Pavant Butte, Utah Geothermal Prospect Revisited

Rick Allis[1], Christian Hardwick[1], Mark Gwynn[1], and Stu Johnson[2]

[1]Utah Geological Survey, Salt Lake City UT
[2]San Diego CA
rickallis@utah.gov • christianhardwick@utah.gov
markgwynn@utah.gov • stuartdjohnson1@gmail.com

Keywords

Pavant Butte, Black Rock Desert, heat flow, gravity, resistivity, magnetotelluric soundings, seismic reflection surveys, stratigraphic reservoirs

ABSTRACT

An equilibrium temperature log run down to 2.2 km depth in the Pavant Butte oil exploration well three years after it was plugged and abandoned indicates temperatures of 240°C at 3 km depth and 280°C at 4 km. Heat-flow measurements from the Black Rock Desert around this well suggest the main thermal anomaly is at least 50 km^2 in area. High permeability in a potential reservoir at about 3 km depth may be provided by a combination of Quaternary faults that have shaped the basin lying beneath this area and stratigraphic permeability within the Cambrian metasedimentary package that lies immediately beneath the Tertiary to Quaternary basin fill. The shape of the bedrock surface is determined from interpretation of a 30 mGal gravity anomaly extending north-south in the central Black Rock Desert. Geophysical log measurements of density and porosity in oil exploration wells reveal a gradational density gradient with depth in the basin and a diminished gradient near the basin flanks. This is due to the change from paleo-lake sediments with high clay content in the central basin, to more sandy, coarser sediments on the basin flanks. The resistivity of the central basin-fill sediments is very low (0.5 – 3.0 ohm-m), which limits the ability of magnetotelluric soundings to delineate the bedrock surface here. Seismic reflection surveying is considered the best technique for mapping the reservoir beneath the basin. Additional heat flow measurements are also recommended to determine whether the geothermal resource is located centrally beneath the basin, or beneath the Pavant Butte volcano on the east side of the basin.

Introduction

In their assessment of the thermal regime beneath the Black Rock Desert, Utah, Gwynn and others (2013) integrated temperature information from numerous shallow thermal gradient wells and bottom hole temperatures (BHTs) from 12 oil exploration wells. The highest heat flow was found to be in Pavant Butte 1, a well drilled to 3.3 km depth by Arco Oil and Gas Co. in 1981. This well is 3.5 km west of Pavant Butte, a volcano that last erupted about 15,000 years ago near the center of the basin beneath Black Rock Desert. The deepest, corrected BHT was inferred to be 230 ± 10 °C, and the best-fit geotherm matched 220 °C at 3 km depth and predicted about 250 °C at 4 km depth (based on characteristic thermal conductivities inferred from lithologies). Recently, Stuart Johnson recovered a previously unpublished temperature profile measured by Phillips Geothermal in Pavant Butte 1 some three years after it was plugged and abandoned. The well was reopened, and a temperature profile down to 2.2 km depth was measured on August 28 1984. The temperature at the maximum measured depth was 197 °C. The best-fit geotherm using thermal conductivities measured on cuttings from Pavant Butte 1 (Edwards, 2013) has a heat flow of 140 ± 20 mW/m^2 and predicts temperatures of 238 °C at 3 km and 281 °C at 4 km depth (Figure 1). These results suggest some of the highest temperatures in Utah may exist near Pavant Butte volcano. Even at the Roosevelt Hot Springs system, the highest measured temperature is 268 °C, and geothermometer estimates on the produced fluids indicate a deep temperature of 288 °C (Capuano and Cole, 1982; Allis and others, 2015).

The purpose of this paper is to review the geophysical characteristics of the Black Rock Desert near Pavant Butte in view of these high temperatures. Possible reservoir targets are discussed if the prospect were to be explored further for geothermal power generation. We conclude with some general comments on the next steps to reduce exploration risk prior to deep drilling.

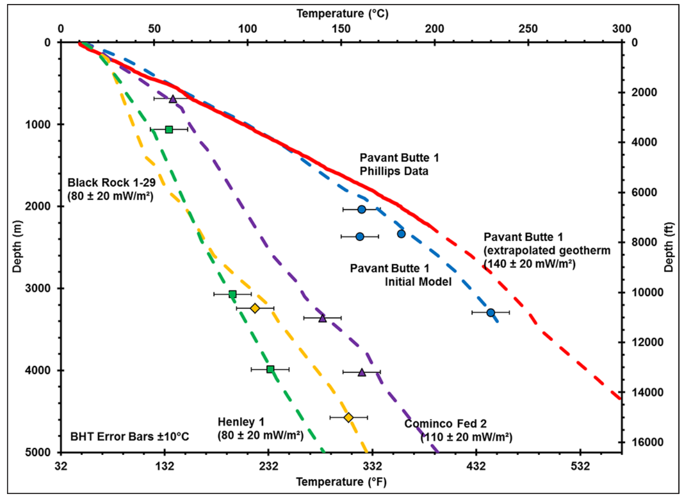


Figure 1. Bottom hole temperatures (BHTs) and geotherms for four wells in the central Black Rock Desert. The "initial model" for Pavant Butte 1 was based on conventional corrections to BHTs from Gwynn and others (2013). The temperature profile measured in Pavant Butte 1 three years later showed temperatures at more than 2 km depth were actually about 20 °C hotter than the corrected BHTs and one drill-stem test (DST) measurement (blue dot without error bars).

Thermal Regime

In light of the new, higher temperature data in the Pavant Butte 1 well, and the availability of more than 150 thermal conductivity measurements on cuttings from three deep exploration wells in the Black Rock Desert (Pavant Butte, Hole-n-Rock, and Gronning; Edwards, 2013), a reassessment of the thermal regime presented by Gwynn and others (2013) is required. Matrix thermal conductivities determined from the cuttings samples were corrected to bulk saturated values using porosity-depth functions for basin fill as discussed below. Figure 1 includes BHTs and geotherms for two wells near Pavant Butte 1 on the west flank of the graben beneath the Black Rock Desert (Cominco Federal 2 and Black Rock 1-29), and one well on the eastern flank of the graben (Henley 1). The locations of these wells and others mentioned in this paper are shown in Figure 2. Temperatures beneath the flanks of the graben are 110 to 140 °C cooler at 3 km depth than in Pavant Butte 1 at 3 km depth because of lower heat flow (80 - 110 mW/m^2 versus 140 mW/m^2) and a lack of insulating (i.e., low thermal conductivity) sediments overlying bedrock on the flanks.

All heat-flow values shown in Figure 2 have been rounded off to the nearest 10 mW/m^2 because of uncertainties in both thermal conductivities and the corrected BHTs. It is possible that most BHTs from the oil exploration wells are under-corrected based on our experience with Pavant Butte 1 and several other wells that have temperature profiles run a long time after drilling (Gwynn and others, 2015). Rather than arbitrarily adjusting the heat flows, they

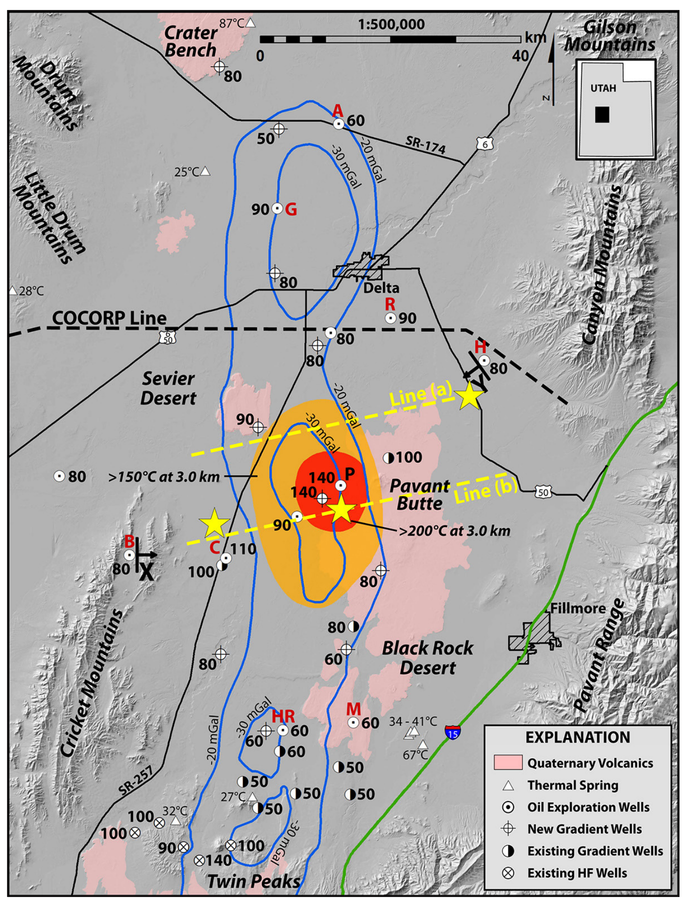


Figure 2. Heat-flow values around the Black Rock Desert based on both shallow and deep drill hole information (uncertainties typically ± 20 mW/m^2). Orange zone is where temperatures exceed 150°C at 3 km depth, and the red zone is where temperatures exceed 200°C at 4 km depth. Deep wells are labeled as follows: A, Argonaut; G, Gronning; R, Rocky Ridge; B, Black Rock 1-29; C, Cominco Federal 2; P, Pavant Butte 1; H, Henley-1; HR, Hole-in-Rock; M, Meadow. New gradient well data are from Gwynn and others (2013) and existing heat flow wells are from Chapman and others (1978). Heat-flow values for the Sass and others (1999) and Amax (1998) wells have been newly calculated and are included as new gradient wells. The line of the gravity interpretation in Figure 7 extends between endpoints X near the Black Rock 1-29 well, and Y near the Henley-1 well. It has a bend 10 km northeast of the Cominco Federal 2 well (Figure 6). The blue gravity contours delineate the basin. Yellow lines (a) and (b) are the two resistivity cross sections shown in Figure 9. The interpreted COCORP line shown in Figure 10 extends due west from between the Henley and Rocky Ridge wells (black dashed line). The three yellow stars are the locations of magnetotelluric stations close to the Cominco, Pavant Butte, and Henley wells.

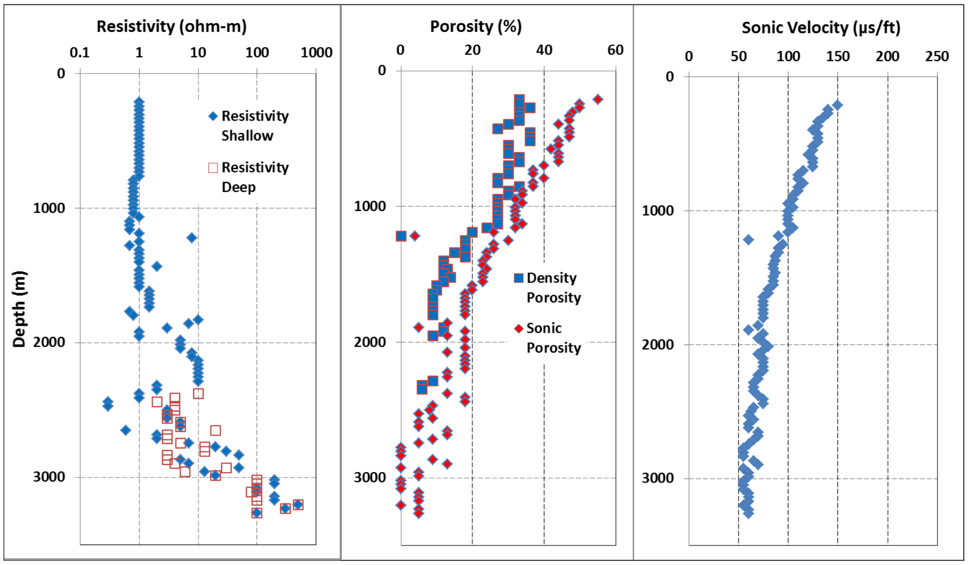


Figure 3. Physical property trends of nearly 3 km of basin fill sediments in Pavant Butte 1, derived from interpretation of wireline geophysical logs. The orange dashed line marks the base of basin fill at 2.98 km depth. The sonic porosity log is derived from the sonic velocity log using the sandstone curve of Raymer and others 1980. There was no "deep" resistivity data from the dual laterolog at less than 2300 m depth, although on the scale of this plot there are no significant differences between the shallow and deep resistivity logs where they overlap. The bedrock lithologies in Pavant Butte 1 are metasedimentary units composed of both carbonate ("marble"; Hintze and Davis, 2003) and clastics.

have been left as the best-fit geotherms based on conventional corrections to the BHTs. The heat flow in the deep wells could be underestimated by at least 10%.

The high temperature anomaly around Pavant Butte is highlighted in Figure 2. Two key factors influencing the area of this anomaly are the location of highest heat flow (assumed to be ~ 140 mW/m^2) and the thickness of insulating basin fill. There are insufficient data to decide whether the highest temperatures at 3 km depth are actually beneath Pavant Butte volcano to the east of the Pavant Butte 1 well, or possibly centrally located beneath the axis of the graben some 3 km west of the well. The area of highest temperature on Figure 2 (more than 200 °C at 3 km depth) is about 60 km^2, and the area with a temperature of more than 150 °C at 3 km depth is about 270 km^2.

Basin Fill Signatures

The physical properties of the Quaternary and Tertiary basin fill strongly influence the surface geophysical signatures of the basin beneath Black Rock Desert. Earlier gravity models of the basin fill thickness assumed a uniform density contrast of 0.5 g/cm^3 with the Paleozoic bedrock (Hardwick and Chapman, 2012). However, the oil exploration wells in the basin have a variety of geophysical logs which allow more detailed determination of the rock property trends with depth. Pavant Butte 1 is one well with having a relatively complete set of logs. Figure 3 shows the trends for sonic velocity, porosity and resistivity. The main trend in the density and sonic velocity logs is caused by decreasing porosity with increasing depth. The very low resistivity in the upper two kilometers of basin fill is mainly due to clay content. Some salt is also present in the northern Black Rock Desert and may lower the in situ resistivity where the pore water is saline. However, massive salt deposits, such as those found in the Argonaut and Rocky Ridge wells, actually have a resistivity of about 100 ohm meters.

A compilation of density data from deep wells around the Black Rock Desert is shown in Figure 4. The very low porosity bedrock density typically ranges between about 2.6 g/cm^3 for quartzite, phyllite, and intrusives, to 2.8 g/cm^3 in dolomite (limestone is typically close to 2.7 g/cm^3). The basin-fill density increases from about 1.7 g/cm^3 at less than about 300 m depth to more than 2.5 g/cm^3 below about 2 km depth. Decreasing density contrast with increasing depth is

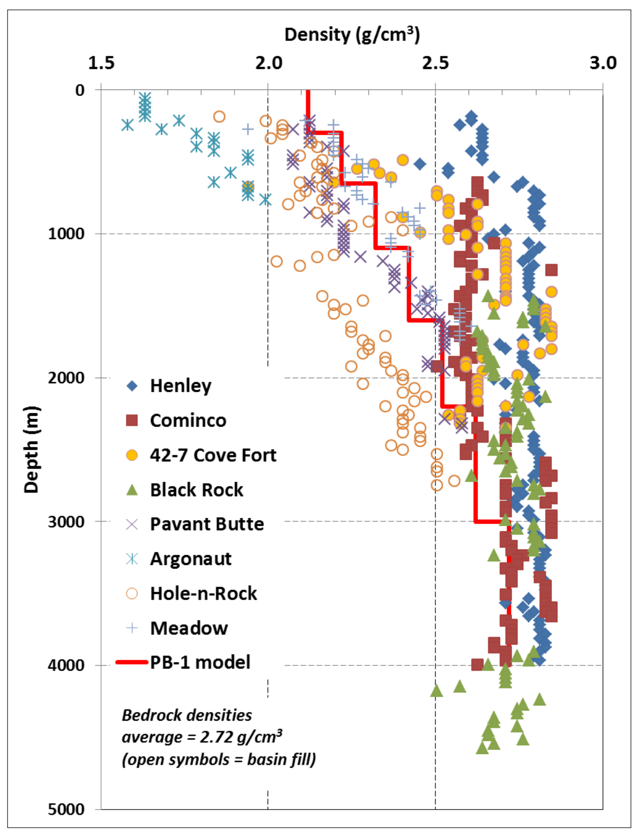


Figure 4. Compilation of density trends derived from geophysical logs run in oil exploration wells around the Black Rock Desert. Well locations are shown in Figure 2. The red line PB-1 is the density contrast model used in the cross section in Figure 6.

clearly important for using gravity to establish a profile of the bedrock surface beneath the graben. Stratigraphic summaries for deep wells in the Black Rock Desert are given in Appendix A of Hintze and Davis (2003).

Gravity Interpretation

The Bouguer anomaly map previously discussed by Hardwick and Chapman (2012) is shown as Figure 5. In that study, a cross section of basin fill and bedrock assumed a uniform density contrast of 0.5 g/cm^3 between the basin fill and the bedrock. However, as shown in Figure 4, the density contrast decreases with increasing depth of burial of the basin fill. Almost half of the 30 mGal gravity low anomaly delineating the basin beneath Black Rock Desert can be accounted for with the uppermost 1 km of basin fill. This effectively decreases the modeled depth to bedrock on the flanks of the basin compared to models using a uniform density contrast with depth, and also may increase the modeled gradient of the bedrock surface dipping into the central portion of the basin.

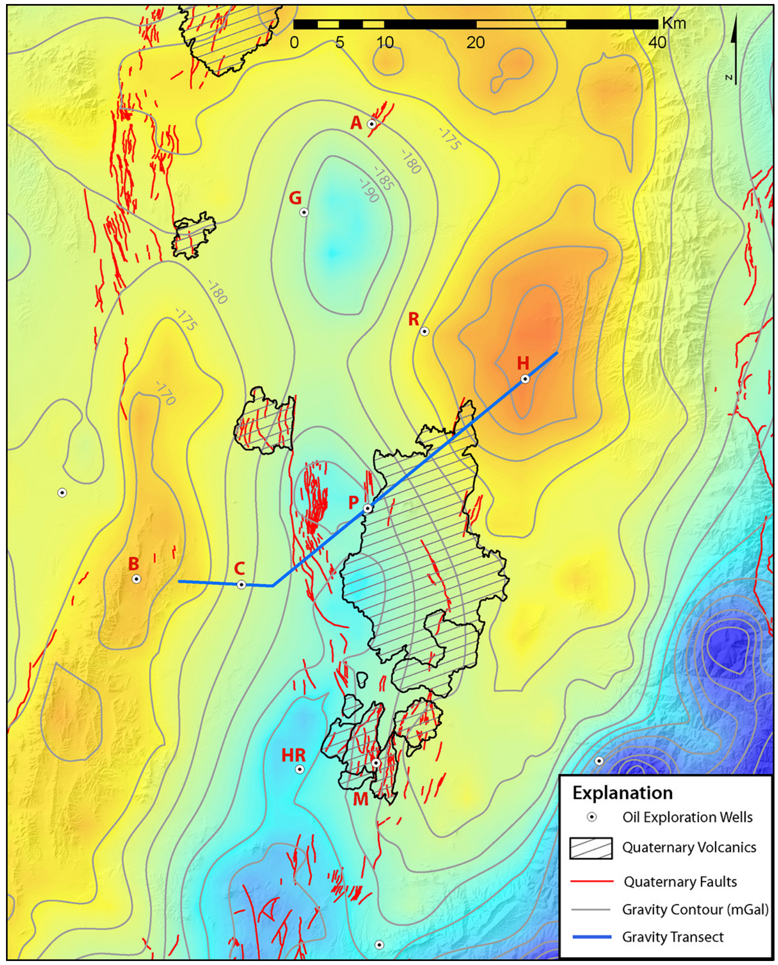


Figure 5. Bouguer gravity anomalies in the Black Rock Desert (5 mGal contour interval). Labels next to deep wells are the same as in Figure 2. The blue line marks the cross section of the gravity model shown in Figure 6.

The gravity model of a cross section through the Black Rock Desert connects the Cominco Federal 2 and Henley 1 deep wells as outer control points, and it passes though the Pavant Butte 1 well near the center of the basin. The bend ensures the line is approximately parallel to the gravity gradient on each basin flank. The model assumes a decrease in density with increasing depth at the location of the Pavant Butte 1 well which matches the observed densities from geophysical logs in that well (Figure 4). These density contrasts are assumed to persist across the basin. The modeled bedrock surface is asymmetric, with the western flank dipping more gradually to the center of the basin compared to the eastern flank (note vertical exaggeration of 1.5:1). If this profile surface is correct, we suspect significant fault control offsetting the bedrock beneath the cone of Pavant Butte (about 5 km east of the well). The west flank of Pavant Butte (formed about 15,000 years ago) is cut by faults that are parallel to the gravity contours. Faulted bedrock beneath Pavant Butte would be a target for enhanced permeability in the Cambrian metasedimentary units.

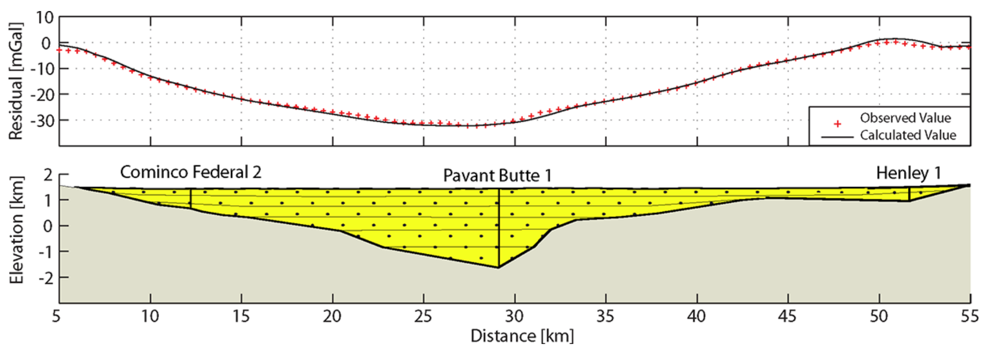


Figure 6. Gravity model for the basin fill along a cross-section passing across Pavant Butte well and Pavant Butte volcano (Figure 5, and X-Y arrows on Figure 2; note vertical exaggeration of 1.5:1). The assumed density contrasts for layers are based on density logs run in the Pavant Butte well (Figure 4). Starting at the bedrock surface, each successive layer within the basin fill represents an additional 0.1 g/cm^3 of density contrast. Details can be seen in Figure 4 as the PB-1 model. A regional gravity gradient has been subtracted, leaving the residual gravity anomaly shown in this cross section. We suspect the prominent gravity high near the Henley 1 well (Figure 5) is due to a thick section of dolomite within the bedrock beneath this area. The geophysical log data from Henley 1 shows at least 3 km of bedrock with a density of 2.8 g/cm^3, compared to average bedrock densities elsewhere of 2.72 g/cm^3.

Resistivity Interpretation

An analysis of the resistivity trends from geophysical logs in deep wells around the Black Rock Desert indicates basin-fill values typically from 1 to 10 ohm-m in contrast to bedrock values of 100 to over 1000 ohm-m (Figure 7). Closer inspection of the near-surface (< 500 m depth) basin-fill resistivity shows the central basin sediment typically has a resistivity of about 0.5 to 3 ohm-m (Pavant Butte 1 and Gronning wells), whereas closer to the west and east flanks of the Black Rock Desert, the near-surface resistivity rises to 3 to 5 ohm-m at the Cominco Federal 2 well, and 30 to 50 ohm-meter at the Henley 1 well. This is attributed to the change in lithology from central paleo-lake sediments with significant clay, to inferred sand and gravel fan deposits at the basin margins. This same pattern is also evident near the base of the clay-rich deposits where they overlie the bedrock (Hardwick and others 2015). The Argonaut and Rocky Ridge wells north and northeast of Pavant Butte also have a massive salt section within the lower basin fill, and the scant resistivity data suggests a resistivity of about 100 ohm-m.

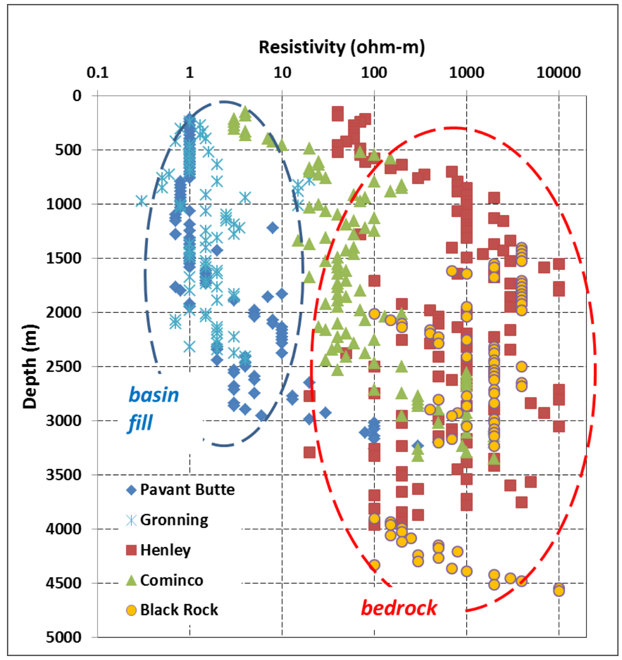


Figure 7. Comparison in resistivity of the basin fill in the Pavant Butte 1 well and the bedrock resistivity observed in the Henley 1 and Cominco-Federal 2 wells on the flanks of the basin. Below 3 km depth, the bedrock resistivity in all wells varies between 100 and 10,000 ohm-m, and appears to be more sensitive to rock type rather than to temperature.

The in-situ resistivities in Figures 7 and 8 highlight an issue with resistivity surveying techniques such as magnetotelluric (MT) soundings. In the central basin, the average resistivity of 2 ohm-m extending to more than 2 km depth requires data from periods of more than about 20 seconds to be sensing the underlying resistive bedrock (based on skin depth, or effective penetration depth considerations). At the basin margins with resistivities of 10 to more than 100 ohm-m extending from the near-surface, the skin depth at 20 seconds period is theoretically sensing down to the middle of the crust. In reality, soundings on the resistive margins of the basin are likely to be sensing two- and three-dimensional effects from lateral resistivity variations for periods greater than about 10 seconds.

Reasonable matches are obtained between the observed downhole resistivity trends derived from geophysical logging and the inferred resistivity variations from interpreting MT soundings (Figure 8a this page, 8b following page). The best-fit models to the MT soundings are non-unique and can vary with the number of layers and layer resistivity assumed in each model. In the three cases shown, the MT stations are between 3 and 5 km from the deep wells, so near-surface resistivity differences between the station site and well are possible (e.g. at Henley 1). At the Cominco Federal 1 well, the inferred resistivity between 0.5 and 2.7 km depth is an order of magnitude higher than that observed in the well. The

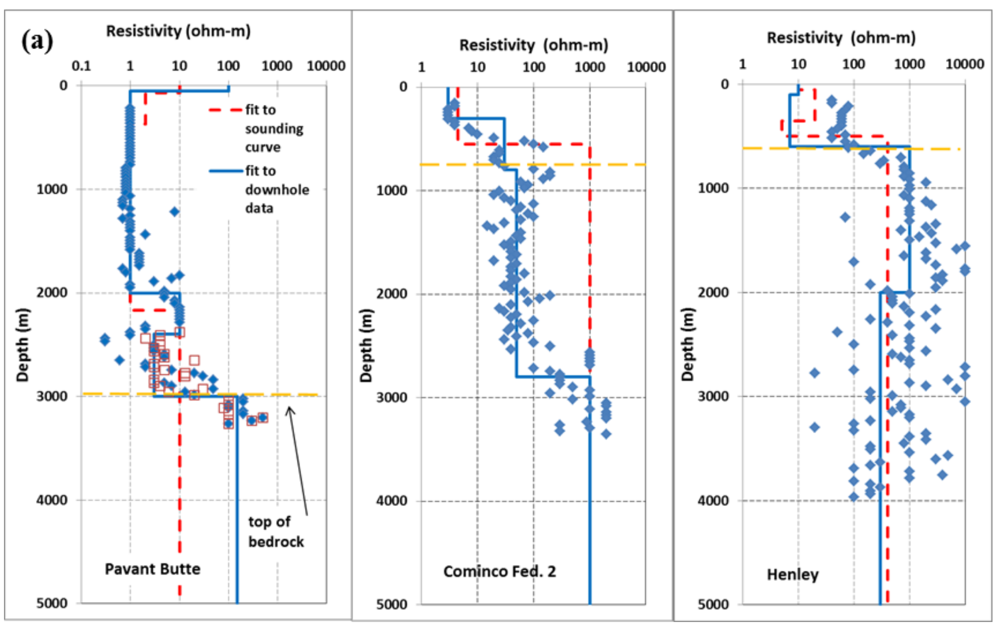
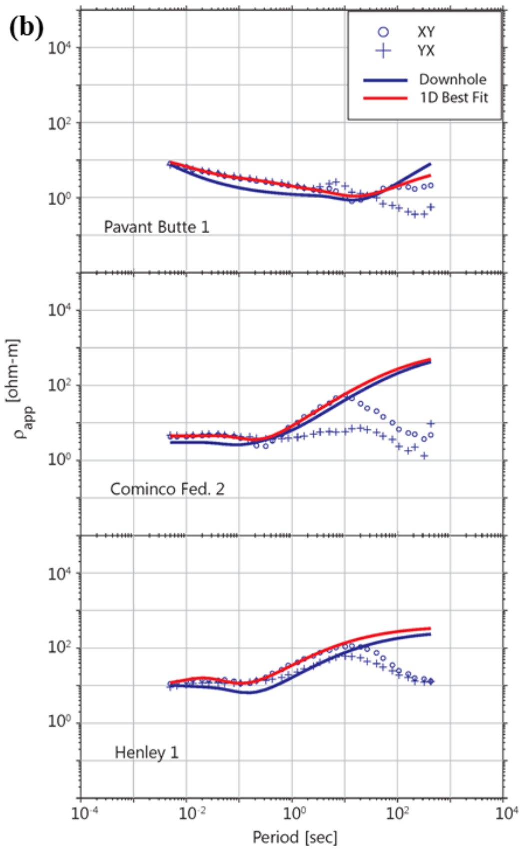


Figure 8a. One-dimensional interpretations of MT soundings near three deep wells where downhole measurements of in situ resistivity are available (locations on Figure 2). The blue lines are best-fit models to the observed drill hole data in (a); the red curves are the best-fit models to the apparent resistivity trends in the MT soundings (b; dashed lines in (a)).



Figre 8b. Caption on previous page with Figure 8a.

effect on the MT sounding curve is small, indicating the relative insensitivity of the MT response to in situ resistivities at these depths. At the Pavant Butte 1 well, there is good agreement with the low resistivity basin fill down to about 3 km. At greater depth the MT sounding is implying an order or magnitude lower resistivity than the observed bedrock resistivity. However, this is probably due to the same 2- and 3-dimensional effects affecting the long-period resistivity at all three sites. The 1-dimensional models give a reasonable estimate of the depth to bedrock on the basin flanks where the bedrock is less than 1 km deep, but are insensitive to bedrock depth in the deepest part of the basin.

Two-dimensional resistivity models of the basin near to the Pavant Butte 1 well are shown in Figure 9 (cross-section lines shown in Figure 2). In the central portion of the basin the resistive bedrock has not been sensed, partly because the interpretation truncated the soundings at 10 seconds to avoid more complicated three-dimensional effects. Wannamaker et al (2013) report on an initial effort at a three-dimensional resistivity model of the Black Rock Desert. They suggest the bedrock beneath the central basin may also be very conductive, but this conflicts with observed high resistivities beneath Pavant Butte. Hardwick and others (2015) analyze the resistivity signatures of the Black Rock Desert in more detail. In general it appears that the MT interpretations are overestimating the vertical extent of low resistivity, but more work is needed to address uncertainties in interpretation of both the resistivity and the gravity data.

Seismic Reflection Interpretation

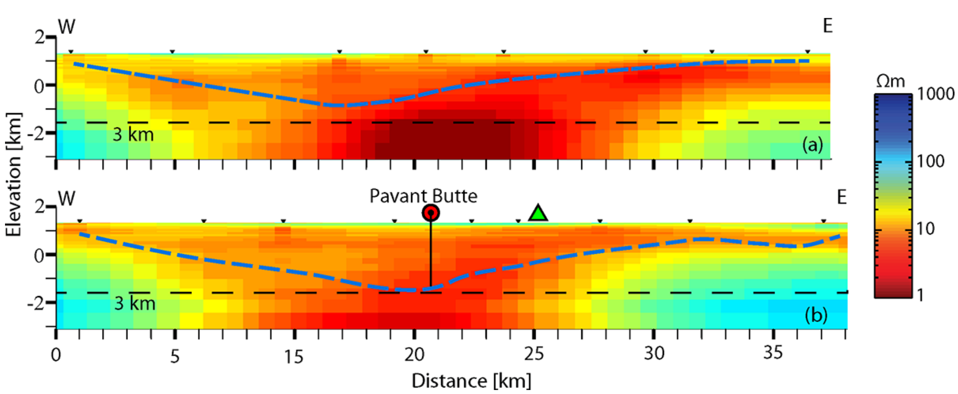


Figure 9. Two resistivity cross sections from Hardwick and Chapman (2012) based on a two-dimensional interpretation of magnetotelluric soundings (truncated to periods of 10 seconds). The two lines are shown in Figure 2 as Lines (a) and (b), with 3 km of depth shown as the dashed line. The triangle on Line (b) marks the summit of Pavant Butte volcano. The sections highlight the low resistivity basin fill with resistive bedrock detected beneath the flanks of the basin. In the central portions of the basin, the effective depth of penetration is between 2 to 3 km, so the bedrock is not detected by the MT soundings.

Schelling et al. (2013) give a structural interpretation of the northern Black Rock Desert based primarily on the non-proprietary COCORP Utah-1 seismic line (reprocessed by Wolverine Oil and Gas Corporation), a small amount of proprietary industry data, and formation tops obtained from nearby deep well data. The prominent reflector that appears to link the bedrock surface beneath the Black Rock Desert with a low-angle detachment surface further west has been called the Sevier Desert Detachment (SDD), but its origin is still debated (Wills and others, 2005; McBride and others, 2010, and references therein). In the center of the basin beneath the Black Rock Desert on this section are several normal faults that may or may not sole out at the reflector depending on its interpretation. The possibility of faulting within the underlying Cambrian carbonates and clastics provides an obvious, high-temperature reservoir target (Figure 10). While not specifically identified in the Pavant Butte 1 well, along Utah COCORP seismic line 1 a "pillow" of sedimentary rocks, which includes evaporites, has been imaged just above the Sevier Desert Detachment/reflector, though there remains some question as to whether the evaporites are early Tertiary or Jurassic in age. Nonetheless, Schelling et al. (2013) suggest salt mobilization may be partially responsible for the anticline-syncline pair identified along the COCORP line near the Python Rocky Ridge well and shown in Figure 10, although extensional faulting also could be partially responsible for the development of this structural system. These authors suggest that the salt section may provide a cap to fluids in the Cambrian bedrock to the east of the Pavant Butte well. The COCORP and industry seismic reflection surveys were collected prior to the mid-1980s, so some new seismic reflection imagery is recommended prior to the drilling of deep geothermal wells.

Conclusions

The thermal regime confirmed by the Pavant Butte 1 oil exploration well indicates a temperature of 240°C at 3 km depth and about 280°C at 4 km. The area of highest temperature appears to be at least 50 to 100 km^2 (red zone in Figure 2). Critical uncertainties are the characteristics of high permeability at that depth and the lateral extent of the proposed reservoir target. Possible high permeability features are the Quaternary fault zone that traverses the central Black Rock Desert basin, and stratigraphic permeability in the Cambrian section similar to that described by Allis and others (2012), and Allis and Moore (2014). A 400 m section of metasedimentary lower Cambrian bedrock was encountered at the bottom of the Pavant Butte 1 well, but there were no strong indicators of high permeability. The lower Cambrian section included limestone (marble), phyllite and quartzite (Hintze and Davis, 2003). Allis and others (2012) noted fractures at 3040 m (mud loss of 15 barrels) and possible fractures from 3064 to 3069 m and from 3266 to 3274 m. The structural interpretation of the COCORP 1 seismic line that is consistent with the stratigraphy in wells around this part of the Black Rock Desert is shown in Figure 11 (derived from Figure 10, Schelling and others 2013). The quality of the seismic reflections at the required depth range (2 to 3 seconds two-way travel time depending on near-surface seismic velocities) is insufficient to resolve the long-standing scientific debate over whether the quaternary faults in the Black Rock Desert sole into the Sevier Desert Detachment, or whether they cut the seismic reflector (refer to McBride and others 2010, for recent reanalysis).

The Quaternary fault zone that trends near the axis of the Black Rock Desert is centered 3 km west of Pavant Butte 1 (sometimes known as the Clear Lake fault zone). Wells deviated west from near the Pavant Butte 1 site may encounter high permeability where the fault zone intersects the Sevier Desert reflector at about 3 km depth. The Paleozoic section beneath the reflector would be the most likely reservoir target. Quaternary faults also cut the Pavant Butte volcano, so wells deviated east from this site may find fracture permeability in the Paleozoic section. In addition,

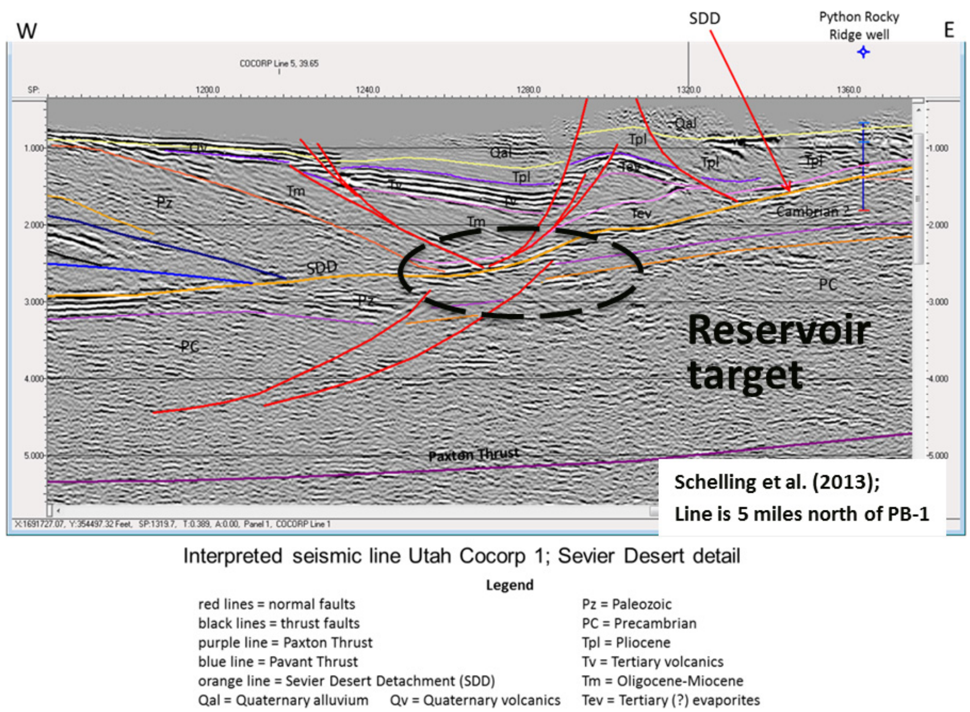


Figure 10. Interpreted COCORP – Utah 1 seismic reflection line extending west from the Rocky Ridge and Henley-1 wells (Figure 2). A potential reservoir target at 3 to 4 km depth where temperatures may be more than 250°C is highlighted. The cross section in Figure 11 is based on this interpretation. The vertical axis is two-way travel time in seconds and the reservoir is between two and three seconds.

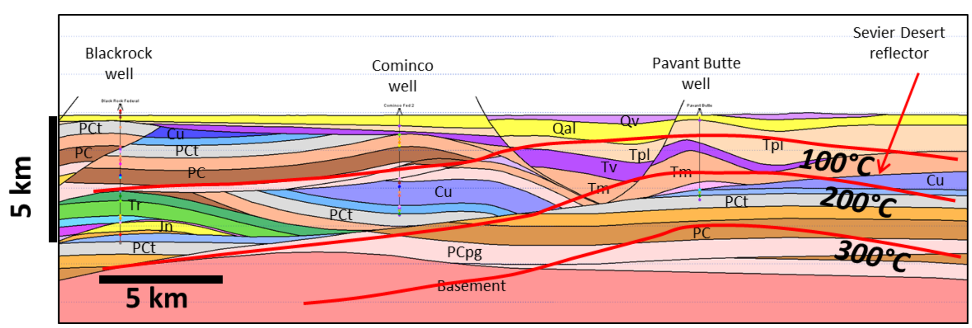


Figure 11. Interpretation of the structure and stratigraphy of a section through the Pavant Butte 1 well in the Black Rock Desert (modified from Schelling and others, 2013). The interpretation is based on the COCORP-1 seismic line, which was about 20 km north of Pavant Butte, and the stratigraphy from the deep wells in the area. The deep well Henley 1 is situated about 10 km east of the right hand edge of the diagram and was also used in the interpretation. The well locations are shown in Figure 2. Isotherms have been superimposed based on the temperature-depth trends shown in Figure 1.

the structure beneath Pavant Butte volcano could have been disrupted by the volcanism as the cone built up with repeated eruptions over the last 100,000 years.

The best geophysical technique for imaging the inferred reservoir is seismic reflection surveying. Both MT and gravity surveying may provide basin-scale constraints on the characteristics of the basin fill bedrock system, but they do not have the resolution to image a geothermal reservoir at 3 km depth. An initial, cost-effective source of new data is a reanalysis of seismic reflection lines surveyed mostly during the early 1980s during oil exploration. Schelling and others (2013) show that several lines cross through or close to the thermal anomaly at Pavant Butte and are available for purchase from vendors. Although the quality will not be very good by today's industry standards, these lines should be investigated before considering new seismic surveys.

The second critical uncertainty identified above is the location and shape of the thermal anomaly. Additional heat-flow wells are recommended as a cost-effective exploration tool to map the thermally conductive anomaly around the Pavant Butte 1 well prior to deep exploration drilling. The primary issue is to verify whether the main thermal anomaly is centered beneath the basin in the central Black Rock Desert to the west of the Pavant Butte well, or beneath the Pavant Butte volcano to the east. The deep Cominco Federal 2 well on the west flank of the basin has a heat flow of 110 mW/m^2, so high temperatures are implied at depth a few kilometers further east beneath the main part of the basin. Where there are no lava flows near the surface (west of the Pavant Butte 1 well), thermal gradient wells need only be about 100 m deep. Other thermal wells penetrating soft paleo-lake sediments of the central basin show a conductive thermal gradient almost to the ground surface. However, east and south of the Pavant Butte 1, water movement within lava flows near surface may complicate the thermal regime. If possible, gradient wells here should penetrate beneath lava, so these wells may have to be at 300 to 500 m deep to ensure the deeper conductive regime is accurately determined.

Finally, new seismic reflection surveying is recommended prior to drilling geothermal wells to at least 3 km depth. Determining the location of faults at about 3 km depth, as well as the stratigraphic continuity of the Paleozoic section below the Sevier Desert reflector is very important for identifying reservoir targets. Deep exploration wells will need to be strongly deviated to optimize intersecting high permeability rock in the Cambrian section immediately beneath this reflector.

Acknowledgements

This work was partially supported by the Geothermal Technologies Office of the Department of Energy through award DE-EE0005128. We thank many colleagues who contributed to earlier phases of this project. Doug Sprinkel (UGS) gave additional insight to the age of the salt found in the Rock Ridge well. Helpful reviews were received from John Pritchett (SAIC) and Stephanie Carney (UGS).

References

Allis, R., Blackett, R., Gwynn, M., Hardwick, C., Moore, J.N., Morgan, C., Schelling, D., and Sprinkel, D., 2012. Stratigraphic reservoirs in the Great Basin - the bridge to development of enhanced geothermal systems in the U.S. GRC Transactions, 36, 351-357.

Allis R., and Moore, J., 2014. Can Deep Stratigraphic Reservoirs Sustain 100 MW Power Plants? GRC Tranactions, 38, 1009-1016.

Allis, R., Gwynn, M., Hardwick, C., Kirby, S., Moore, J., and Chapman, D., 2015. Re-evaluation of the Pre-Development Thermal Regime of Roosevelt Hydrothermal System, Utah. Proceedings, 40th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, January 26-28, pp. 12.

AMAX Exploration Inc. (1998), Temperature-gradient data for southwestern Utah obtained by Amax during the late 1970s and early 1980s, Energy and Geoscience Institute unpublished data.

Capuano, R., and Cole, D.R. 1982. Fluid-mineral equilibria in a hydrothermal system, Roosevelt Hot Springs, Utah. Geochimica et Cosmochemica Acta, 46, 1353-1364.

Chapman, D.S., Blackwell, D.D., Parry, W.T., Sill, W.R., Ward, S.H., and Whelan, J.A., 1978, Regional heat flow and geochemical studies in southwest Utah: U.S. Geological Survey Final Report, contract 14-08-0001-G-341, pp. 118.

Edwards, M.C. 2013. Geothermal resource assessment of the Basin and Range Province in Western Utah. Master of Science thesis, Department of Geology and Geophysics, University of Utah, December 2013, p. 213.

Gwynn, M., Blackett, B., Allis, R., and Hardwick, C., 2013. New geothermal resource delineated beneath Black Rock Desert, Utah. Proceedings, 39th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, February 11-13, 1511-1519.

Gwynn, M., 2015. Geothermal potential in the basins of East-Central and Southeastern Nevada. This volume, GRC Transactions.

Hardwick C.L., and Chapman, D.S., 2012. Geothermal resources in the Black Rock Desert, Utah: MT and gravity surveys. GRC Transactions, 36, 903-906.

Hardwick, C.L., Allis, R., andWannamaker, P., 2015. Observations and implications of magnetotelluric data for resolving stratigraphic reservoirs beneath the Black Rock Desert, Utah, USA. This volume, GRC Transactions.

Hintze, L.F., and Davis, F.D., 2003. Geology of Millard County, Utah. Bulletin 133, Utah Geological Survey, pp. 305.

McBride, J.H., Stephenson, W.J., and McBride, E.I.P., 2010. Reanalysis of the COCORP Utah Line 1 deep seismic reflection profile: toward an improved understanding of the Sevier Desert detachment question. Geosphere, 6, 840-854.

Raymer, L.L. Hunt, E.R., and Gardner, J.S., 1980. An improved sonic transit time-to-porosity transform. SPWLA 21st Annual Logging Symposium, July 8-11, pp. 13.

Sass, J.H., Priest, S.S., Blanton, A.J., Sackett, P.C., Welch, S.L., and Walters, M.A., 1999, Geothermal industry temperature profiles from the Great Basin: U.S. Geological Survey Open-File Report 99-425, on-line.

Schelling, D., Allis, R., and Sprinkel, D., 2013. Role of seismic reflection profiles in delineating basin-centered geothermal reservoirs. GRC Transactions, 37, 1051-1057.

Wannamaker, P.E., Maris, V., and Hardwick, C.L., 2013. Basin and rift structure of the central Black Rock Desert, Utah, and initial thermal implications, from magnetotellurics. GRC Transactions, 37, 41-44.

Wills, S., Anders, M.H., and Christie-Blick, N. 2005. Pattern of Mesozoic thrust surfaces and Tertiary normal faults in the Sevier Desert subsurface, west-central Utah. American Jour. Science, 305, 42-100.