Geothermal Potential in the Basins of Northeastern Nevada

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Keywords

Heat flow, thermal conductivity, bottom-hole temperatures, stratigraphic reservoir, porosity, permeability, Marys River Basin, Toano Draw, Pine Valley

ABSTRACT

Previous geothermal exploration, including many relatively shallow thermal gradient wells, has shown that NE Nevada is a region with high heat flow and geothermal potential. This study reassesses over 150 publicly available bottom-hole temperatures (BHTs) and drill stem tests (DSTs) from past oil exploration to evaluate the thermal regime at 2–4 km depth. The region consists of numerous basins containing low-thermal-conductivity sediments and volcanics overlying Paleozoic bedrock consisting primarily of carbonates and lesser amounts of siliciclastics. Several Paleozoic formations are known to have high permeability and may be potential reservoirs. The depth of most basins ranges from about 2 km up to about 4 km, and due to the insulating properties of the basin-fill, the highest temperatures and best geothermal prospects may lie beneath the basins.

Results show the heat flow ranges from about 75 mW/m^2 in the Ruby and Goshute Valleys in the southeast part of the study area, to more than 90 mW/m^2 in Marys River Basin and Huntington Valley. In the highest heat-flow basins, the temperatures are in the range of 160°C to more than 180°C at 3–4 km depth, and appear to be close to the economic temperature-depth target for stratigraphic geothermal reservoirs of 150–200°C at 2–4 km depth identified in other work. The quality of the downhole temperature data is not sufficient to determine whether the temperature scatter within basins is due to the effects of deep groundwater circulation, or is simply excessive, uncorrected cooling due to the effects of drilling immediately before the BHT and DST measurements were made.

Introduction

Marys River and Toano Draw Basins in northeastern Nevada have previously been identified as having geothermal potential based on deep bottom-hole temperature (BHT) data from oil and gas wells (Allis et al., 2012, 2013; Allis and Moore, 2014). This paper, as part of a project to promote geothermal development in sedimentary basins, and partially funded by the U.S. Department of Energy, continues the investigation into these basins and others in northeastern Nevada (Figure 1). A major goal of this work is to focus exploration on the most appropriate target locations. The overall study area is about 78,500 km² and includes most of Elko County and the northern half of Eureka County. Geophysical and lithologic logs, along with drill stem test (DST) and various other reports from the petroleum industry constitute the majority of the

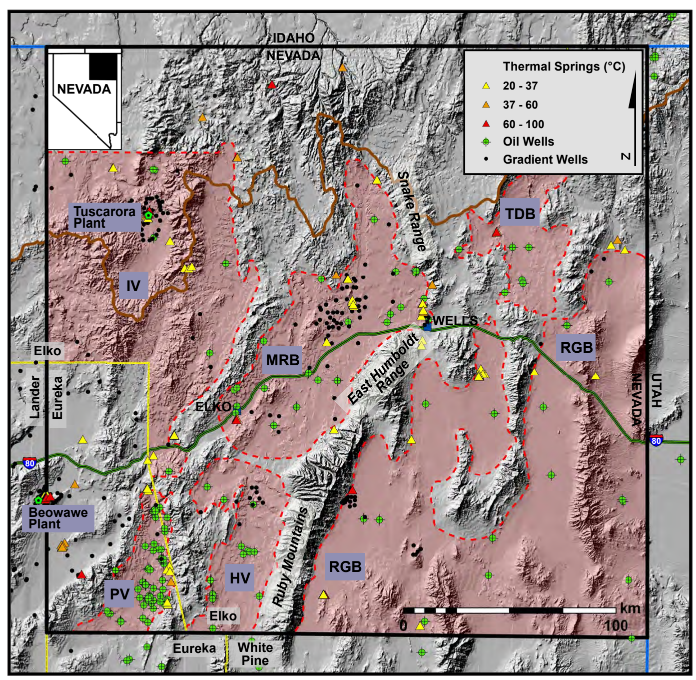

Figure 1. Study area location in northeastern Nevada. Study sub-areas are defined by red-shaded polygons with dashed lines. Sub-areas are: Huntington Valley (HV), Marys River Basin (MRB), Independence Valley (IV), Pine Valley (PV), Ruby-Goshute Basin (RGB), and Toano Draw Basin (TDB). Tuscarora and Beowawe geothermal plants are included. The Great Basin Carbonate and Alluvial Aquifer System is shown by the solid brown line.

data evaluated. An extensive collection of these data are available on the Nevada Bureau of Mines and Geology (NBMG) website (http://www.nbmg.unr.edu/lists/oil/oil.htm).

Northeast Nevada has been known to have high heat flow since at least the 1960s (Roy et al., 1968, 1972; Sass et al., 1971; Lachenbruch and Sass, 1977, 1978; Blackwell, 1978, 1983; Blackwell et al., 1991, 2011; Blackwell and Richards, 2004). The Blackwell et al. (2011) heat flow map suggests that heat flow over nearly the study entire area is 80–110 mW/m², thereby exceeding the "high heat flow" threshold discussed by Lachenbruch and Sass (1977), Blackwell (1983), Blackwell et al. (1991), and Tester et al. (2006). High heat flow and thick, insulating, low-thermal-conductivity sediments, like those found in the study area basins, promote higher temperatures at shallower depths compared to bedrock formations where thermal conductivity is higher. Laterally extensive bedrock formations below the sediment-filled basins must host suitable temperatures, permeability characteristics, and fluid volumes to allow them to function as stratigraphic geothermal reservoirs (SGR). Allis et al. (2011, 2012, 2013), Holbrook et al. (2012, 2014), Gwynn et al. (2013), and Allis and Moore (2014) discuss many of the geologic aspects of the SGR concept while the technical and economic feasibility is explored by Deo et al. (2014) and Mines et al. (2014). These works suggest that temperatures of 150–200°C at depths of about 2–4 km may be feasible for binary plant development. The study area is located within the Great Basin, which, Anderson (2013), building on the work of Porro et al. (2012), concluded ranks in the top 3 of 8 sedimentary basins for SGR development based on temperatures, depths, and permeability factors. Almost all of the oil wells in the study area were drilled in basins within the boundaries of the Great Basin Carbonate and Alluvial Aquifer System (GBCAAS) study area defined by Heilweil and Brooks (2011) and shown in Figure 1. This is important because it suggests that carbonates, which likely have superior permeability compared to siliciclastic rocks (Kirby, 2012), underlie the basins.

Geothermal potential in the region was recognized by at least the early 1970s, having been mapped (Garside and Schilling, 1979; GDAN, undated; Garside, 1994; Shevenell et al., 2000; Coolbaugh et al., 2005; Shevenell and Garside, 2005; Zehner et al., 2009; Penfield et al., 2010), studied (Hose and Taylor, 1974; Jewell, 1982; Smith, 1983; Faulder et al., 1997; Goranson, 2005; Garg et al., 2007), and extensively drilled by a number of geothermal exploration companies (Chevron Geothermal, Phillips Petroleum Company, GTS Sino Geothermal, and AMAX Geothermal; Sass et al., 1999). The discovery well (Ginn 1-13, 2898 m depth) in the Beowawe geothermal field was drilled in 1974 and encountered a maximum temperature of 215°C (Smith, 1983; Faulder et al., 1997; Garg et al., 2007). The 16.6 MW dual-flash plant has been active since 1985 and is just outside the southwest corner of the study area defined in Figure 1 (Garg et al., 2007; Penfield et al., 2010). The binary 18 MW Tuscarora plant was completed in 2012 (GEA, 2013), and is located in the northwest quadrant of the study area. The production temperature is 215°C (Goranson, 2005; Penfield et al., 2010). Both plants tap hydrothermal systems.

Topography

The study area is fairly typical of Basin and Range topography, with basins bounded by linear, roughly NNE-trending ranges. However, the mountains north of these basins are less well defined due in part to a lower base level of erosion into the Snake River to the north compared to the Humboldt River to the south (Coats, 1987). The Ruby Mountains (metamorphic core complex) along with the East Humboldt and Snake Ranges are the most prominent ranges, and together they divide the study area approximately in half. Ranges typically consist of Paleozoic sedimentary rocks, but portions of some basins are bounded by Tertiary volcanics (Coats, 1987; Frerichs and Pekarek, 1994). The basins typically contain several km of Quaternary and Tertiary basin fill. A basin depth map derived from the gravity models of Saltus and Jachens (1995), merged with some newer data from Watt and Ponce (2007), as described by Heilweil and Brooks (2011), suggests that some basins may be deeper than 3–4 km. Saltus and Jachens (1995), however, do warn that the depths should be viewed in a more relative than absolute manner.

The overall study area was broken up into sub-areas to simplify data presentation and evaluate the relative geothermal potential in each generalized basin area (Figure 1). The sub-areas include Toano Draw (TDB), Marys River Basin (MRB), Huntington Valley (HV), Pine Valley (PV), Independence Valley (IV) and Ruby-Goshute Basin (RGB). These sub-areas are defined primarily by topography and the density of oil wells. Therefore, the boundaries are rather arbitrary and the primary basin may merge with, and encompass, other named topographic features. This is especially true in the northwest (IV) and southeast (RGB) parts of the study area where wells density is diffuse.

Geologic History

In general, the geology of northeastern Nevada is complex. The study area was part of a stable continental margin from the late Proterozoic to the Devonian, characterized by thick accumulations of predominantly carbonate rocks that were deposited on a broad, shallow marine platform (Heilweil and Brooks, 2011).

These units comprise many of the ranges and underlie many of the basins in the region (Heilweil and Brooks, 2011). During this time, siliciclastic rocks were being deposited farther west in present-day northwestern Nevada and a transition zone of intermediate lithologies occupied the intervening area (Roberts et al., 1958; Peterson, 1968; Smith and Ketner, 1968; Stokes, 1979; Wilson and Laule, 1979; Coats, 1987). The works of Granger et al. (1957), Willden and Kistler (1979), Snoke (1992), and Camilleri (2010a), suggest that no intermediate facies were deposited from at least the Ruby Mountains eastward, although Coats (1987) reports that the transitional Lower Devonian-Lower Silurian Roberts Mountain Formation is present farther north in the Snake Range. Heilweil and Brooks (2011) show that all the sub-areas, except for IV, are located within the GBCAAS. The IV sub-area contains more intermediate rocks (carbonates with increasing shale) and extends beyond the GBCAAS.

The Late Devonian-Late Mississippian east-west compression of the Antler Orogeny resulted in the Roberts Mountain thrust belt that placed siliciclastic rocks from the west, and possibly some of the intermediate rocks, above the eastern-deposited carbonates (Roberts et al., 1958; Peterson, 1968; Smith and Ketner, 1968; Wilson and Laule, 1979; Coats, 1987; Heilweil and Brooks, 2011). Other compressional events occurred in the late Paleozoic, but did little to effect the distribution of rocks in the study area (Crafford, 2008; Heilweil and Brooks, 2011). Post-Antler Late Mississippian to Permian foreland basin deposits of carbonate and detrital rocks are also found in the study area and extend at least as far eastward as TDB (Stokes, 1979; Wilson and Laule, 1979; Speed, 1983; Coats, 1987; Dickinson, 2006).

Jurassic to late Tertiary plutonic rocks, mainly silicic to intermediate in composition, are scattered across Elko County (Coats, 1987). Tingley (1981) reports that tungsten is mined from schists along the borders of pegmatites on the eastern side of the East Humboldt Range, and Camilleri (2010b) mapped granitic intrusions 30 km farther to the east in the Wood Hills. Late Cretaceous granodiorite is present beneath parts of the Blackburn oil field in Pine Valley (Johannesen and Cole, 1990). The majority of the Mesozoic was characterized by uplift and extensive erosion in northeastern Nevada (Stokes, 1979). Large accumulations of Tertiary volcanics, primarily felsic in composition, form some bounding ranges and contribute to the fill in some basins.

Low angle detachment faulting associated with the exhumation of the Ruby Mountains metamorphic core complex probably occurred in the middle Miocene (Stewart, 1983; Coats, 1987). Basin and range extensional faulting began in the early Miocene (ca. 17.5 Ma; Dickinson, 2006) and has overprinted earlier compressional tectonics. The ongoing extension results in elongated mountain ranges separated by subsiding basins and has been described by Granger et al. (1957), Zoback and Thompson (1978), Stewart (1978, 1983), Eaton (1979), Coats (1987), Dickinson (2006), and many others. The basins typically contain thick accumulations of basin fill that may exceed 3–4 km. Some basins contain sub-basins separated by buried horst blocks (Heilweil and Brooks, 2011). Such structures appear to be present in TDB (Frerichs and Pekarek, 1994), PV (Hulen, et al. 1990; Flanigan, 1994), and possibly other basins in the study area.

Temperature Data

Thermal Springs

The NBMG Map 161 database shows that approximately 370 thermal springs are in the study area (Penfield et al., 2010). Of these, 269 are listed as hot springs with temperatures of 37–98°C and the remaining 101 are warm springs with temperatures of 20–37°C. Many of these springs are located around the Tuscarora and Beowawe geothermal fields. Cation and silica geothermometry data have been reported at almost 80 of the springs to suggest reservoir temperatures of 17–230°C (cation) and 23–243°C (silica). Charge balance and other qualitative checks of these data were not scrutinized because the deep well temperatures are the focus of this study.

Thermal-Gradient Wells

The NBMG Map 161 database (Penfield et al., 2010) contains data for about 200 thermal-gradient wells in the study area. These wells are primarily clustered around the Tuscarora and Beowawe geothermal developments, in central MRB, and on the east side of the Ruby Mountains (Figure 1). A majority of the wells are shallow (<100 m deep, or do not have depth data available), although a few were drilled deeper (up to 2054 m). Reported heat flow values (36–1960 mW/m²) reflect both conductive and advective thermal regimes since many wells were drilled near hot springs. Conductive heat flows vary widely, but tend to be >80 mW/m² (some are much higher). The database of Sass et al. (1999) includes 48 gradient wells in the study area, but all with conductive gradients are incorporated into the Penfield et al. (2010) database. While these data suggest that there are high heat flow and prospective geothermal gradients in northeastern Nevada, their variability and shallow depths leave major uncertainties about the thermal regime at 2–4 km depth.

Oil and Gas Wells

Geophysical logs and various reports for oil and gas wells in the study area were obtained from the NBMG website (http://www.nbmg.unr.edu/lists/oil/oil.htm). Deep petroleum wells in the northeastern part of Nevada are sparse compared to the east-central part of the state. Well data in the northern part of the study area and in southern Idaho are nonexistent. Of about 150 wells in the study area, only 92 have BHT and/or DST data and many of these are located in several developed oil fields in Pine Valley. So, while there is a small pocket of robust well data in PV, well density in the rest of the study area is typically sparse (Figure 1). The total depth in the wells ranges from 311 to 4409 m. The wells host 187 DSTs or corrected BHTs at varying depths.

BHT Corrections

The methods of Henrikson (2000) and Henrikson and Chapman (2002) were used to correct for drilling-induced temperature perturbations in most wells. In some cases, however, reliable shut-in time data required for these corrections were not available. Temperatures in these wells were corrected by applying a depth-dependent correction factor calibrated to corrected BHTs throughout western Utah. The method was developed by calculating the correction magnitude required to match the corrected value attained with more accurate methods over a given depth interval. Because the basins in western Utah and eastern Nevada are similar, this method results in reasonable corrections for these cases. Corrected BHTs are generally consistent with reliable DST data in the study area, which should be representative of undisturbed formation temperatures (Harrison et al., 1983; Hermanrud et al., 1990; Förster and Merriam, 1995; Beardsmore and Cull, 2001). The method is also quite consistent with the Kehle equation as defined by Gregory et al. (1980), which was found to correlate well with DST data in the Idaho thrust belt (Welhan and Gwynn, 2014). These, and most other correction methods, are generally considered accurate to about ± 10°C or better (Hermanrud et al., 1990; Goutorbe et al., 2007; Edwards, 2013). The range of corrected BHTs for all wells is 24–186°C.

Thermal Conductivity and Heat Flow Data

No actual thermal conductivity data were available for this study, so values were estimated based on published averages from Lappin (1980), Robertson (1988), Sass et al. (1999), Beardsmore and Cull (2001), and Gosnold et al. (2012). Lithologic data are available for most of the wells in the form of well reports, core reports, and lithologic/mud logs. Heat flows, the products of temperature gradient and thermal conductivity, were calculated for one or more representative wells in each sub-area. These

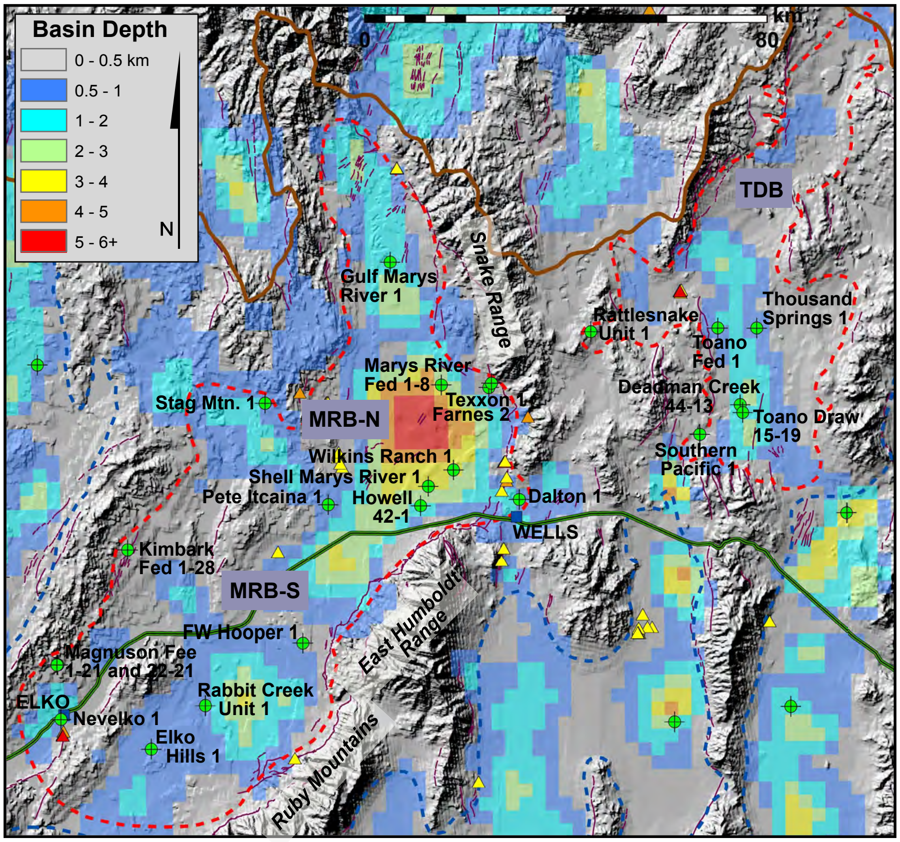

Figure 2. Oil wells in Marys River Basin (divided into north and south units) and Toano Draw Basin. Sub-area polygons, well symbols (gradient wells not shown), and thermal spring symbols are the same as in Figure 1. Basin depth map overlay described by Heilweil and Brooks (2011) depicts the locations of the deepest basins. Quaternary faults are purple. The Great Basin Carbonate and Alluvial Aquifer System is shown by the solid brown line.

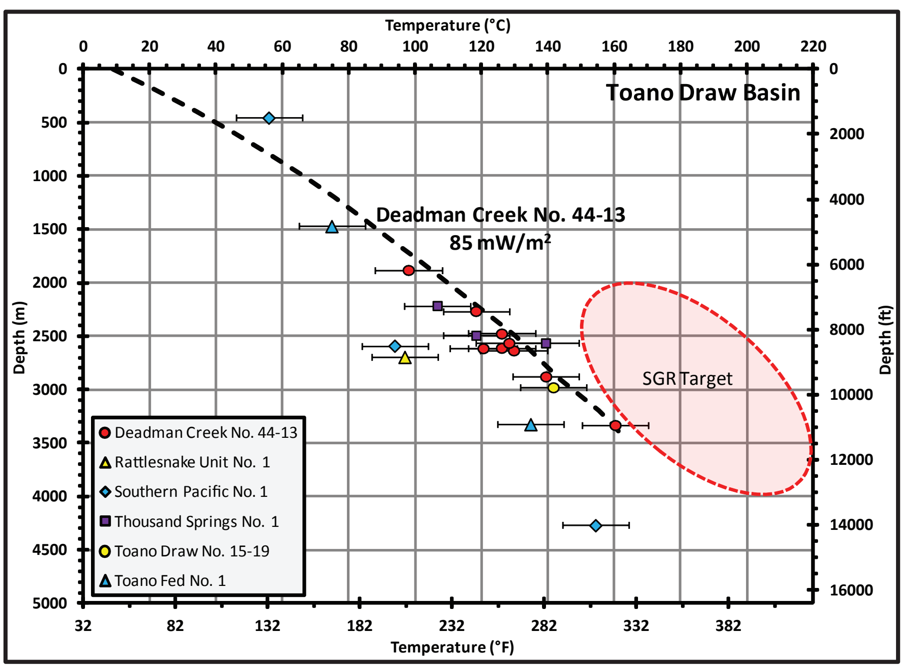

Figure 3. Temperature-depth plot for the wells with temperature (BHT and DST) data in Toano Draw Basin. See Figure 2 for locations. Error bars are ±10°C. Stratigraphic Geothermal Reservoir (SGR) economic target is shown (Allis and Moore, 2014).

were calculated by using geotherm models as described in Gwynn et al. (2103) and Welhan and Gwynn (2014). The models compute and plot the geothermal gradient over 100 m intervals by dividing the characteristic interval thermal conductivity into a selected heat flow input value. The heat flow value is then adjusted until the geotherm coincides with plotted temperature-depth data. The well, or wells, used to generate the geotherm for each sub-area were selected based on depth, location, and the quantity/quality of available temperature and lithologic data. Each of these wells is thought to provide a fairly representative heat flow value and geotherm for their respective sub-areas. The geotherm, temperature data, and the SGR target zone based on the analysis of Mines et al. (2014) are shown in the figure for each sub-area. A more rigorous investigation of thermal conductivity and heat flow in northeast Nevada will be presented in Gwynn et al. (in prep).

Results

The six wells (19 BHT/DSTs) in TDB suggest there may be SGR potential in the basin (Figures 2 and 3). Heat flow for the Deadman Creek No. 44-13 well is about 85 mW/m². The well was drilled near the center of the basin, so the thick accumulation of low-thermal-conductivity sediments results in a higher gradient compared to a well with less fill. Individually, the Rattlesnake Unit No. 1, Southern Pacific No. 1, and Toano Federal No. 1 wells reveal temperatures too low to meet the SGR target. The first two wells penetrated Paleozoic strata at the surface and at about 500 m, respectively, so the lower temperatures are likely thermal conductivity effects. The Toano Federal No. 1 well appears to be located in a deeper section of the basin, but lithologic data are lacking. Well and gravity data suggest there are intermediate horst blocks within the basin, so it is possible that the well penetrated one of these and encountered higher thermal conductivity strata at a relatively shallow depth. Alternatively, localized advective effects may be sweeping heat at this location. The remaining three wells in TDB (Deadman Creek No. 44-13, Thousand Springs No. 1, Toano Draw No. 15-19) were drilled in deeper sections of the basin and their temperatures suggest that these locations may be marginally prospective. The thermal effect of basin depth is illustrated in TDB and shows that seismic and other data will be critical to properly assess potential drilling locations (i.e. the deeper basin areas).

Ten wells, with a total of 26 BHT/DSTs, are in the northern MRB area (Figures 2 and 4). Heat flow for the Howell No. 42-1 well is about 90 mW/m², and the data for the Pete Itcaina No. 1, Wilkins Ranch No. 1, and the hotter data for Shell Marys River Federal No.1 (most of the scattered and cooler data in this well are probably unreliable) wells also plot on this geotherm. These four wells are located in the deeper part of MRB and their temperature profiles graze the SGR target zone, while the BHT for the Marys River Federal No. 1-8 well plots within the target zone. The Gulf Marys River Federal No. 1 well is cooler, but temperatures may become marginally prospective if the well was deeper. The lower temperatures in the Stag Mountain No. 1well prevent it from meeting the SGR target. Basin depth is reported to be about 2000 m in this well, but it is near the basin margin and the temperature could be affected by cool groundwater recharge. The Texxon No. 1 and Farnes No. 2 wells were drilled to less than 325 m near the margin of MRB. The gradients are high (51 and 87°C/km), but the effect of minimal basin fill (relatively low thermal conductivity) and a great thickness of rocks with higher thermal conductivity would likely depress the deep gradients below the SGR target zone. The Dalton No. 1 well has a very high gradient of 88°C/km, but is located near a number of thermal springs that likely influence near-surface temperatures through advection.

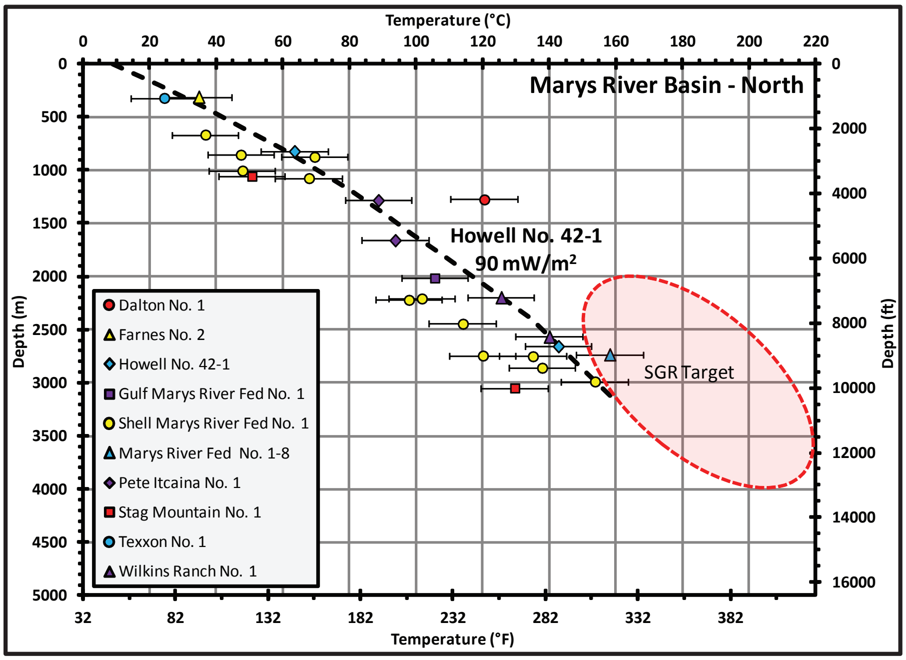

Figure 4. Temperature-depth plot for the wells with temperature (BHT and DST) data in northern Marys River Basin. See Figure 2 for locations. Error bars are ±10°C. Stratigraphic Geothermal Reservoir (SGR) economic target is shown (Allis and Moore, 2014).

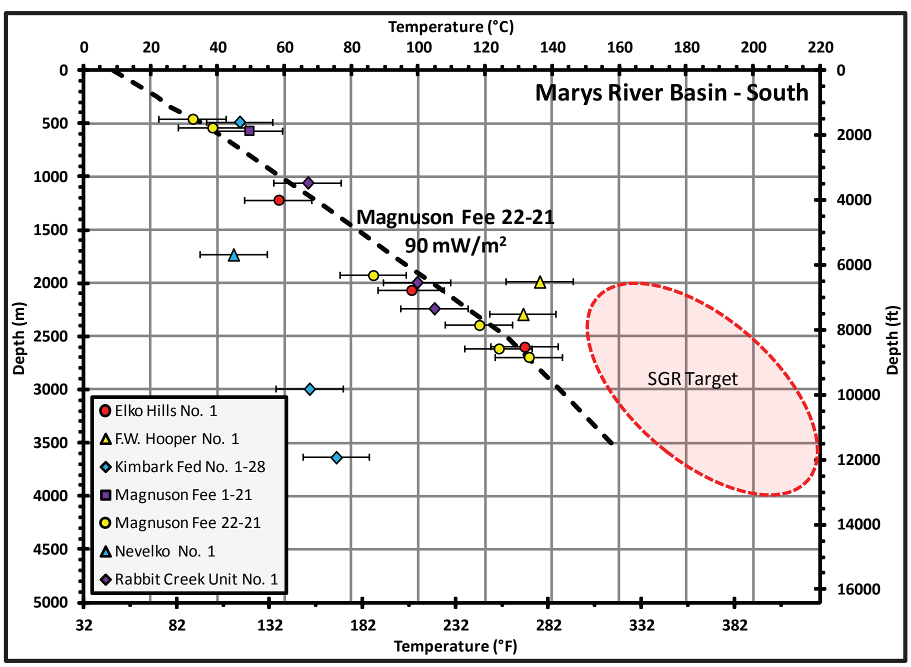

Figure 5. Temperature-depth plot for the wells with temperature (BHT and DST) data in southern Marys River Basin. See Figure 2 for locations. Error bars are ±10°C. Stratigraphic Geothermal Reservoir (SGR) economic target is shown (Allis and Moore, 2014).

Temperature data in southern MRB come from seven wells with18 BHT/DSTs (Figures 2 and 5). The Kimbark Federal No. 1-28 well hosts much lower temperatures than most of the other wells. The Kimbark well is in the Coal Mine Canyon fault zone and may be affected by groundwater inflow from the adjacent Adobe Range. Temperatures in the Nevelko No. 1 well are also low, but the reason is less clear. The Magnuson Fee 22-21well was used to calculate a heat flow of 90 mW/m². Because this well only penetrated about 0.5 km of low-thermal-conductivity basin fill before entering the Paleozoic section, a well drilled in a deeper part of the basin might have a higher gradient than the geotherm in Figure 5. Except for the F.W. Hooper No. 1 well, which would likely intercept the SGR target if drilled deeper, the remaining wells plot near the calculated geotherm, which places them near the margin of the SGR target zone. The F.W. Hooper No. 1 well contains the greatest thickness of low-thermal-conductivity basin fill (about 1900 m), which is probably the main contributor to its higher gradient.

Nine wells with 23 BHT/DSTs constitute temperature data in the HV sub-area. Heat flow calculated in the Cord No. 24-1 well is approximately 95 mW/m² (Figures 6 and 7). This well intercepts the SGR target zone, while several other wells approach, but do not reach, the target. The most notable of these are the Federal BL No.1, U.S.A. Jiggs No. 1, and Jiggs Unit No. 2 wells, all of which were drilled relatively close to one another and to the Cord No. 24-1 well. These four wells have similar heat flows and fit the same geotherm above about 2.5 km. However, the Cord No. 24-1 well is reported to have bottomed in the Tertiary Elko Formation (relatively low thermal conductivity) while the others bottomed in Paleozoic carbonates (relatively high thermal conductivity). The thermal

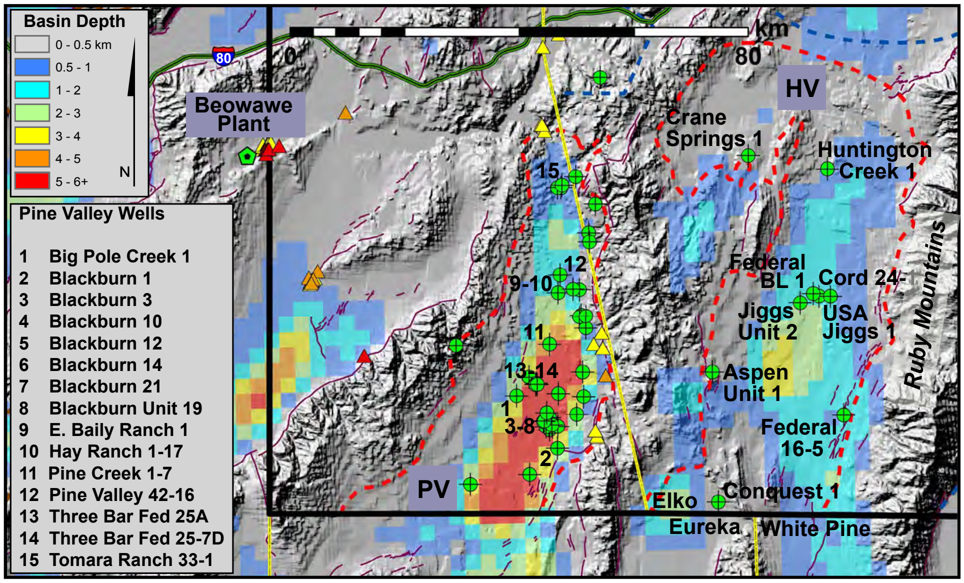

Figure 6. Oil wells in Huntington and Pine Valleys. Sub-area polygons, well symbols (gradient wells not shown), and thermal spring symbols are the same as in Figure 1. Basin depth map overlay described by Heilweil and Brooks (2011) depicts the locations of the deepest basins. Due to the density of the data, only the 15 most prospective wells are labeled in PV (referenced by numbers). Quaternary faults are purple.

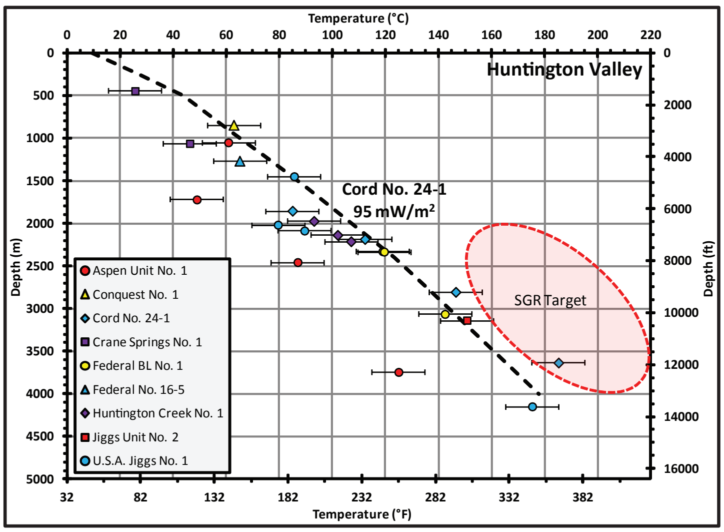

Figure 7. Temperature-depth plot for the wells with temperature (BHT and DST) data in Huntington Valley. See Figure 6 for locations. Error bars are ±10°C. Stratigraphic Geothermal Reservoir (SGR) economic target is shown (Allis and Moore, 2014).

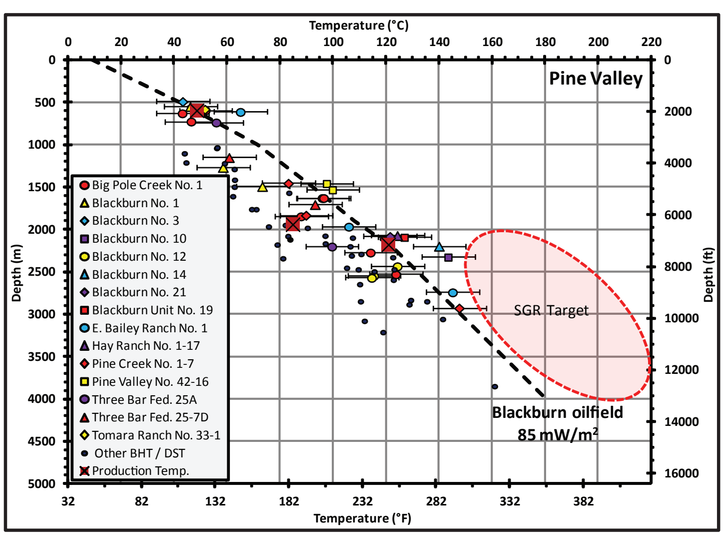

Figure 8. Temperature-depth plot for the wells with temperature (BHT and DST) data in Pine Valley. See Figure 6 for locations. Only data for the 15 most prospective well are shown individually. All other data are displayed generically. Error bars are ±10°C. Stratigraphic Geothermal Reservoir (SGR) economic target is shown (Allis and Moore, 2014). Red boxes indicate production temperatures from three oil fields in PV. From shallowest to deepest they are: Tomera Ranch, North Willow Creek, and Blackburn.

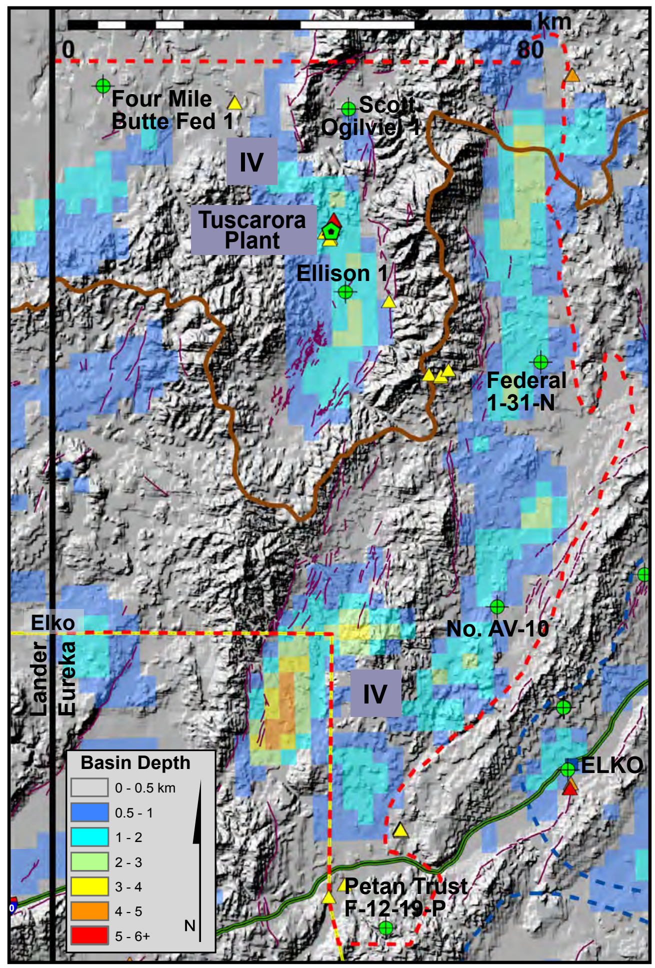

Figure 9. Oil wells in Independence Valley. Sub-area polygon, well symbols (gradient wells not shown), and thermal spring symbols are the same as in Figure 1. Basin depth map overlay described by Heilweil and Brooks (2011) depicts the locations of the deepest basins. Quaternary faults are purple. The Great Basin Carbonate and Alluvial Aquifer System is shown by the solid brown line.

conductivity difference below about 2.5 km depresses the gradients relative to the Cord No. 24-1 well. This effect would be seen at even shallower depths in wells with less basin fill. Temperatures for the Aspen Unit No. 1 and the Crane Springs No.1 wells suggest that they are in less prospective SGR areas, most likely because they are sited in shallow parts of the basin.

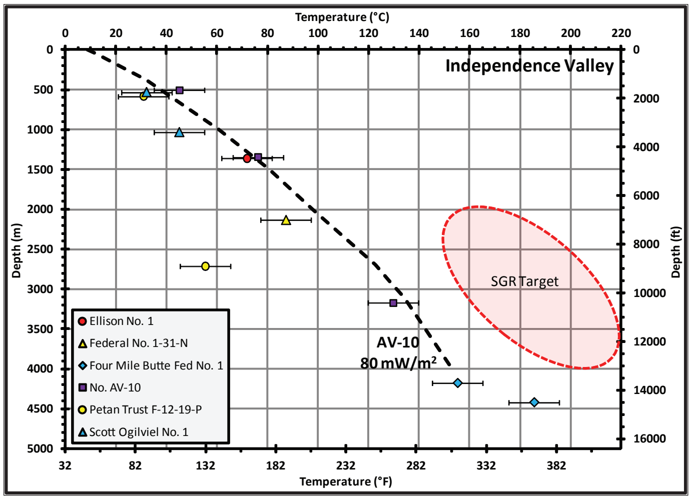

Figure 10. Temperature-depth plot for the wells with temperature (BHT and DST) data in Independence Valley. See Figure 9 for locations. Error bars are ±10°C. Stratigraphic Geothermal Reservoir (SGR) economic target is shown (Allis and Moore, 2014).

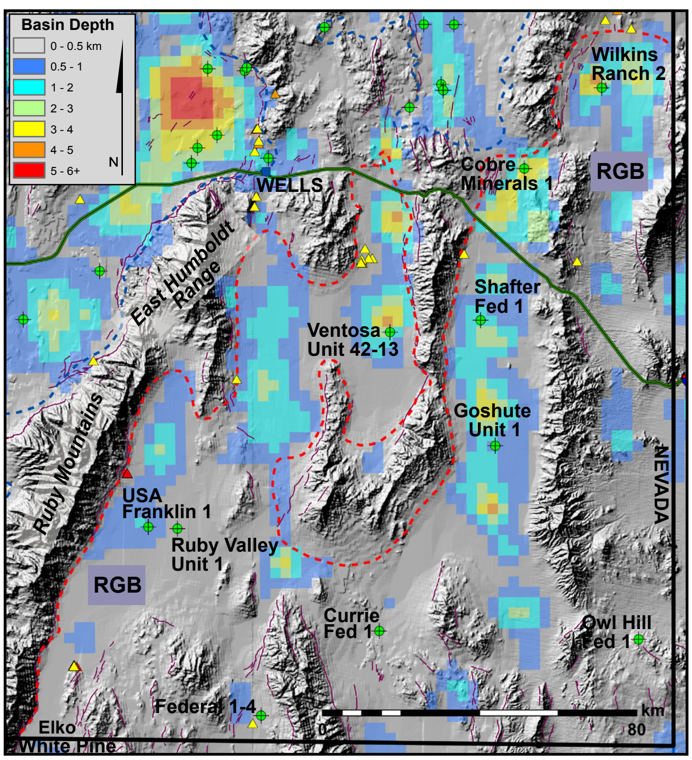

Figure 11. Oil wells in Ruby-Goshute Basin. Sub-area polygon, well symbols (gradient wells not shown), and thermal spring symbols are the same as in Figure 1. Basin depth map overlay described by Heilweil and Brooks (2011) depicts the locations of the deepest basins. Quaternary faults are purple.

A number of oil fields are located in PV, and 43 wells provide the 74 BHT/DSTs shown in Figure 8. Data for the 15 wells with the highest gradients are plotted individually (named) along with the remainder of the data in Figures 6 and 8. An 85 mW/m² geotherm based on Blackburn production temperatures and generalized thermal conductivity values plots just below the SGR target zone. If the East Bailey Ranch No. 1, Hay Ranch No. 1-7, Blackburn Unit No. 19, and Blackburn Nos.10 and 14 wells were drilled deeper, they would likely intercept the target zone. In this part of Blackburn field, many of the wells penetrate the Devonian Nevada Group dolomite (Hulen et al, 1990). The gradients in five other wells might marginally intercept the SGR zone and the remaining five, along with the unnamed wells are less prospective. Production temperatures for the Tomera Ranch (Hansen et al., 1994a), North Willow Creek (Hansen et al., 1994b), and Blackburn (Flanigan, 1994) oil fields fit within the scatter of the BHT/DST data.

Deep well data for the IV and RGB sub-areas (Figures 9–12) are limited and scattered over large areas, but suggest that temperatures are too low to intersect the SGR target zone in both areas. Data plot coherently among all the wells in each sub-basin. Heat flow in the AV-10 (IV) and the USA Franklin No. 1 (RGB) wells are 80 mW/m² and 75 mW/m² respectively. These, and most other wells, in these two sub-areas are drilled into the basins where the insulating effect of low-thermal-conductivity sediments should be greatest (yielding higher gradients compared to bedrock). Just because the limited well data suggest that the IV and RGB sub-area temperatures may be too low for SGR development does not necessarily mean the areas have low geothermal potential. For example, the IV sub-area hosts the hydrothermal Tuscarora geothermal field. Additionally, the sparse well data may simply be keeping a potential SGR development hidden in these areas.

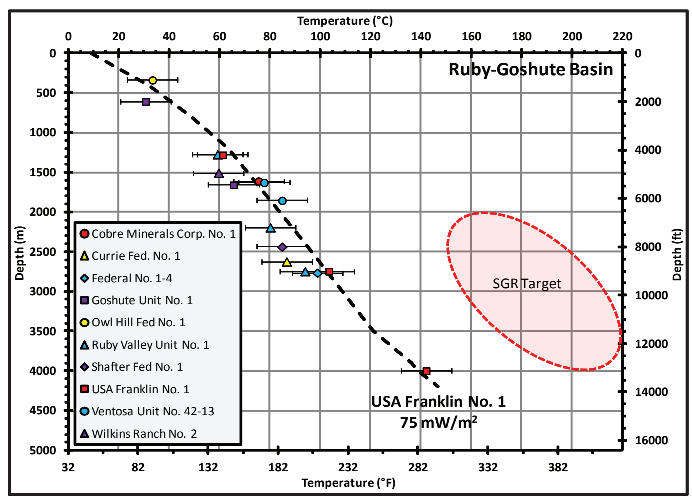

Figure 12. Temperature-depth plot for the wells with temperature (BHT and DST) data in Ruby-Goshute Basin. See Figure 11 for locations. Error bars are ±10°C. Stratigraphic Geothermal Reservoir (SGR) economic target is shown (Allis and Moore, 2014).

Conclusions

Figure 13 shows all temperature data from the study. As a group, many of the data can be projected to at least marginally

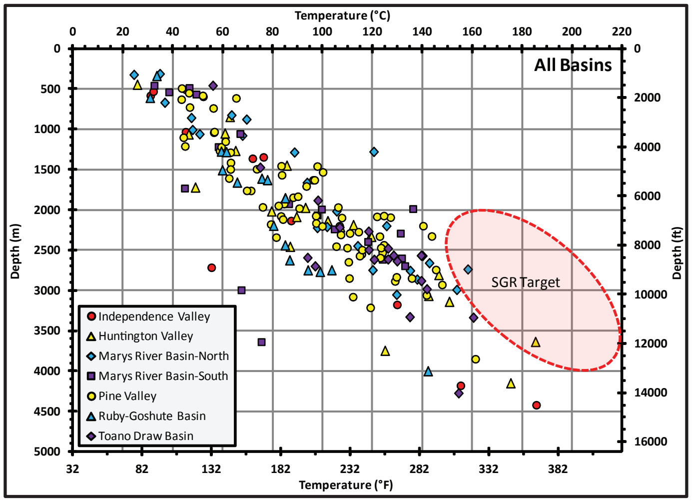

Figure 13. Temperature-depth plot for all wells with temperature (BHT and DST) data in the study area. Error bars are ±10°C. Stratigraphic Geothermal Reservoir (SGR) economic target is shown (Allis and Moore, 2014).

intercept the SGR target zone. The temperature scatter in the basins could be due to deep ground water circulation, complex geology, and/or temperature perturbations caused by drilling.

This limited investigation into regional heat flow shows that values are lowest in the RBG and IV sub-areas (75 and 80 mW/m²), while the other zones form a NE-trending band of slightly higher (85–95 mW/m²) heat flows. Consequently, the two zones with lower heat flow (RGB and IV) appear to have less SGR potential. However, the few wells in these two areas are widely spaced and may not fully characterize the thermal regimes. An additional factor is that heat flow in each sub-area is based on a single well (sometimes supported by a few others) and could be influenced by data uncertainties such as BHT corrections and thermal conductivity estimates. Higher temperatures were expected in RGB since the southern boundary is only about 20 km north of the hot wells in the highly prospective North Steptoe Basin, where temperatures are 180–200°C at depths of 3–4 km (Allis et al., 2012; Allis and Moore, 2014). It is possible that large-scale groundwater flow is sweeping heat from the RGB, in much the same way that seems to be happening in the southern portion of the Black Rock Desert in Utah (Gwynn et al., 2013) and in the Eureka Low of south-central Nevada (Lachenbruch and Sass, 1978, 1979; Sass and Lachenbruch, 1982; Masbruch et al., 2012). The remaining sub-areas (TDB, MRB North and South, HV and PV) all show at least marginally prospective temperatures, but they generally graze the bottom of the economic target zone. Data from wells in these areas show the importance of drilling in the deeper sections of the basins where the potential SGR is near the target depth and the insulating effects of the Quaternary and Tertiary basin fill can be maximized.

While temperature data suggest there is SGR-development potential in these basins, an important additional factor is whether adequate permeability exists in the target depth range. Much of the uncertainty stems from the complexity of the geology, but there is evidence, based on well data and the work of Mueller and Snoke (1993), Satarugsa and Johnson (2000), Wannamaker and Doerner (2002), Camilleri (2010a), and Heilweil and Brooks (2011), that potentially suitable units (primarily carbonates) are present at depth. Kirby (2012) compiled permeability data from the western U.S. and found that the mean permeability at depths of 3–5 km is 30 mDarcy (mD) for siliciclastic and 75 mD for carbonates. Although carbonates may form better aquifers, clean sandstones may also be suitable (Allis and Moore, 2014). Within the Great Basin, hydrogeologic data and pressure data from DSTs suggest widespread lateral permeability is present in the aquifer units beneath the basins (Masbruch et al., 2012, Allis, 2014). Drilling fluid losses in a number of wells provides additional support.

Seismic data will be critical to future exploration owing to the complicated and minimally constrained geology of the basins. Schelling et al. (2013) studied the availability and quality of existing seismic data for nine areas of geothermal interest in the Great Basin and determined that the data may help resolve the character of stratigraphic reservoirs. Nine seismic lines are available in the MRB-TDB area and Shelling (2013) reported the quality of two of these to be among the best he examined. Other exploration strategies outlined by Jennejohn (2009) and Young et al. (2012) may also be important. Along with seismic data, the acquisition of additional gravity data and new thermal-gradient wells deeper than 200 m should be the focus of future exploration. Additionally, cuttings and some intervals of core from 36 of the oil wells in the study area are archived by the NBMG (Schilling, 1977; Davis, 2001). Thermal conductivity studies of these samples would refine heat flows calculations.

Acknowledgements

This paper is part of a project titled: "Novel Geothermal Development of Sedimentary Basins in the United States," Moore, J.N., and Allis, R.G. (co-Principal Investigators), which is partially funded by the Geothermal Technologies Program of the U.S. Dept. of Energy (Award DE-EE0005128).

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