor quantities of sand and gravels. Basalt flows up to about 50 m thick were penetrated in three of the wells (P-2A, PA-4, and PA-5A).

Temperature Profiles

Temperature-depth profiles were recorded on several occasions at each well using high-precision temperature logging equipment. The equipment consists of a thermister probe attached to reel-mounted four-conductor cable and the measurement accuracy is ±0.01°C. Equilibrated bottom-hole temperatures in these shallow wells ranged from 18.1°C to 29.2°C (Table 1).

Geothermal gradients were calculated based on the most linear segment of the most recent (at/or near thermal equilibrium) temperature-depth log for each well and ranged from 41 to 105°C/km (Figure 4).

Table 1. Summary of thermal data for new temperature-gradient wells in the Black Rock Desert.

Map ID	Completion Date	Temp. Log Date	Probe Depth (m)	BHT (°C)	Gradient (°C/km)	N.P. Average T.C. (W/m·K)	D.B. Average T.C. (W/m·K)	Heat Flow (mW/m²) [1]
CL-1	1-Mar-11	25-Oct-12	145	24.9	105	1.20 [2]	1.20 [2]	125
CS-4	11-Apr-11	20-Jul-11	244	29.2	65	1.25 [3]	1.25 [3]	81
P-2A	25-Apr-11	10-Oct-12	242	24.8	59	1.42	1.32 [4]	84
PA-1	17-Aug-12	10-Oct-12	151	18.3	41	1.24	1.26	51
PA-2	8-Aug-12	10-Oct-12	151	22.0	61	1.32	-	81
PA-3	4-Aug-12	10-Oct-12	152	21.4	60	1.32	1.31	79
PA-4	9-Sep-12	10-Oct-12	164	25.6	68	1.24	-	84
PA-5A	22-Sep-12	25-Oct-12	127	18.1	41	1.27 [5]	1.28 [5]	52
PA-6	22-Aug-12	10-Oct-12	152	22.4	68	1.18	1.18	80
PA-7A	13-Sep-12	11-Oct-12	182	22.3	50	1.17	-	58

BHT = Bottom-Hole Temperature
N.P. = Needle Probe
D.B. = Divided Bar
T.C. = Thermal Conductivity

[1] = Uses needle probe thermal conductivity values.
[2] = Estimated due to sample condition and ambiguity.
[3] = Estimated due to sample condition.
[4] = Only 10 samples from 61- 244 m were tested. N.P. average for these 10 samples only was 1.28 W/m·K.
[5] = 25 m of basalt chips not included.

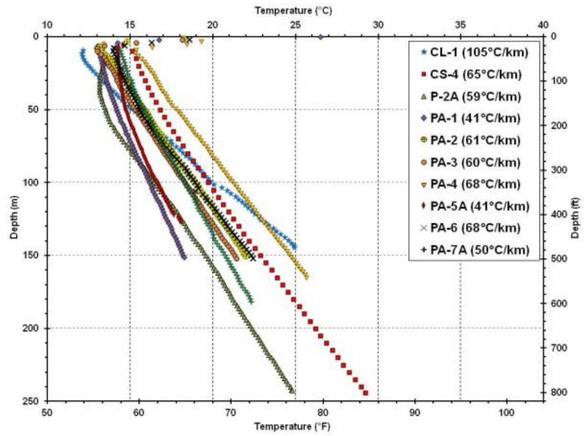

Figure 4. Temperature-depth profiles for 10 shallow thermal gradient wells located in the Black Rock Desert completed in 2011-2012.

The latest available surveys for PA-5A and PA-7A suggest the wells had not yet fully returned to pre-drilling temperatures, so the gradients are probably slightly depressed and lower than true gradients. The anomalously low gradient observed in PA-1 may be the result of high-conductivity salt found in the Argonaut well 7 km to the east. Almost 1,600 m of salt, gypsum, and anhydrite were penetrated at a depth of about 780 m in this well and the proximity of this salt mass to PA-1 would depress the gradient even if the salt does not extend as far west as PA-1.

Geophysical Logging

Wireline geophysical surveys (gamma, electric and sonic) were acquired by the USGS Western Region Research Drilling Unit and by the Utah Geological Survey (UGS) Groundwater Program on four of these new thermal-gradient wells (CS-4, P-2A, PA-3, and PA-6). The average calculated sonic porosities in these wells were about 46-50%. The interpreted lithologies from the wireline logs were consistent with those observed in the drill cuttings.

X-Ray Diffraction

The Energy and Geoscience Institute at the University of Utah (EGI) performed bulk and clay fraction X-ray diffraction (XRD) analyses on samples from P-2A. Nine samples at depths from 61-235 m were analyzed. All of the samples contained chlorite, smectite, and illite clay minerals. The presence of smectite suggests these samples have not been subject to temperatures above 180°C (Jones and Moore, 2012a), an expected result for this shallow well. Quartz, plagioclase, potassium feldspar, calcite, and dolomite were also found in all samples.

Thermal Conductivity

Thermal conductivities of all 401 samples of clay drill cuttings from the PA-series wells and from P-2A (Figure 5) were measured using a Decagon Devices KD2 Pro Thermal Properties Analyzer (needle probe). Needle probe accuracy is ±10%, which is about ±0.1 W/m·K for these samples. The overall average thermal conductivity determined for a given well from these measurements was about 1.3 W/m·K with a range of 1.0-1.8 W/m·K.

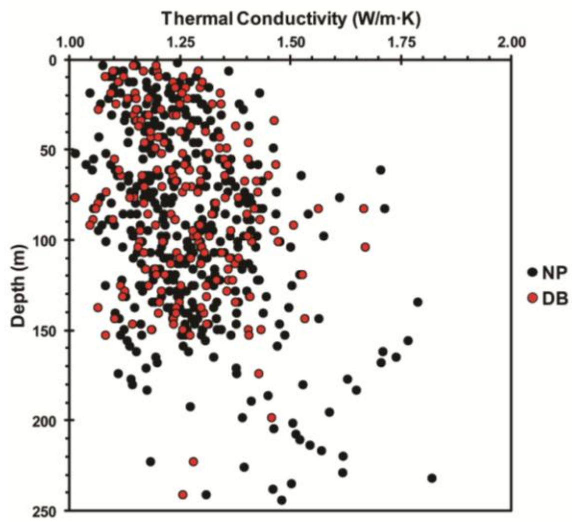

Figure 5. Plot showing the thermal conductivity of cuttings at specified depths in eight new thermal gradient wells drilled in the Black Rock Desert. Black circles are needle probe measurements from all wells and red circles are divided bar measurements from four of the wells.

Some samples from P-2A, PA-1, PA-3, PA-5A, and PA-6 have also been analyzed at the University of Utah Thermal Studies Laboratory using a divided bar apparatus. About 170 divided bar analyses were performed using a simplified sample preparation method whereby a quantity of the sample was placed directly into the test cells. Although results between instruments varied by up to 23% for a given sample, most differed by much less than 10%, and the overall average for each of the wells except P-2A differed by 2%. The 10 samples from P-2A analyzed with the divided bar were prepared using a more traditional and complex procedure that allows the matrix conductivity to be calculated and combined with the estimated porosity to determine the in situ thermal conductivity. Porosity estimates for these samples, derived from a sonic porosity log, were 44-49%. For nine of these samples, the thermal conductivity values between the two instruments vary by less than 10%. The overall average thermal conductivity for

P-2A measured with the divided bar was about 7% lower than that measured with the needle probe, most likely due to the difference in the number of samples tested (10 divided bar vs. 61 needle probe).

Core samples consisting of hydrated clay sediments were recovered from PA-3, PA-5A, and PA-6 so that thermal conductivity measurements could be taken on pseudo in situ samples for comparison to measurements made on the drill cuttings collected from adjacent sections of the boreholes. Needle probe measurements have been performed on the cores, but divided bar measurements have not yet been completed.

Initial comparison of needle probe measurements of the cores and cuttings from PA-3 and PA-5A reveals that thermal conductivity is about 10-15% lower in the cuttings, suggesting that conductivities determined from cuttings probably represent a minimum value. It appears that the PA-6 core experienced some degree of compression that increased the measured thermal conductivity. Sass et al. (1979a, 1979b) determined that the thermal conductivity of clay sediments similar to those in the BRD measured in cores were about 5% lower than those measured in situ using down-hole equipment. This means that in situ thermal conductivities in the BRD may be nearly 20% higher than suggested by the cuttings. The average thermal conductivity values derived from cuttings in each well were multiplied by the corresponding gradient to calculate heat flow at these sites. Likewise, the average conductivities from the new thermal-gradient wells nearest to the existing gradient and oil exploration wells were used in the heat flow calculations at these other locations. Therefore, heat-flow determinations at all sites are likely skewed toward conservative minimums.

RESULTS AND DISCUSSION

Mapped heat flow values show that the background heat flow in the BRD is conservatively about 80-85 mW/m². While a lower heat flow, about 50-60 mW/m², is found in the southern end of the BRD and in a small area farther north around the Argonaut and PA-1 wells, heat flow as high as 125 mW/m² is found closer to the Pavant Butte 1 and CL-1 wells. High heat-flow areas of the Great Basin typically exhibit values of 80-100 mW/m² (Lachenbruch and Sass, 1977, Blackwell, 1983, Blackwell et al., 1991, Tester et al., 2006), so the BRD can reasonably be classified as a high heat-flow area.

In sections of the basin containing more than 2 km of relatively low thermal conductivity basin fill, such as is found in the Pavant Butte 1 and Hole-in-Rock wells, a heat flow of 85mW/m² should result in a temperature greater than 150°C at 3 km depth. In the BRD, the -185 mGal contour is assumed to represent the area of the basin where the basement is more than about 2 km deep, but this approximation will be refined later in 2013 as detailed modeling of the basin structure and depth to bedrock is completed. Mapped heat-flow values were then used to estimate where temperatures of more than 150°C at 3 km depth would likely be encountered (Figure 6). The result is an area of about 350 km² surrounding the Pavant Butte 1 and CL-1 wells, both of which exhibit heat flow of about 125 mW/m². A smaller area of about 60 km² around these wells is likely to be more than 200°C at 3 km depth.

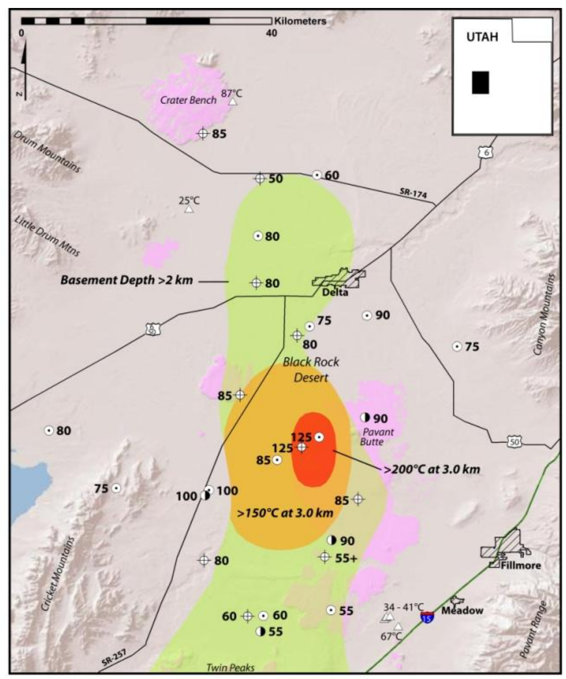

Figure 6. Derived heat flows (mW/m²) from thermal-gradient wells and corrected bottom-hole temperature measurements in oil exploration wells in the Black Rock Desert. The spring and well symbols are as described in Figure 1. The green area is defined by the -185 mGal Bouguer contour and shows the approximate area where depth to basement is about 2 km or greater. The orange zone is the estimated area where temperatures greater than 150°C may be found at 3 km depth. The red zone is the estimated area where temperatures greater than 200°C may be f ound at 3 km depth.

X-ray diffraction data suggest that temperatures above 200°C may be present, or have been present, at even shallower depths. Nineteen cuttings samples from the Pavant Butte-1 well were studied in 30-60 m intervals between about 2,250 m and 3,390 m depths. Interlayered illite-smectite is only present in the samples above 2,340 m. Below this depth, the presence of chlorite and illite without interlayered illite-smectite suggests temperatures above 220°C have been present (Jones and Moore, 2012b).

While the near-surface heat-flow determinations suffer from a degree of uncertainty, primarily related to thermal conductivity data, there is greater uncertainty in the data derived from the deep oil exploration wells. Bottom-hole temperatures in oil and gas wells form a notoriously noisy dataset due to a number of factors. Although a number of methods exist for correcting the disturbed BHTs, the uncertainty remains quite high, and for this reason corrected BHTs in this study are assumed to be within ±10°C of equilibrium temperatures. Additionally, variations in the thermal conductivity of various rock types can be large, so heat flow calculations derived from these data may also suffer from relatively high uncertainty. Indeed, the heat flow calculation for Pavant Butte 1 can be made to vary between about 100 and 130 mW/m² by using thermal conductivity values near either end of the range of reasonable thermal conductivities for a given lithology. However, in several cases, the calculated heat flow from the better-constrained shallow wells and nearby deep exploration wells were very similar. The heat-flow values in the Pavant Butte-1/CL-1, Cominco Fed 2/SB-ST-1, and Hole-in-Rock/PA-7A pairs were very close within the pairs, suggesting that the calculations are reasonable.

The central area of the high-heat-flow anomaly suggests a focused heat source at depth is superimposed on the basin-scale thermal regime as discussed by Allis et al. (2011, 2012, 2013). Extensive Quaternary volcanism has taken place in the BRD as recently as about 600 years ago in the Ice Springs basalt field southeast of Pavant Butte (Oviatt, 1991; just south of P-2A on Figure 1) and at Pavant Butte itself about 15,000 years ago (Blackett and Wakefield, 2004). This volcanic activity points toward the possibility, if not probability, that cooling intrusions are still present at depth and are a heat source in excess of that normally associated with Basin and Range extension.

While evidence for an attractive geothermal heat source is strong, the question of suitable permeability at depth remains a critical factor in assessing the geothermal potential of the resource. Potential geothermal reservoirs could exist in the near-horizontal carbonate strata present beneath the basin fill at 3-4 km depth. These units crop out in the adjacent Cricket Mountains west of the BRD and have been successfully drilled for groundwater at a lime plant. A more detailed report on this study is being drafted and will be completed later this year.

SUMMARY

Ten new thermal-gradient wells were drilled in the BRD in 2011-2012 to better characterize geothermal potential in the area. Data from these wells, combined with data from 12 deep oil exploration wells and four previously drilled thermal gradient wells, show that the BRD is located in a high-heat-flow basin where the background heat flow is generally about 80 mW/m². Within the center of the basin, a zone estimated to cover 350 km² exists where heat flow in excess of 85 mW/m² is present and where temperatures of at least 150°C may be expected at about 3 km depth. A smaller zone estimated to cover an area of roughly 60 km² is present where the heat flow may be as high as 125 mW/m², which equates to a temperature of 200°C or greater at 3 km depth. With sufficient permeability, a substantial geothermal resource may exist in the underlying carbonate bedrock formations of the BRD.

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