Stratigraphic Reservoirs in the Great Basin— The Bridge to Development of Enhanced Geothermal Systems in the U.S.

Rick Allis[1], Bob Blackett[1], Mark Gwynn[1], Christian Hardwick[1], Joe Moore[2], Craig Morgan[1], Dan Schelling[3], and Douglas A. Sprinkel[1]

[1]Utah Geological Survey, Salt Lake City, Utah
[2]Energy and Geoscience Institute, University of Utah, Salt Lake City, Utah
[3]Structural Geology International, Salt Lake City, Utah

Keywords

Stratigraphic reservoirs, enhanced geothermal systems, geothermal resources, structure, stratigraphy, Great Basin, Basin and Range

ABSTRACT

Deep basins within the high heat flow parts of the Great Basin of the western U.S. may have stratigraphic reservoirs below about 3 km depth with temperatures of more than 150°C. These reservoirs are sub-horizontal and may be larger in area and geothermal power potential than the traditional fault-hosted hydrothermal reservoirs that have been developed in the past. The characteristics of two basins, Black Rock Desert, Utah, and north Steptoe Valley, Nevada are reviewed. Both basins have high temperatures and sufficient signs of stratigraphic permeability to justify more intensive investigation of their geothermal power potential. Other basins in the Great Basin appear to have similar characteristics and may also have significant potential. Stratigraphic reservoirs in the Great Basin could provide the next major increment in geothermal power production in the U.S.

Introduction

Over 25 geothermal systems have been developed in the Great Basin of Western U.S. with a total installed capacity of almost 1000 MWe (GEA website, 2012). Although the systems near the western and eastern boundaries of the Great Basin have the highest temperatures and clear magmatic associations (Coso, Long Valley, Steamboat Springs, Roosevelt, and, perhaps, Cove Fort), most systems in the interior seem to be predominantly non-magmatic (Kennedy and van Soest, 2007). The dominant heat source for these systems appears to be regionally high heat flow caused by extension and thinning of the crust of the Great Basin (Lachenbruch and Sass, 1978; Blackwell, 1983). Variations in the heat flow in the central Great Basin have been attributed to factors such as groundwater flow, thermal refraction, and crustal radioactivity. The corresponding sub-surface temperature is also very dependent on the thermal conductivity (or thermal resistance) of the rocks, with the Tertiary-Quaternary basin-fill sediments (unconsolidated Quaternary sediments and Tertiary sedimentary and volcanic rocks) typically having thermal conductivities about half that of common bedrock lithologies due to higher porosity, and therefore much higher temperature gradients. The unconsolidated basin fill therefore acts as a thermal blanket boosting underlying bedrock temperature by as much as 50°C for more than 2 km of fill.

Allis et al. (2011) pointed out that deep basins in the higher heat flow areas of the Basin and Range (especially the northern Great Basin) may have significant geothermal production potential where characteristically permeable bedrock formations, such as the widespread lower Paleozoic carbonate units, are present at depth (Heilweil et al., 2011, Massbruch et al., 2012). These sub-horizontal stratigraphic reservoirs (aquifers) contrast

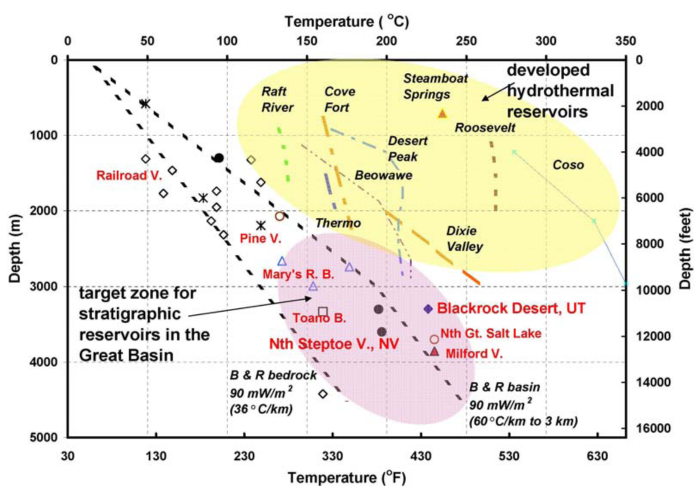

Figure 1. Compilation of selected thermal data from the Great Basin, Western U.S. Geothermal reservoirs are labeled in black italics. Corrected bottom hole temperatures (BHT) from oil and gas exploration wells are labeled in red (locations shown in Fig. 2). Black dashed lines are geotherms for 90 mW/m^2, assuming only bedrock from the surface (thermal conductivity = 2.5 W/m °C), and 3 km of sediment (thermal conductivity = 1.5 W/m °C) overlying bedrock. Black Rock Desert and North Steptoe Valley are highlighted.

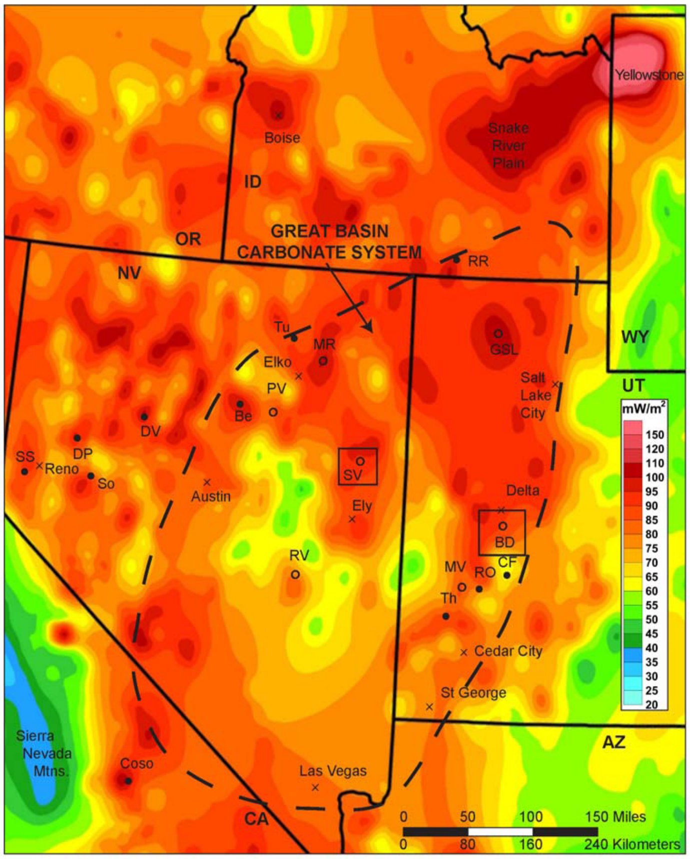

Figure 2. Great Basin, Western U.S., with Paleozoic carbonate province outlined, and a heat flow layer derived from Blackwell et al., 2011. Features in Fig. 1 are located, with geothermal reservoirs shown as a black dot, and oil exploration wells or areas shown as open circle. The two boxes labeled SV (Steptoe Valley) and BD (Blackrock Desert) are the focus of Figs. 4 – 9. Abbreviations: SS Steamboat Springs, So Soda Springs, DP Desert Peak, DV Dixie Valley, Be Beowawe, Tu Tuscarora, MR Mary's River Basin, RV Railroad Valley, RR Raft River, GSL Great Salt Lake, CF Cove Fort, RO Roosevelt, MV Milford Valley, Th Thermo.

with the more traditional near-vertical reservoirs associated with normal faulting. McNitt (1995) also pointed out that many of the developed, non-volcanic geothermal reservoirs in the Great Basin appear to be significantly larger than the fault zone that controls the leakage of thermal waters to the near-surface. He suggested that tilted bedrock units in the extended terrain were also important for influencing fluid flow from depth.

Fig. 1 shows temperature profiles from selected developed geothermal reservoirs in the Great Basin. The profiles are typically from the deepest, hottest wells in each development. In many cases the productive reservoirs lie between about 1 – 2 km depth, and range between about 150 and 250°C. Also shown on this figure are two geotherms for a heat flow of 90 mW/m^2 assuming bedrock to the surface, and 3 km of basin fill on top of bedrock. Bottom hole temperatures (BHTs) from selected basins with at least 2 km of basin fill in the Great Basin are also shown on Fig. 1 (Utah Geological Survey [UGS], work in progress). The locations of these basins are superimposed on the heat flow map of Blackwell et al., (2011) (Fig. 2). Fig. 1 shows that if stratigraphic reservoirs can be found at 3 – 4 km depth, then the temperatures of 150 – 250°C indicate a potential geothermal resource suitable for development. Such reservoirs should be much larger in area and possibly have larger potential than a normal fault-hosted reservoir at similar temperatures. The sub-horizontal, tabular reservoirs beneath the centers of basins are an obvious exploration target complementing the search for traditional hydrothermal upflows along range-bounding faults in the Great Basin.

Two critical questions are whether good reservoir permeability (i.e., ~ 100 mD) can be found at this increased depth, and whether the costs of deeper drilling still allow for viable development. Both topics are currently being investigated as part of a DOE-funded project at the University of Utah and the UGS. A preliminary compilation of permeability data from both groundwater hydrology and oil and gas databases suggests that there is no obvious reason why good permeability cannot be found at depths up to 5 km (Fig. 3; data from NETL, 1999 GASIS; Belcher et al., 2001, and USGS Nevada Water Science Center website). Temperature also may not be a factor limiting permeability at depths of 3 – 5 km. The Mississippian dolomite reservoir in the Madden play of northern Wyoming has temperatures of 200 – 225°C at 6 – 7 km depth and good permeability (Dyman and Cook, 1998; Williams, 2000). However, as in all geothermal reservoirs with temperatures of ~ 200°C, hydrothermal alteration and the presence of primary or secondary clay mineralogy will be important in determining reservoir quality (permeability). We suspect relatively "clean" lithologes such as carbonates and quartzites will be preferred targets over mixed siliclastic rocks. Reservoir permeability enhancement techniques that are now common in the oil industry will likely be required for optimizing performance of geothermal stratigraphic reservoirs.

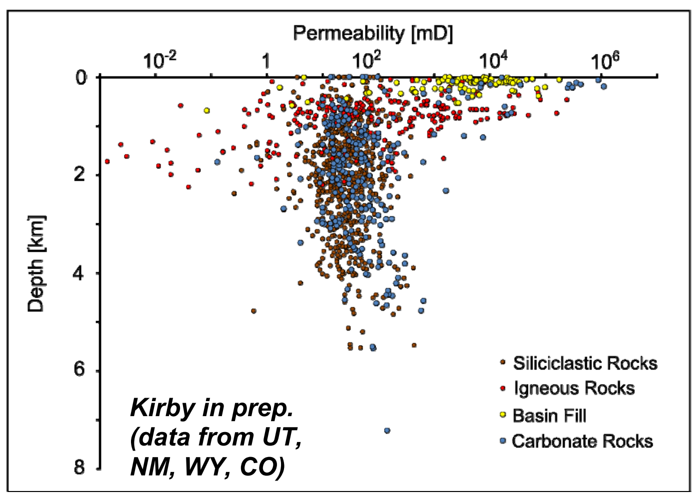

Figure 3. Compilation of permeability data for Utah, New Mexico, Colorado, and Wyoming, derived from both oil and gas well test results, and groundwater test results.

In this paper we investigate the geothermal potential of two basins in the Great Basin with high heat flow (Black Rock Desert, Utah, and north Steptoe Valley, Nevada – map outlines on Fig. 2). Both appear to have adequate temperature and prospective stratigraphic targets that make them attractive for more intensive exploration. Many more such targets exist in the Great Basin, so understanding the characteristics of these basins should help identifying and evaluating more of them.

Black Rock Desert, Utah

Temperature

The Black Rock Desert is situated near the eastern boundary of the Great Basin, and at the northern end of what is informally known as the Sevier thermal anomaly adjacent to that boundary (Fig. 4). A north-trending gravity low of about -30 mgal in amplitude indicates a basin containing about 3 km of Tertiary to Recent basin fill with Paleozoic bedrock underneath (Hardwick and Chapman, 2012). Arco Oil and Gas Company drilled two exploration wells in the early 1980s near the deepest part of this basin (Pavant Butte 1 and Hole-n-Rock 1), and confirmed 2.8 – 3.0 km of sedimentary basin fill resting on top of lower Paleozoic units. Corrected BHTs are shown in Fig. 5 for Pavant Butte 1 and two wells on the west side of the basin (Cominco Federal-2 and Chevron Black Rock Federal 1-29, located on Fig. 4). Temperatures at 3 km depth are significantly higher in Pavant Butte 1 than the other two wells. This is primarily due to the much greater thickness of sedimentary fill drilled in Pavant Butte 1 (i.e., low thermal conductivity), but there is also a smaller effect due to an apparent increase in heat flow towards that well (85 to 100 mW/m^2). The geotherms on this figure are derived from characteristic thermal conductivities for all three wells based on the observed lithologies. Unfortunately, BHTs in the Hole-n-Rock well appear to be too low and unreliable due to extensive loss of drilling fluids into the host rock. Several thermal gradient wells up to 500 m depth have been drilled in the northern Black Rock Desert (Figs. 4 and 5). They show gradients consistent with the geotherm for Pavant Butte 1 (gradients of 60 – 100°C/km). There are a few thermal gradient wells in the southern Black Rock Desert that range in depth from 70 - 90 m and indicate gradients of 40 – 70°C/km. Additional thermal gradient wells will be drilled later this summer, so until then it is unclear whether the temperature at 3 km depth beneath the southern Black Rock Desert is as high as that in the north.

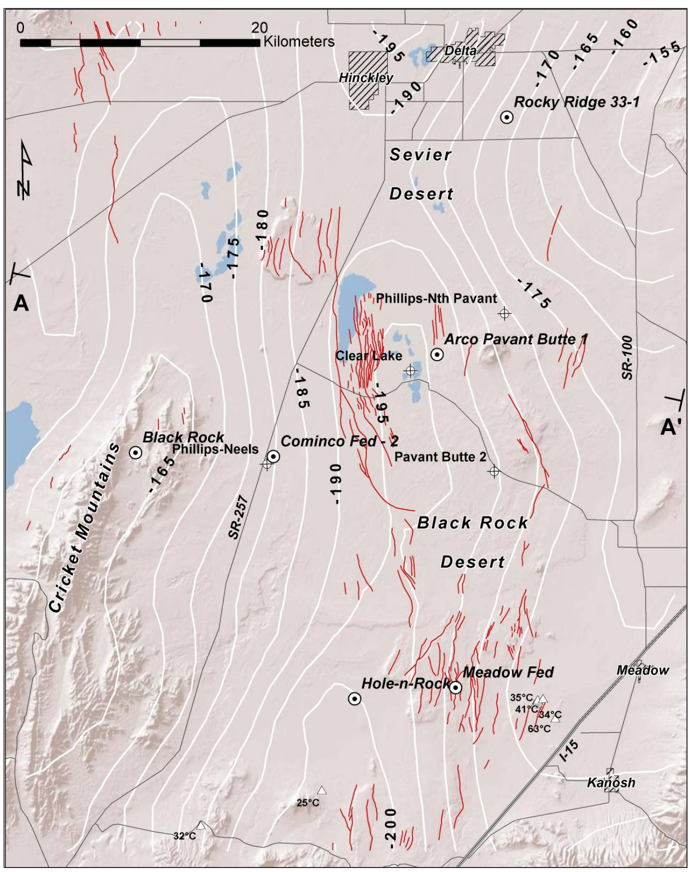

Figure 4. Location of the Blackrock Desert, which is a basin filled with up to 3 km of relatively unconsolidated Tertiary-Quaternary sediments. Deep oil exploration wells shown with circle and dot, shallow thermal gradient wells shown with circle and cross (temperatures on Fig. 5). Warm springs (triangles) and Quaternary faults (red lines) are from Utah Geological Survey databases. White contours are the Bouguer gravity anomaly (5 mgal interval).

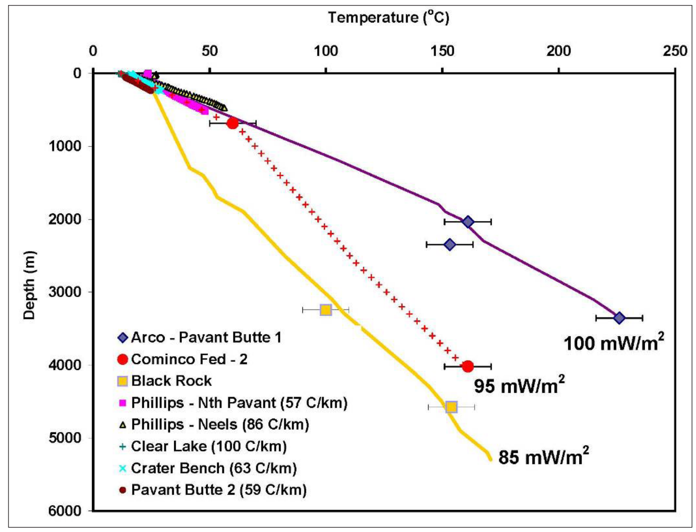

Figure 5. Corrected bottom hole temperatures from three deep wells and five thermal gradient wells along the west-east profile across the Blackrock Desert (identified in Fig. 4). Arco-Pavant Butte 1 has 2990 m of unconsolidated sediment Paleozoic bedrock, whereas Cominco Federal 2 has 500 m of sediment, and Chevron Black Rock Federal 1 has less than 100 m of sediment. Geotherms for the three deep wells have been calculated assuming characteristic thermal conductivities for the lithologies.

Bedrock Stratigraphy

Figs. 6a and b show the detailed stratigraphy of the Pavant Butte 1 and Hole-n-Rock 1 wells based on a reinterpretation of the logging data. The purpose was to characterize the bedrock geology and look for evidence of significant permeability. In the case of Pavant Butte 1, 400 m of bedrock was drilled beneath the Sevier Desert reflector, with modest mud losses and possible fractures apparent in the limestone units at 3020 – 3081 m depth, and possible fractures in the quartzite at 3268 – 3276 m depth. Porosities derived from sonic logs ranged from very low to about 15%.

The Hole-n-Rock 1 well drilled 580 m of bedrock and encountered considerable drilling circulation losses and evidence of fractures in limestone and dolostone units (Fig. 6b). Several cores were fractured to highly fractured. Matrix permeability measurements on the limestone and dolostone ranged from less than 0.1 mD to 7 mD, but these are not representative of the in situ fracture permeability. Neutron-derived porosities between 0 and 20% were interpreted between 2776 and 2928 m. A drill stem test (DST) from a perforated zone between 3145 and 3168 m depth indicated a pressure close to hydrostatic from the ground surface

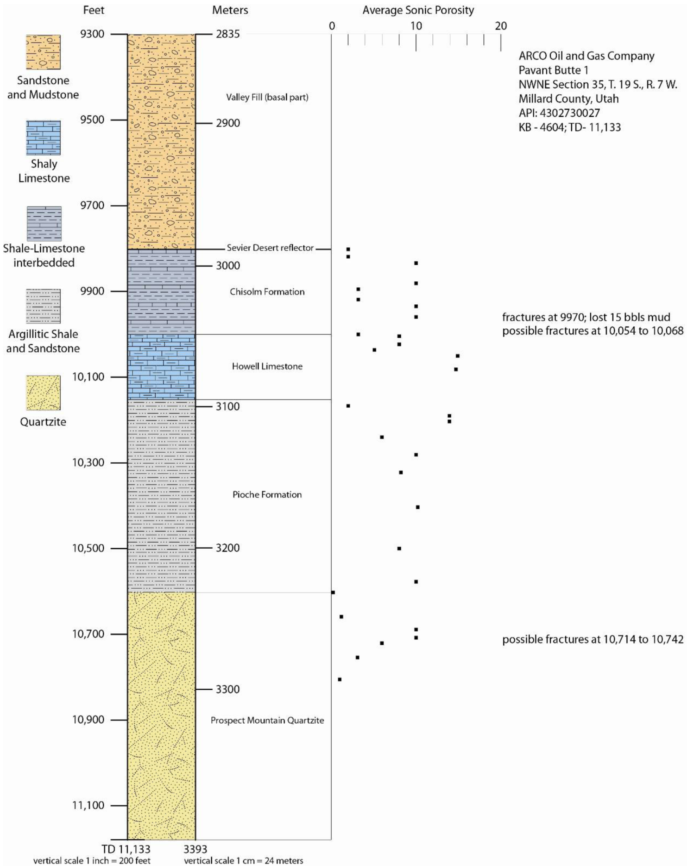

Figure 6a. Detailed stratigraphy of the bedrock section from exploration well Arco-Pavant Butte 1 in northern Black Rock Desert.

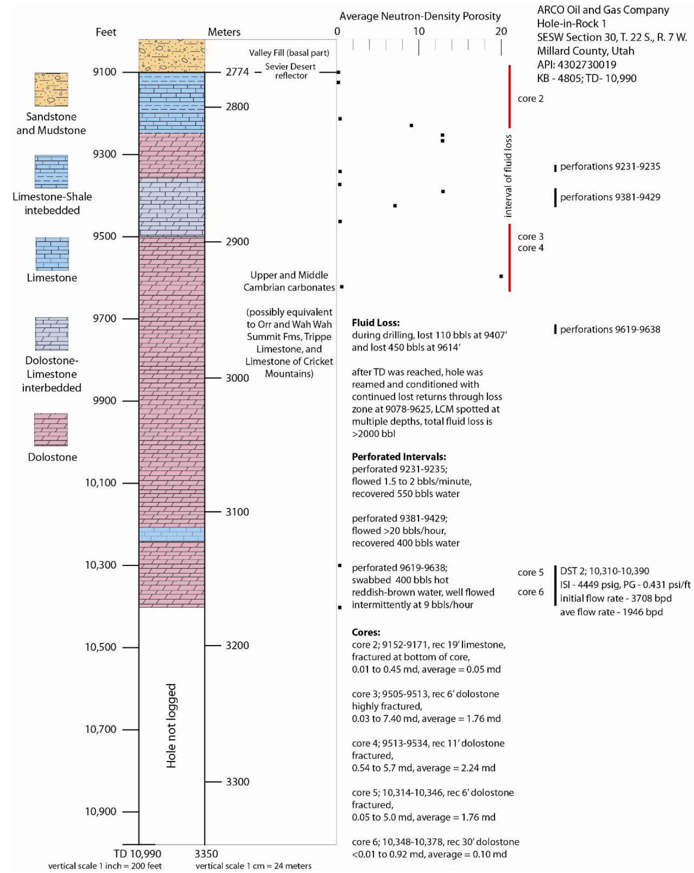

Figure 6b. Detailed stratigraphy of the bedrock section of oil exploration well Arco Hole-n-Rock 1 in the southern Black Rock Desert.

and a permeability of 42 mD. Flow-testing at several intervals between 2800 and 3200 m depth was unfortunately insufficient to characterize the potential productivity of this bedrock section.

Structural cross sections across northern Black Rock Desert and extending into eastern Nevada have been constructed based on reprocessed Cocorp seismic data, well data from the oil exploration industry, and surface geology. Figs. 7 and 11 show details from the interpreted seismic profiles and structural cross sections which cross the two basins discussed here. For the northern Black Rock Desert, Utah Cocorp line 1 was used as the basis for the geological interpretation shown along the associated structural cross section, which is located roughly 10 km south of the Cocorp seismic line and that crosses the Pavant Butte 1well (A-A' in Fig. 4). Formation tops from the Cominco Federal 2 and Chevron Black Rock wells were used as additional control for cross section construction. The reprocessed, interpreted seismic profile is shown on Fig. 7a, and the interpreted structural cross section detail is shown in Fig. 7b. A dominant reflector package on Cocorp line 1 is known from well-control to define a major break between the lower Paleozoic bedrock and Paleogene to Recent sedimentary fill. Some consider this feature as a detachment fault (Sevier Desert detachment), as interpreted on this cross section, but whether an active detachment exists at 3 km depth beneath Black Rock Desert remains controversial (Anders and Christie-Blick, 2011). Farther west and down-dip along this prominent reflector (location of Black Rock well) is a stack of thrust packages related to Sevier-age crustal shortening. Beneath the Sevier (Black Rock) Desert reflector is 3 km of lower Paleozoic and Precambrian sedimentary rocks, so the critical question is whether any units in this package have the characteristically high permeability that is seen in deep oil and groundwater wells as shown in Fig. 3.

North Steptoe Basin, Nevada

Temperature

Several deep oil exploration wells and two geothermal exploration wells have been drilled in north Steptoe Valley (Fig. 8). Hunt Energy Corporation carried out intensive exploration for a geothermal resource on the west side of the valley adjacent to the northern end of the Egan Range where the late Quaternary Steptoe Valley fault system jogs west to the Cherry Creek Range (Redsteer and Anderson, 2000). This exploration included 40 thermal gradient wells, many to 150 m and some to 600 m, and two wells to 1400 m (37-23) and 3300 m (74-23). Temperature information for these wells was extracted from Chovenac (2003), with the 90-day static profile in Hunt Energy well 74-23 supplied by SMU thermal lab (M. Richards, pers. comm.)

The deepest well in this basin was drilled by Placid Oil Company (Steptoe Federal 17-14), reaching a depth of 3600 m and a corrected bottom hole temperature of 200 °C. The geotherm for this well (95 mW/m^2) has a very similar shape to the static profile in the Hunt 74-23 well (Fig. 9). The basin fill in the 74-23 well was 1600 m thick and 2090 m in well 17-14 (fluvial-lacustrine

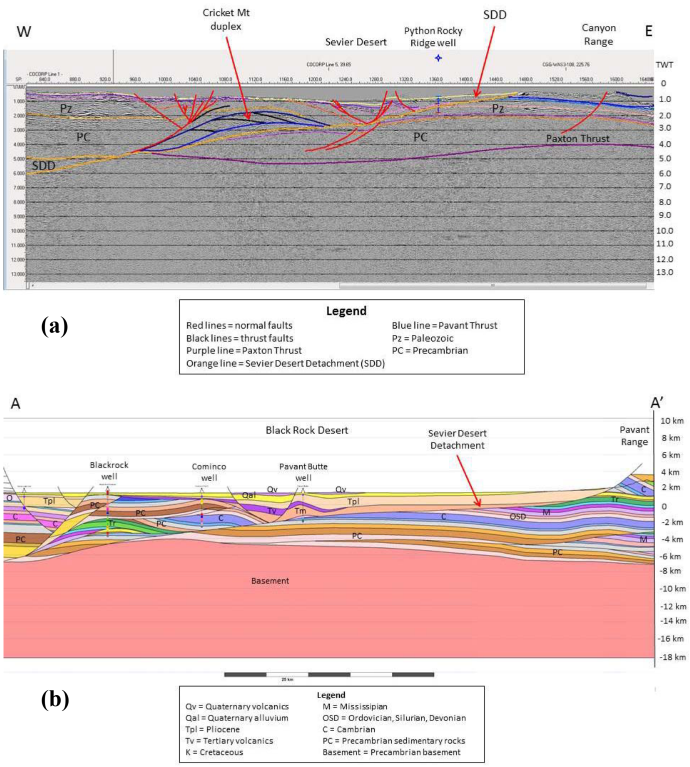

Figure 7. (a) Interpreted seismic profile from reprocessed Utah Cocorp Line 1. (b) Detailed structural cross section constructed using interpreted seismic line Utah Cocorp 1 and formation tops from oil exploration wells. Ravant Butte well = Pavant Butte 1, Cominco well = Cominco American Federal 2, Blackrock well = Chevron Black Rock Federal 1-29. Tpl = Pliocene, Tr = Triassic.

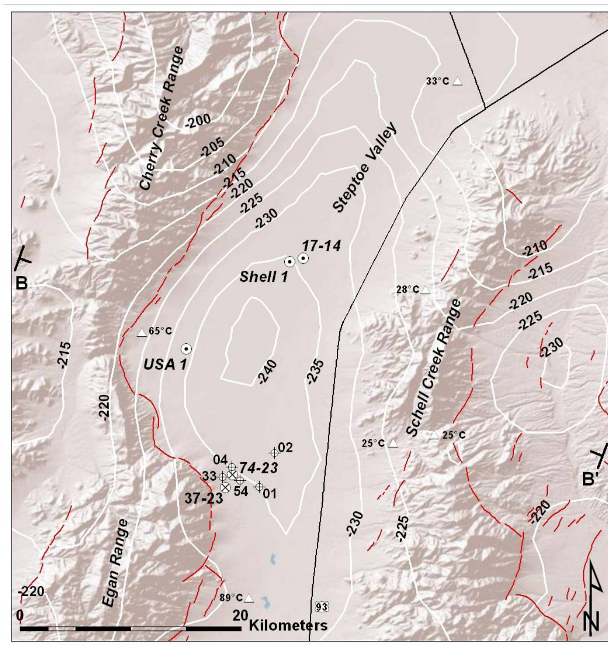

Figure 8. Northern Steptoe Valley, Nevada, showing wells with temperature information used in Figure 9. Circles with dots are abandoned oil exploration wells, circles with diagonal crosses are geothermal exploration wells, and smaller circles with vertical crosses are relatively shallow thermal gradient wells. Triangles are warm springs, and red lines are Quaternary faults. Contours are Bouguer gravity with 5 mgal interval. 17-14 = Placid Steptoe Federal 17-14, USA 1 = LL&E,USA - Steptoe Valley 1.

sediments and volcanics). The bedrock thermal gradient in these two wells is 42 °C/km, and the gradient wells drilled by Hunt Energy indicated 65 – 85°C/km between 300 and 600 m depth. As in the Black Rock Desert, this decrease in thermal gradient with increasing depth is due to the low thermal conductivity of the basin fill compared to bedrock conductivity. The similarity in the thermal regime between the Hunt wells to the south and the Shell - Placid wells to the north indicates the whole of this basin in north Steptoe Valley, extending at least 20 km in a north-south direction, has a similar thermal regime.

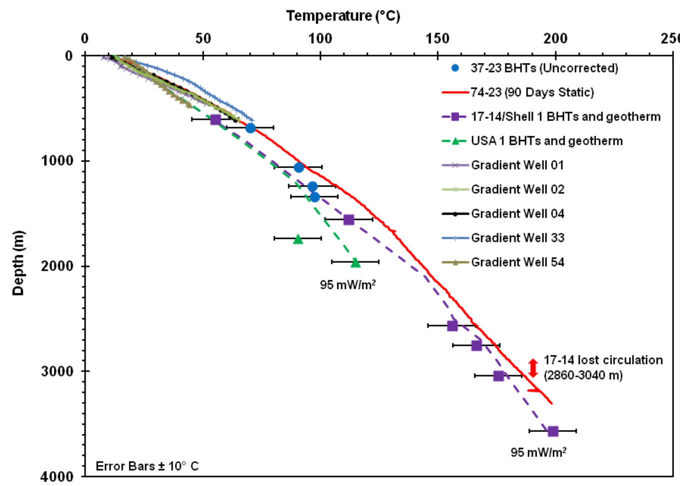

Figure 9. Temperature data from wells in north Steptoe Valley (located on Fig. 8).

The Bouguer gravity contours in Fig. 8 are a poor representation of the valley fill because of the wide station spacing and smoothing of the local gravity gradients. The data are taken from the national database (PACES) maintained by University of Texas, El Paso. However, some gravity measurements by both Hunt Energy and by Chovenac (2003) show much steeper gradients. According to these references, the location of well 74-23 is 15 mgal lower than the gravity value at the adjacent range front, and this is consistent with the depth to bedrock in the well given a reasonable density contrast between bedrock and basin fill (500 kg/m^3). This is a good example of how the density of gravity data needed for reservoir definition (ideally at least 4 stations / km^2) needs to be significantly higher than what is often in the national database in the Great Basin, a point also made by McNitt (1995).

Bedrock Stratigraphy

The detailed stratigraphy for Placid Steptoe Federal 17-14 is shown in Fig. 10. The bedrock section of almost 1500 m is predominantly limestone and dolostone extending to a total depth of 3570 m. Porosities vary between 0 and 20%, and a major loss zone was encountered near the interpreted base of the Guilmette Formation and the top of the underlying Simonson Dolomite at about 2900 m depth. Both these formations are known to have regionally high permeabilities, and often represent major groundwater aquifers where they occur at shallower depth (Heilweil and Brooks, 2011). This well shows they also have high permeability at depth.

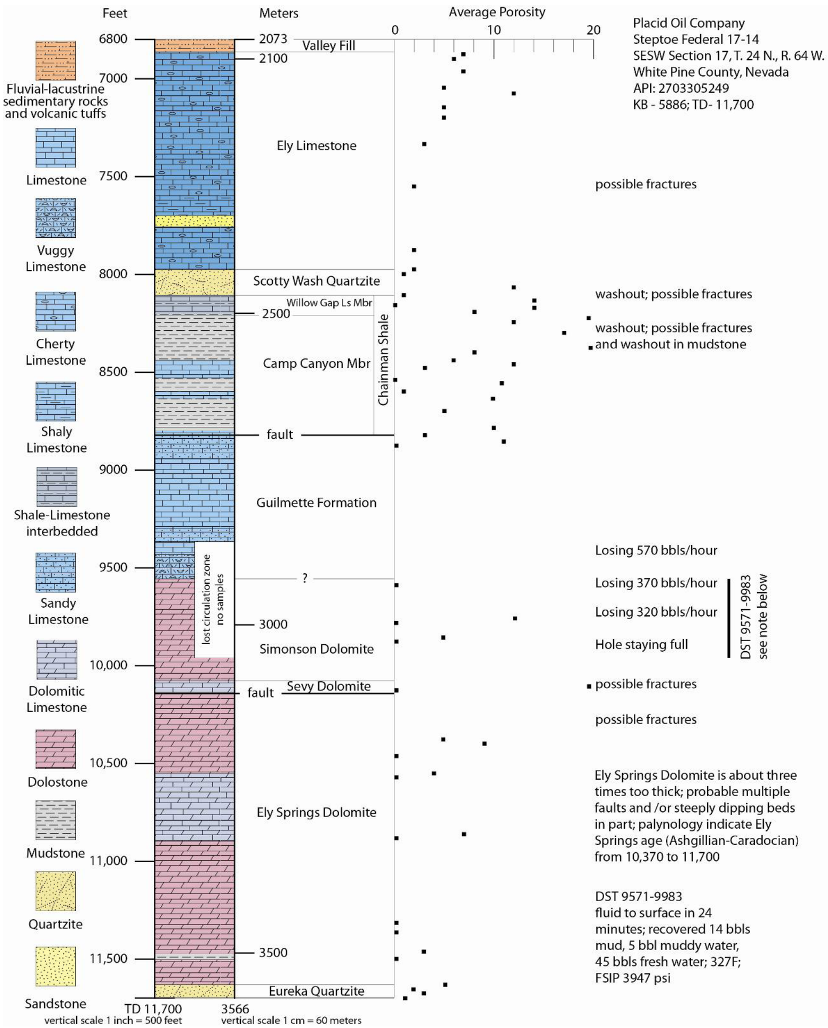

Figure 10. Detailed stratigraphy of bedrock section of oil exploration well Placid Steptoe Federal 17-14 in northern Steptoe Valley, Nevada.

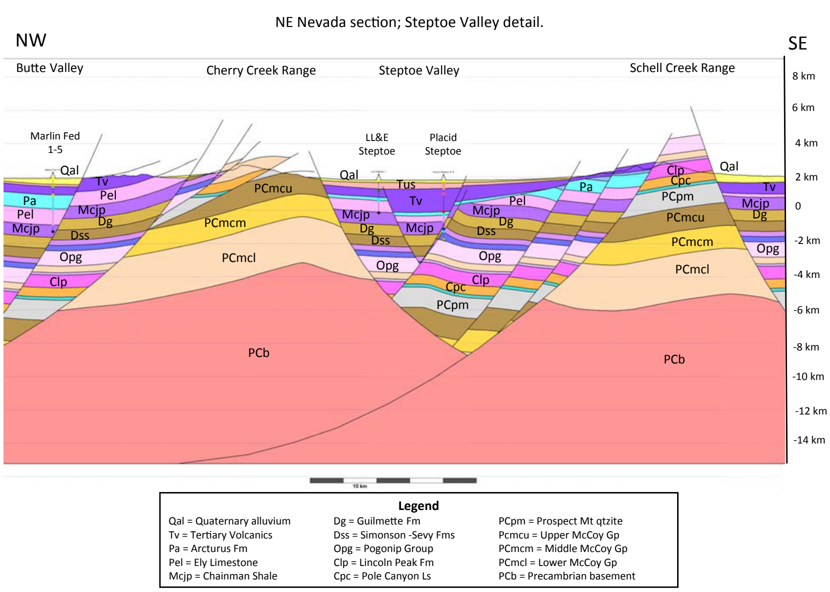

Figure 11. Detailed structural cross section across the Steptoe Valley constructed using Nevada Cocorp seismic line 4 and formation tops from oil exploration wells.

The structural interpretation for north Steptoe Valley is shown in Fig. 11 (B-B' on Fig. 8), based in part on data from the Nevada Cocorp line 4. The quality of the seismic imagery on this line is poor, so the interpretation is more heavily based on known well penetrations in oil wells and known stratigraphy from outcrops in the adjacent ranges. Another 3 km of section from Ordovician to the Precambrian occurs beneath the bottom of well 17-14.

Conclusions

In the two basins considered here, the heat flow is sufficiently high (90 – 100 mW/m^2), and the basin fill deep enough (> 2 km) for temperatures of 170 to 230°C to occur at about 3 km depth. The location of the highest heat flow in the Black Rock Desert has not yet been determined, and should be clarified this summer when several thermal gradient wells are drilled into the basin. Unfortunately, the available thermal data is mostly in the northern Black Rock Desert, so the thermal regime farther south remains uncertain. The Arco Hole-n-Rock 1 well in the south encountered significant permeability in Upper Cambrian carbonate units between 2.8 and 3.0 km depth, so if the thermal regime is similar to that in the north, this could be a stratigraphic reservoir worthy of further investigation as a development prospect. Similarly, in north Steptoe Valley, the Placid 17-14 well had a major loss zone between 2.9 and 3.1 km depth coinciding with carbonate formations known for their high permeability. The area of this basin (at least 100 km^2 with more than 2 km of basin fill) also indicates the bedrock beneath the basin may have substantial geothermal potential.

Deep temperatures where bedrock crops out in the ranges adjacent to the basins are typically much cooler due to the absence of the thermal blanketing effects of unconsolidated basin-fill sediments. At Black Rock Desert the temperature at 3 – 4 km underneath the Cricket Mountains is between 50 – 100°C cooler than that in the Pavant Butte1 well. Near the edges of the basins there will be a transitional thermal regime, complicated by the effects of thermal refraction due to the conductivity contrast, and possibly also by localized fluid movement on range-bounding faults (Blackwell, 1983). An interesting question is the state of the deep thermal regime within the sedimentary bedrock sections beneath the two basin and range systems investigated here. In both basins, the consolidated sedimentary bedrock section (Paleozoic to Precambrian) extends at least another 3 km, and based on extrapolation of the conductive thermal gradients observed in the deep wells near the basin centers, the temperature at the base of the sections could be close to 300°C at about 6 km depth. The geometry of the basin fill - bedrock interface will be an important control on this thermal regime, as will be the occurrence and nature of permeability (i.e., fault or stratigraphic) and possible fluid flow. This will be studied later in the project.

This paper is a progress report on whether sedimentary basins in the U.S might have significant geothermal power potential. Our initial findings for these two high-heat flow basins in the eastern Great Basin are that both may have the required temperature and permeability to justify more detailed exploration efforts. Our cursory examination of several other basins in the Great Basin suggests that other basins also have this potential. Based on this, stratigraphic reservoirs in the Great Basin could provide the next major increment in geothermal power production in the U.S.

Acknowledgements

This study is funded by The UGS and DOE (Award DE-EE0005128). Discussions and data from the SMU thermal lab helped clarify the thermal potential of the Great Basin. Jay Hill (UGS) assisted with several of the figures.

References

Allis, R., Moore, J., Blackett, R., Gwynn, M., Kirby, S., and Sprinkel, D. S. 2011. The potential for basin-centered geothermal resources in the Great Basin. GRC Transactions, 35, 683-688.

Anders, M.H., and Christie-Blick, N. 2011. Is the Sevier Desert reflection of west-central Utah a normal fault? Geology, 22, 771-774.

Belcher, W.R., Elliott, P.E., and Geldon, A.L. 2001. Hydraulic-property estimates for use with a transient ground-water flow model of the Death Valley regional ground-water flow system, Nevada and California. USGS Water Resources Investigations 01- 4210.

Blackwell, D.D. 1983. Heat flow in the northern Basin and Range Province. Geothermal Resources Council Special Report no. 13, 81-92.

Blackwell, D.D., et al., 2011 Heat flow map of the conterminous United States, Google.org/egs, 2011.

Chovenac, Y.M. 2003. Geothermal analysis of Schellbourne, east-central Nevada, Steptoe Valley. MS Geology thesis, University of Texas, Arlington.

Dyman, T., and Cook T. 1998. Summary of deep oil and gas wells in United States through 1998, Chapter B, prepared in cooperation with Department of Energy-National Energy Technology Laboratory and Gas Technology Institute, U.S. Geological Survey, Dept. of Interior.

GEA, 2012. Geothermal Energy Association website information, including 2012 report: http://www.geoenergy.org/reports/2012AnnualUSGeothermalPowerProductionandDevelopmentReport_Final.pdf

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

Heilweil, V.M., and Brooks, L.E., eds., 2011. Conceptual model of the Great Basin carbonate and alluvial aquifer system. U.S. Geological Survey Scientific Investigations Report 2010-5193, 191 p.

Kennedy, M.B., and van Soest, M.C. 2007. Flow of mantle fluids through the ductile lower crust: helium isotope trends. Science, 318, 1433-1436.

Lachenbruch, A.H., and Sass, J.H. 1978. Models of extending lithosphere and heat flow in the Basin and Range Province. In: Smith, R.B., and Eaton G.P. (eds.) Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, AGU Memoir 152, 209 – 250.

Massbruch, M.D., Heilweil, V.M., Brooks, L.E., and Allis, Rick 2012. Implications of deep groundwater flow in the eastern Great Basin for evaluating geothermal potential. GRC Transactions, 36.

McNitt, J. 1995. A new model for geothermal exploration of non-volcanic systems in extended terrains. GRC Transactions, 25, 115-118.

NETL, 1999. GASIS Release 2, oil and gas well test results. Department of Energy. Morgantown.

Redsteer, M.H., and Anderson, R.E., compilers, 2000. Fault number 1272, Steptoe Valley fault system, in Quaternary fault and fold database of the United States: U.S. Geological Survey website, http://earthquakes.usgs.gov/regional/qfaults

Williams, P., 2000. Wyoming Oil and Gas Investor, March 2000 Issue, p. 30-41.