Role of Seismic Reflection Profiles in Delineating Basin-Centered Geothermal Reservoirs

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Keywords

Geothermal reservoirs, seismic reflection surveys, basins, exploration, Great Basin, western U.S.

ABSTRACT

Seismic reflection techniques have not proved very useful in delineating hydrothermal reservoirs in the Great Basin due mainly to the challenging geologic setting of interlayered fan and playa deposits adjacent to steeply down-faulted bedrock. However, basin-centered geothermal reservoirs in the Great Basin offer a much simpler sedimentary setting with sub-horizontal reflectors analogous to most large oil and gas producing basins where seismic reflection imaging is a powerful exploration technique. A review of 1980s-vintage, public-domain COCORP seismic surveys in western Utah and eastern Nevada allows construction of balanced structural cross sections. Important constraints were stratigraphic information derived from numerous nearby oil exploration wells, and outcrop geology exposed in the ranges. Examples are shown for two regions - Black Rock Desert, Utah, and North Steptoe Valley, Nevada - where geothermal reservoirs appear to be located at about 3 km depth. Subsequent evaluation of selected industry seismic reflection data collected over the last 40 years from western Utah and Nevada indicates variable quality, but a potentially valuable data resource for more detailed structural and stratigraphic analysis of basin-centered Paleozoic reservoirs. In some basins there are multiple seismic lines available to be licensed for these studies, making 3D structural modeling of the basins and their associated faults possible at a fraction of the cost of new seismic data acquisition. The Black Rock Desert, Marys River Basin, and North Steptoe Basin are identified as obvious geothermal reservoir targets where industry seismic reflection data will be helpful. A summary map is presented for the Great Basin showing the location of past industry seismic reflection lines and an overlay of major basins derived from gravity surveys. When combined with thermal gradient and heat flow measurements allowing the prediction of the temperature at 3 – 4 km depth, these three geophysical techniques (seismic reflection, gravity, and heat flow) are a powerful tool for prioritizing basin-centered reservoirs most suitable for future power development.

Introduction

Temperatures of more than 150 °C can found at depths of 3 – 4 km in high-heat-flow basins (more than 80 mW/m^2; Allis et al. 2011, 2012, 2013). The largest area within the U.S. having regionally high heat flow is the Great Basin, and this has been identified as the most likely future area for large-scale geothermal power generation (Figure 1). In many basins within the Great Basin of the western U.S., 1 – 3 km of unconsolidated Tertiary-Recent basin-fill sediments overlie several additional kilometers of consolidated, Paleozoic – Precambrian sediments

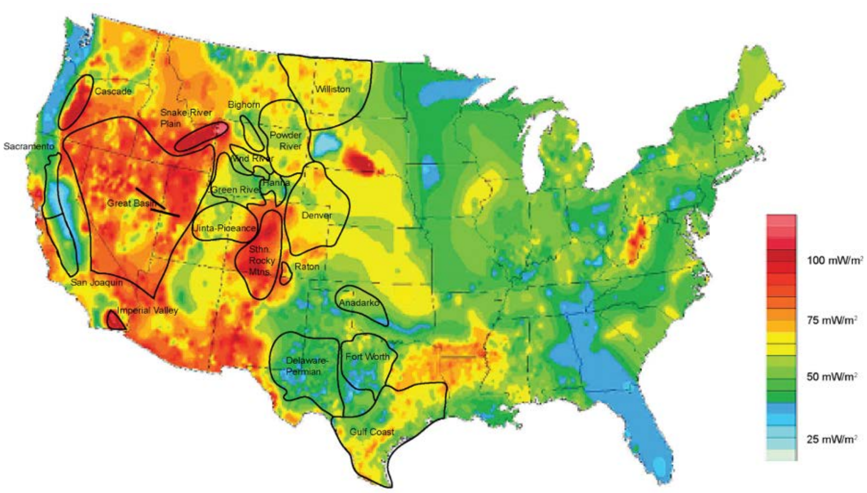


Figure 1. Basins and regions of the western U.S. that have been considered for geothermal power development by Tester et al., (2006; EGS reservoir potential) and by Allis et al. (2013; basin-centered reservoir potential). Colors refer to regional heat flow (Blackwell et al., 2011). The two black lines within the eastern Great Basin are the two seismic profiles in Figure 2.

along with intrusive and/or metamorphic rocks. Some of these older "bedrock" units are known to have characteristically high permeability and may represent geothermal reservoirs. In contrast to relatively steeply-dipping fault systems at the basin margins which sometimes host hydrothermal systems, sub-horizontal stratigraphic units may also represent geothermal reservoirs. Such reservoirs may have relatively large areas (~ 100 km^2) compared to many hydrothermal systems (less than 10 km^2), and therefore they may have electric power potentials of hundreds of megawatts (MW).

The Great Basin is structurally complex, having undergone both pre-Tertiary compressional deformation (during the Paleozoic Antler and Cretaceous Sevier orogenies) and Tertiary extensional deformation. In addition, significant lateral changes in the stratigraphy are present due to the predominance of shelf sedimentation during much of the Paleozoic in the eastern Great Basin, and deeper water sedimentation further west during that time. This paper investigates whether potential stratigraphic reservoirs beneath the central parts of basins of the Great Basin may be identifiable and mapped with seismic reflection techniques, especially when coupled with information from existing, deep exploration wells and outcrop geology adjacent to the basins. Although seismic reflection data acquisition is standard practice in oil exploration, it is relatively expensive for geothermal exploration, and has often not been very helpful for exploration of hydrothermal systems in the Great Basin. One reason may be the sub-vertical nature of many hydrothermal reservoirs and the challenging geologic setting of interlayered fan and playa deposits adjacent to steeply down-faulted bedrock. However, there is a surprising amount of existing seismic reflection data traversing basins and ranges within the Great Basin, acquired as part of past oil exploration efforts, which is available to be licensed. This is obviously a much less expensive option than acquiring new seismic data if the profiles traverse basins of interest and the data quality is adequate for delineating sub-horizontal basin-centered reservoirs.

This study is in two parts: firstly, two public-domain COCORP seismic reflection profiles acquired in the 1980s from western Utah and eastern Nevada are interpreted together with adjacent well data; secondly, proprietary, industry seismic profiles from selected areas of the Great Basin, where there may be basins with geothermal potential, have been inspected to gauge the availability, quality, and the cost of acquiring (licensing) access to the data. In the first part, we restrict the discussion to one section of each profile where a basin exists having known geothermal potential (more than 175 °C at less than 4 km depth; Allis et al., 2013). Both parts of this study suggest that existing seismic reflection data in the Great Basin may offer a valuable dataset for geothermal exploration.

Interpreting COCORP Profiles

Based on early indications of elevated bottomhole temperatures in several oil exploration wells in the Black Rock-Sevier Desert, western Utah, and the northern Steptoe Basin, eastern Nevada (Allis et al., 2011), two structural cross sections using COCORP seismic profiles were constructed. The first structural cross section, called the Pavant Butte Section in this study, was constructed between the Wasatch Plateau of central Utah to the east and the Cherry Creek Range of eastern Nevada to the west (Figure 2; COCORP profiles Utah 1 and NV 5). The Pavant Butte structural section crosses the Black Rock (Sevier) Desert at the Arco-Pavant Butte well, where high subsurface heat flows have been identified, and where Tertiary rocks like directly on early Paleozoic carbonates. The second structural cross section, called the Steptoe Section, has been constructed in a northwest-southeast orientation between the Confusion Range of far-western Utah and the Cortez Mountains of north-central Nevada (Figure 2; COCORP profiles NV 5, NV 4, and NV 6). This latter cross section was positioned to make use of the three COCORP seismic lines, and to cross Tertiary basins of northeastern Nevada having high heat-flow values, including the northern Steptoe Valley.

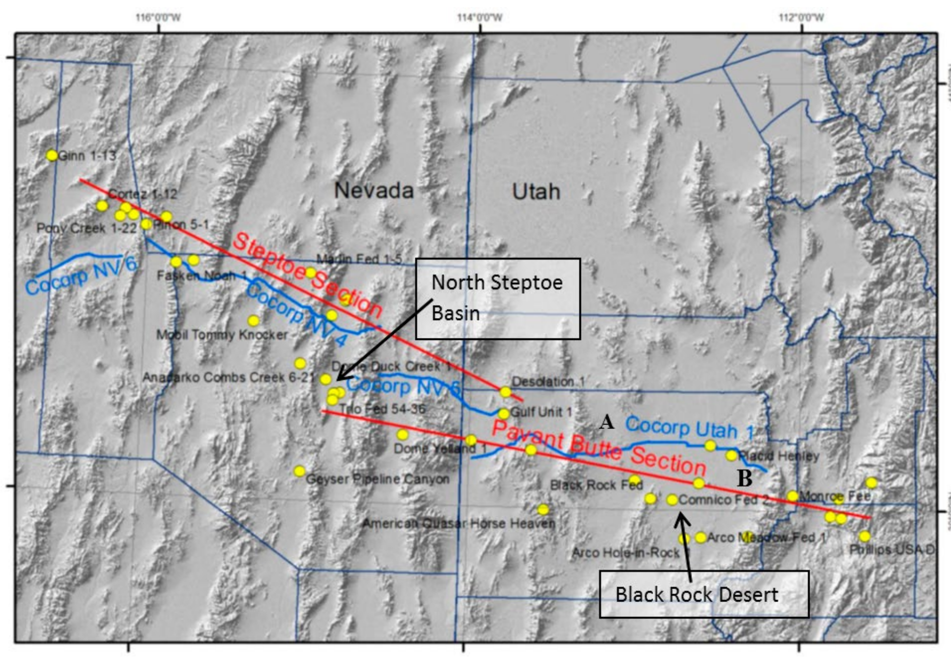


Figure 2. Shaded -relief map of western Utah and northeastern Nevada showing the locations of the structural cross sections constructed during this study (red lines), COCORP seismic lines available for interpretation (blue lines), and wells used for structural analysis. A – B marks the ends of the seismic interpretation shown in Fig. 3a.

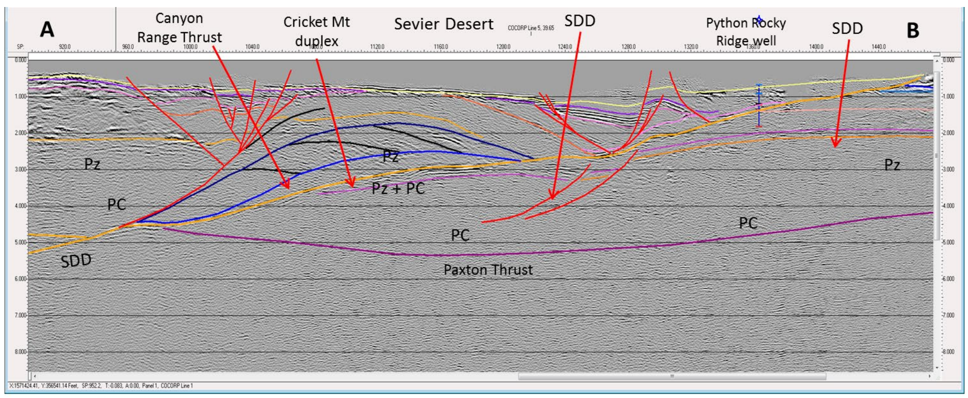
The construction of detailed structural cross sections involves the incorporation of available surface and subsurface data, and an understanding of structural styles and systems in the area of interest. Surface geological and structural data available for western Utah and northeastern Nevada has been obtained from numerous geological maps published by the U.S. Geological Survey, the Utah Geological Survey, and the Nevada Bureau of Mines and Geology. Structural data, including strike and dip data, were digitized by Structural Geology International for later import into

Lithotect™ , the software used in the construction of the Pavant Butte and Steptoe structural cross sections. Subsurface data used during the present study include a small amount of proprietary (industry data available to Structural Geology International) and non-proprietary (COCORP) reflection seismic profiles, and well data (primarily formation top penetrations) from wells drilled near the structural cross sections (Figure 2). Seismic interpretation of the COCORP and proprietary data was undertaken by D. Schelling using the IHS Kingdom Suite software, and was imported into the Lithotect software package from Halliburton for additional structural analysis. The COCORP seismic profiles had been reprocessed by Wolverine Oil and Gas Corporation and generously made available to Structural Geology International for construction of these cross sections. Surface and subsurface data, including well-borehole and formation-top data, surface strike and dip data, and seismic interpretations, were then projected into the lines of section for the two structural cross sections. Where interval velocity data were available, seismic interpretations were converted from time to depth prior to projection into cross section lines. In addition, because of changing stratigraphic thicknesses and nomenclature, separate stratigraphic columns were prepared for six differing sectors of the two structural cross sections.

Black Rock Desert, Pavant Butte Cross Section, Western Utah

The Black Rock (Sevier) Desert is underlain by a pronounced reflector set that dips gently (10° to 20°) to the west (Figures 3 and 4). The recently-drilled Python Rocky Ridge well proves to be associated with a pronounced structural and/or stratigraphic discontinuity along which lower Tertiary sedimentary rocks are juxtaposed against underlying Paleozoic carbonates, with a possible Jurassic (Arapien Formation?) section separating the other two stratigraphic packages. This discontinuity has been interpreted by some authors as being a low-angle, extensional detachment surface (Von Tish et al., 1985; Coogan and DeCelles, 1996; Stockli et al., 2001), and by several other authors as an early Tertiary unconformity (Anders and Christie-Blick, 1994; Wills et al., 2005). Though an interpretation as an unconformity is possible in the Pavant Valley area, east of Pavant Butte and the Pavant Butte well, the "Sevier Desert reflector" can be traced to the west beneath both a northern extension of the Cricket Range and the House Range, where this pronounced reflector set can no longer be interpreted as an unconformity, and where well data suggest it corresponds with a low-angle, west-dipping fault.

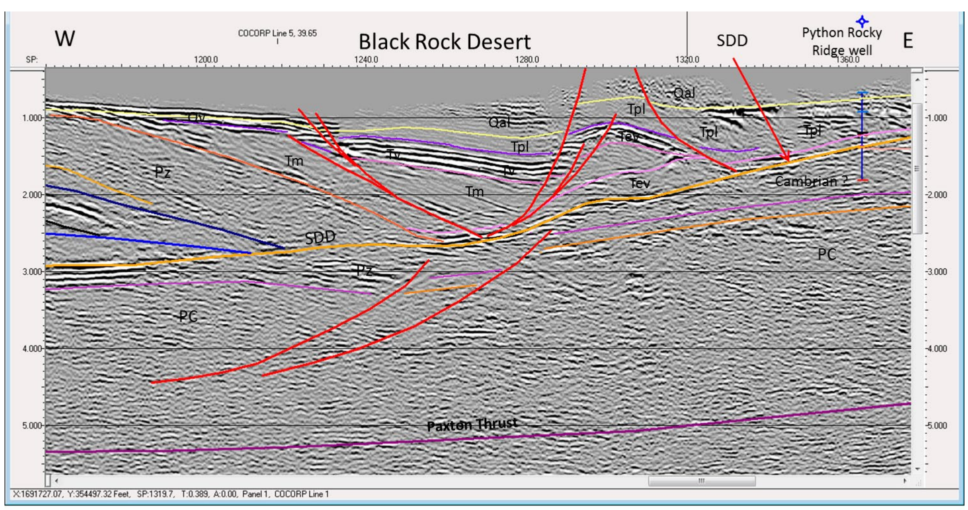
Of greater significance to geothermal resource evaluation in the Black Rock-Sevier Desert area is the presence of lower Tertiary sedimentary rocks directly overlying lower Paleozoic (Cambrian) carbonates and clastics where the Sevier Desert Detachment/reflector was penetrated by the Pavant Butte well, as shown on the Pavant Butte structural cross section (Figures 3 and 4). While not specifically identified in the Pavant Butte 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



Explanation

red lines = normal faults
black lines = thrust faults
purple line = Paxton Thrust
orange line = Sevier Desert Detachment (SDD)
Pz = Paleozoic
PC = Precambrian
blue line = Pavant Thrust

Figure 3a. Interpreted image of Utah COCORP seismic line 1, where it crosses the Black Rock Desert, Utah (refer to Figure 2 for location). Horizontal lines show the two-way travel time in seconds. Details are shown in Figure 3b.



Explanation

red lines = normal faults
black lines = thrust faults
purple line = Paxton Thrust
blue line = Pavant Thrust
orange line = Sevier Desert Detachment (SDD)
Qal = Quaternary alluvium
Qv = Quaternary volcanics
Pz = Paleozoic
PC = Precambrian
Tpl = Pliocene
Tv = Tertiary volcanics
Tm = Oligocene-Miocene
Tev = Tertiary (?) evaporites

Figure 3b. More detailed view of interpreted image of Utah COCORP seismic line 1 in Fig 3a. Note the basin fill (Tm) extends to about 2.5 seconds two-way travel time beneath the Black Rock Desert. SDD is the Sevier Desert Detachment.

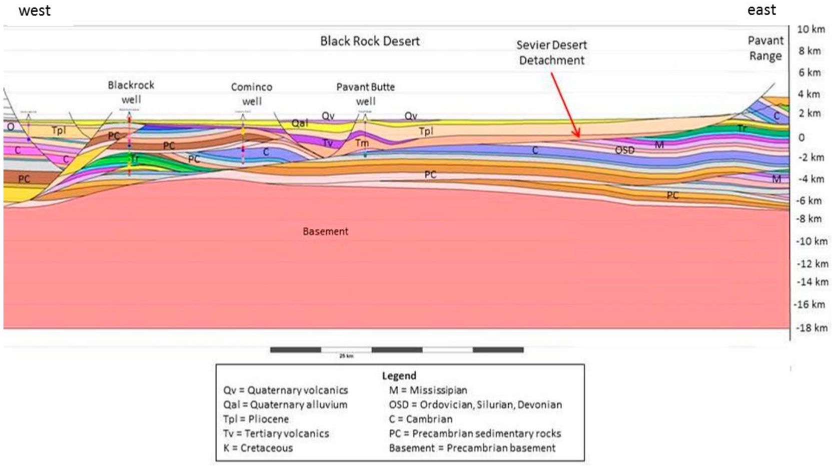


Figure 4. Detail of structural interpretation of the Black Rock Desert sector of the Pavant Butte line. Upper Cambrian carbonates (within formation labeled C) are known to have high permeability where they outcrop adjacent to the Black Rock Desert. The bottom hole temperature in the Pavant Butte well is 220 ± 10° C at 3200 m depth.

some question as to whether the evaporites are early Tertiary or Jurassic in age. Nonetheless, salt mobilization may be partially responsible for the anticline-syncline pair identified along Utah COCORP seismic line 1 near the Python Rocky Ridge well and shown on the Pavant Butte structural cross section (Figure 4), though extensional faulting could be partially responsible for the development of this structural system as well. In any case, the presence of evaporites above the Sevier Desert Detachment could have significant implications for "fault" seal along the detachment surface, and therefore preservation of hot fluids in underlying, Paleozoic sedimentary sequences.

The Pavant Butte 1 well drilled 400 m of bedrock 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% (Allis et al., 2012). At the southern end of the Black Rock Desert, 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. 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 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. The same Upper Cambrian carbonate units crop out in the Cricket Mountains on the west side of the Black Rock Desert. A ground water well penetrating these units found good permeability (Bob Robison, Graymont Resources, pers. comm. 2012).

The highest temperatures in the bedrock beneath the Black Rock Desert appear to be in a 60 km^2 area close to Pavant Butte (more than 200 °C at 3 km depth), with a 350 km^2 area having a temperature more than 150 °C at 3 km depth (Gwynn et al., 2013). The structural interpretation of additional seismic lines crossing through this area will be important when planning exploration drilling for the inferred reservoir (discussed in more detail below).

Steptoe Structural Cross Section; Northeastern Nevada

Along the Steptoe structural cross section, the only extensional basin (graben or half-graben) that shows more than 2 km of Tertiary valley fill is the northern Steptoe Valley, where wells drilled by LL&E, Placid Oil, and Shell Oil provide constraints on both the geometry and depth of the Tertiary graben (Figure 5). While seismic imaging along Nevada COCORP line NV-4 is generally quite poor, imaging of the Tertiary valley fill is often sufficient to determine, albeit with limited accuracy, the depth of

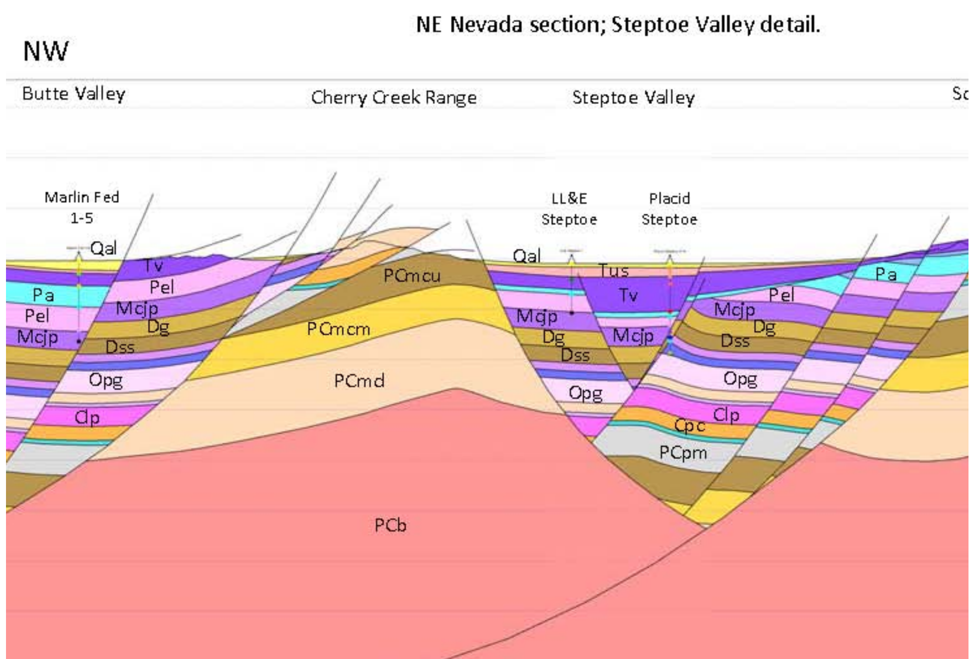


Figure 5. Portion of the Steptoe structural cross section where it crosses the northern Steptoe Valley. The central graben with the Placid Steptoe well contains 2.4 km of unconsolidated Tertiary-Quaternary sediments (Tus) and Tertiary volcanics (Tv) and has temperatures of 200 ± 10 °C at 3500 m depth. The Devonian limestones and dolomites (Dg and Dss) have high permeability.

the extensional basins traversed by the Steptoe section, east of the Pinon Range. In any case, as shown along the Steptoe structural cross section, the Placid Steptoe 17-4 well drilled through roughly 2400 m of Tertiary and Quaternary sedimentary and volcano-sedimentary rocks before crossing an unconformity (and/or low-angle extensional fault?) and entering an upper Paleozoic stratigraphic section, including the Pennsylvanian Ely Limestone and underlying Mississippian Chainman Shale. In contrast, the nearby LL&E Steptoe 1 well drilled through only 1200 m of Tertiary and Quaternary sedimentary and volcano-sedimentary rocks before penetrating the Ely Limestone, indicating the presence of a significant extensional fault separating the LL&E and Placid Steptoe wells. The Placid Steptoe 17-4 well reached a total depth of 3567 m within the Ordovician Eureka Quartzite (having penetrated at least two extensional faults below the base-Tertiary unconformity). A Cambrian carbonate stratigraphic section can be reliably interpreted as being present to an approximate depth of 6000 m in the central part of the Steptoe Valley, even assuming the presence of a low-angle denudation fault in the Lower Cambrian stratigraphic section, as has been mapped to the east in the Schell Creek Mountains and to the west in the Cherry Creek Range (Fritz, 1968; Hose et al., 1976).

The bedrock section drilled by the Placid well 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; Masbruch et al., 2012). This well shows these formations also have high permeability at depth, and the seismic interpretation provides a basis for targeting geothermal exploration wells.

Availability of Proprietary Seismic Data in the Great Basin

In the second part of this study, available industry seismic reflection data from western Utah and Nevada were evaluated to determine if any of the data would be useful in further structural analyses of specific basins identified as having geothermal resource exploration potential. The offices of American Geophysical Corporation (AGC) and Seismic Exchange Incorporated (SEI) in Denver, Colorado, were visited to examine a selection of seismic-reflection profiles acquired by the oil and gas industry over the last 40 years. Because of the surprising amount of seismic data potentially available, nine "areas of geothermal interest" were identified in the Great Basin, and the quality and character of 25, 2D seismic reflection profiles were examined from these areas of interest.

There is a large variation in both the quality and quantity of seismic reflection data, and space constraints in this paper do not allow a discussion of each area of interest. As an example of a basin with considerable data, the Black Rock Desert seismic profiles are discussed in detail and highlighted in Figure 6. In this area, nine seismic lines were examined for quality of data within the Tertiary and sub-Tertiary (Paleozoic) stratigraphic sections, including both north-south and east-west oriented seismic lines, and lines which crossed wells in the area, including the Pavant Butte and Hole-n-Rock wells of the Black Rock Desert, and the Sunset Canyon well from the western Pavant Range. Seismic quality varied from excellent to poor for both the Tertiary and Paleozoic stratigraphic sections; out of the nine lines examined five lines are worth acquiring (i.e., licensing), either in part or whole, in order to undertake a detailed structural analysis of the Sevier Desert Detachment's hanging wall (Tertiary) and footwall (Paleozoic) stratigraphic sections in the Black Rock - Sevier Desert areas. In addition, because of previous industry interest in the oil and gas potential of this area, there is enough seismic data from this basin to undertake a subsurface, 3D structural analysis of the basin, which is not the case in many of the other basins examined during this study.

An unusual feature of the Black Rock Desert area is that several of the GSI seismic lines, including seismic lines GSI-SU-1, GSI-SU-7, GSI-SU-11, and GSI-SU-25, were published as paper copies by Mitchell and McDonald (1987). Although the hard copies can be examined, the quality of the proprietary digital data should, presumably, be superior. In addition, the maps provided with the Mitchell and McDonald (1987) publication are imprecise, and therefore the data as published cannot be used as part of an accurate, 3D structural interpretation of the Black Rock Desert. Nonetheless, the paper copies included in the Mitchell and McDonald publication give a good indication of the data quality to be expected for the Black Rock Desert area of central Utah.

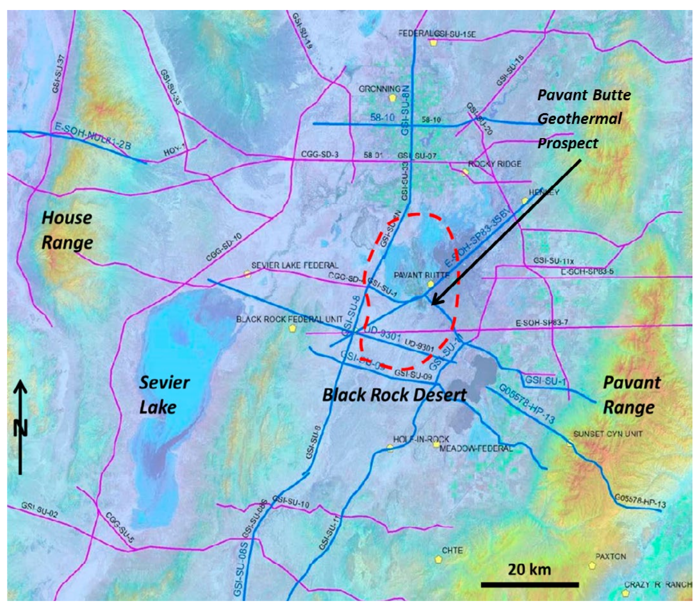


Figure 6. Location of industry (proprietary) seismic profiles (blue lines) in the area of Black Rock Desert, Utah, which are able to be licensed from seismic data suppliers. The background is an overlay of digital terrain and a satellite image. The red dashed line is the outline of the hottest part of the region identified by thermal gradient wells (Gwynn et al., 2013).

A compilation of all the seismic profiles available from the Great Basin is shown in Figure 7a and 7b. Because of the detail, the map has been split into eastern and western Great Basin maps. The color overlay on Figure 7 shows the approximate basin thickness (unconsolidated Tertiary and Quaternary sediments and volcanics)

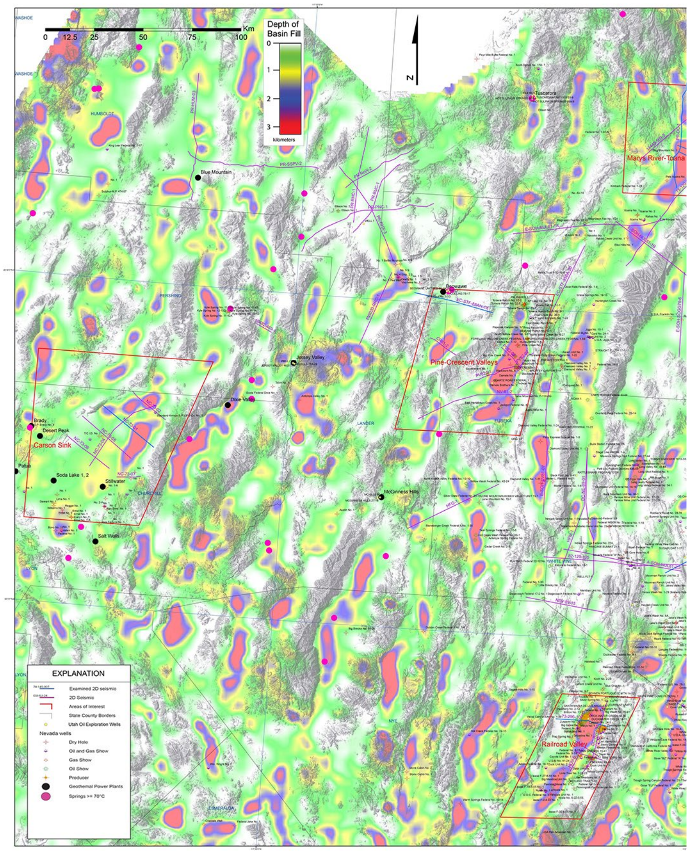


Figure 7a. Location of proprietary seismic profiles from the western Great Basin. Refer to caption beneath Figure 7b for full explanation.

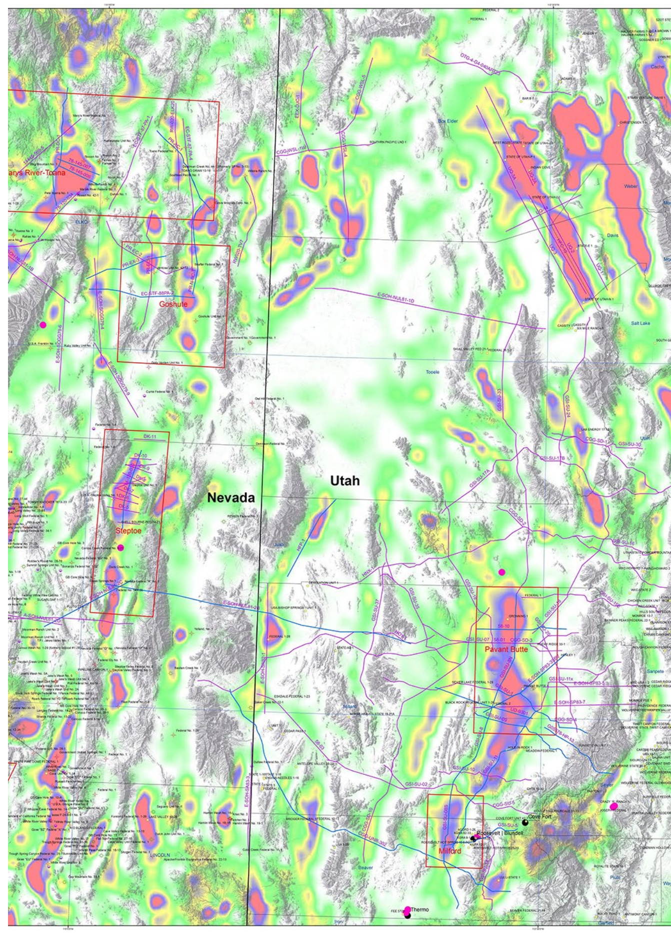


Figure 7b. Location of proprietary seismic profiles in the eastern Great Basin (blue lines). Red boxes outline areas of geothermal interest that were identified at the start of this study. Colored regions are basins determined from gravity measurements (Saltus and Jachens, 1995; color key is at the top of Figure 7a). Other symbols are defined in the Explanation at the bottom of Figure 7a.

based on gravity modeling of Saltus and Jackens, (1995). The pink to red colors highlight basins where the sedimentary fill is at least 2 – 3 km deep. If the heat flow is typical for the Great Basin (80 – 90 mW/m^2), then temperatures of 150 – 200 °C are possible at about 3 km depth (Allis et al., 2012, 2013). Red boxes outline the eight areas of geothermal interest identified at the time of starting this investigation of the quantity and quality of seismic data. A total of 25 lines were inspected in this cursory study of the value of the seismic reflection data.

Seismic data can be licensed from suppliers such as the American Geophysical Corporation and Seismic Exchange Incorporated in Denver. The cost depends on many factors such as the level of interest and demand from the oil exploration sector at the time of request, and the amount of data being licensed. In low-interest areas likely for most geothermal prospects in the Great Basin, the going rate (2013) seems to be between $2,000 and $3,000 per mile. Parts of seismic lines can be purchased, with a minimum purchase of 5 miles of data per line.

Figure 7 demonstrates that there is a considerable amount of proprietary seismic reflection data available for assisting geothermal exploration in the Great Basin. The figure also shows that there are many basins where the thickness of unconsolidated basin fill is more than 2 km. Large areas of the Great Basin have heat flows of more than 80 mW/m^2, and therefore many basins will have temperatures of at least 150 °C at 3 km depth, with some basins such as the Black Rock Desert in Utah, and the North Steptoe and Marys River basins in eastern Nevada, known to have temperatures close to 200 °C at 3 km depth (Allis et al., 2012). The quality of the data inspected in this study of 25 profiles in the Great Basin is variable, but overall this is a potentially valuable dataset for delineating stratigraphy and structure at depth in prospective basins.

Conclusions

Several reprocessed COCORP seismic reflection lines have been compiled into structural interpretations along two profiles in western Utah and eastern Nevada. Although the geological history of early compression and late extension is complex, the subsurface basin geometry and Paleozoic platform sedimentation patterns can be mapped when information from past oil exploration drilling and outcrop geology are incorporated into the interpretations. Potential reservoir units at 3 – 4 km depth are delineated, demonstrating the value of seismic reflection data for basin-centered geothermal exploration.

Proprietary seismic data acquired by the oil and gas industry from the Great Basin of western Utah and Nevada over the last four decades were also examined to determine their quality for structural and stratigraphic analyses of basins (valleys) having geothermal resource exploration potential. Although only 25 seismic lines from the study area were examined as part of the present work program, this proved to be sufficient to rank seismic data, seismic acquisition programs, and Tertiary fault basins for additional structural and stratigraphic analyses in the context of geothermal exploration. The two basins for which seismic data are considered sufficient for additional 2D and/or 3D structural analyses are the Black Rock Desert of central Utah, located along the eastern boundary of the Basin and Range tectonic province, and the Marys River basin of northeastern Nevada, both of which are believed to have high geothermal resource potential (Allis et al., 2012). In both areas it is recommended that multiple seismic lines be licensed to conduct further structural/stratigraphic analyses, including possible 3D structural modeling of the basins and associated boundary faults (including the low-angle Sevier Desert Detachment fault of the Black Rock Desert). Despite lack of imaging in the pre-basin fill Paleozoic stratigraphic section, it is considered here to be worth examining additional seismic data from the North Steptoe basin of eastern Nevada for the mapping of fault systems in the subsurface, particularly if faults are critical for high-temperature water circulation. A map which compiles the availability of proprietary seismic reflection data in the Great Basin together with basin thickness derived from a regional gravity interpretation highlights the large number of basins within the Great Basin where seismic data are available. When coupled with thermal gradient and heat flow determinations which allow the prediction of the temperature at 3 – 4 km depth in bedrock units beneath the basins, these three geophysical techniques provide powerful screening tools for prioritizing basin-centered geothermal reservoirs suitable for power development.

Acknowledgments

This project was partially supported by a contract from the Geothermal Technologies Program of the United States Dept. of Energy (Award DE-EE0005128: “Novel Geothermal Development of Sedimentary Basins in the United States,” Moore, J.N. and Allis, R.G. Principal Investigators). We thank Jay Hill (Utah Geological Survey) for assistance with several of the figures, and Frank Monastero and Mike Hylland for helpful reviews.

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