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Final Technical Report

Novel Geothermal Development of Deep Sedimentary Systems in the United States

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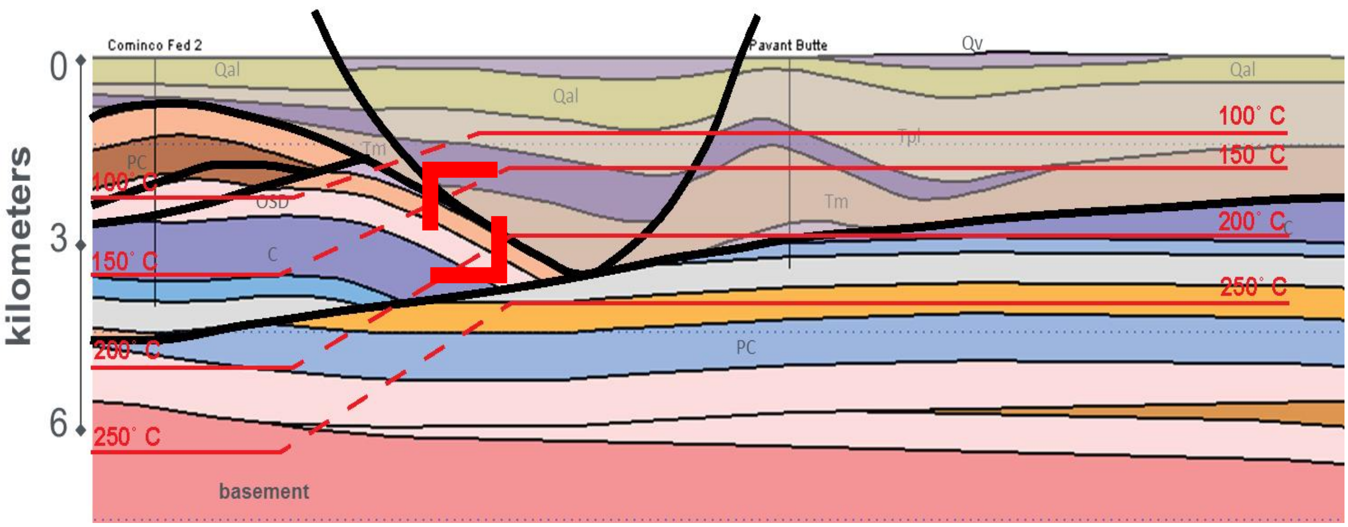

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Will Stratigraphic Reservoirs Provide the Next Big Increase in U.S. Geothermal Power Generation?

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ABSTRACT

Economic and reservoir engineering models show that stratigraphic reservoirs have the potential to contribute significant geothermal power in the U.S. If the reservoir temperature exceeds about 150 – 200 °C at 2 – 4 km depth, respectively, and there is good permeability, then these resources can generate power with a levelized cost of electricity (LCOE) of close to 10 ¢/kWh (without subsidies) on a 100 MW power plant scale. There is considerable evidence from both groundwater geology and petroleum reservoir geology that relatively clean carbonates and sandstones have, and can sustain, the required high permeability to depths of at least 5 km. This paper identifies four attractive stratigraphic reservoir prospects which are all located in the eastern Great Basin, and have temperatures of 160 – 230 °C at 3 – 3.5 km depth. They are the Elko basins (Nevada), North Steptoe Valley (Nevada), Pavant Butte (Utah), and the Idaho Thrust Belt. The reservoir lithologies are Paleozoic carbonates in the first three, and Jurassic sandstone and carbonate in the Idaho Thrust Belt. All reservoir lithologies are known to have high permeability characteristics. At North Steptoe Valley and Pavant Butte, nearby transmission line options allow interconnection to the California power market. Modern techniques for drilling and developing tight oil and gas reservoirs are expected to have application to geothermal development of these reservoirs.

Introduction

Most geothermal power developments in the U.S. have either tapped reservoirs overlying recent magmatic intrusions (Kennedy and Van Soest, 2007), and/or tapped hydrothermal reservoirs notable for permeability enhanced by near-vertical faulting (Faulds and others, 2013). Exploration since the 1970s has located the obvious hydrothermal reservoirs because of surface signatures such as hot springs, thermal ground, hydrothermal alteration, and silica deposits. Most reservoirs that are accessible and have been found to be commercially viable have already been developed; therefore, in recent years the rate of new developments has slowed, and total operating capacity in the U.S. has remained in the range of 2500 to 3500 MWe due to a variety of resource, environmental, and financial constraints (GEA, 2015).

A type of geothermal reservoir that has been investigated in Australia and Europe, but has not been an obvious exploration target in the U.S., is stratigraphic reservoirs. These reservoirs have their main permeability constrained within naturally permeable sedimentary formations, and therefore the reservoirs tend to be sub-horizontal, rather than sub-vertical and associated with fault zones and hydrothermal upflow. In reality, there is a continuum between the two types of reservoir, with faulting and stratigraphic permeability both important factors influencing the total reservoir volume, and therefore the sustainability of a production well field (McNitt, 1995). Two examples of this in the Great Basin of the U.S. are at Soda Lakes, Nevada, and at Cove Fort, Utah (Figure 1). In both cases the reservoirs have surface hydrothermal signatures controlled by faults, but the lateral extent of the reservoirs at depth is also clearly stratigraphic (McNitt, 1990; Rowley and others, 2013).

Studying the potential of stratigraphic reservoirs for future power generation has been supported by a U.S. Department of Energy project, with progress reported in series of publications (Allis and others, 2012, 2013; Allis and Moore, 2014). With the project now in its final year, this paper reviews several critical factors influencing the viability of these reservoirs, and then highlights what are the best prospects we have identified so far. The goal of this paper is to show that large-scale geothermal power developments are possible if modern technologies for drilling and permeability enhancement from petroleum exploration can be adapted and applied to stratigraphic geothermal resources. If the geothermal industry focuses on reservoir potential at 3 – 4 km depth, and developments that are 100's of MWe in scale are considered, then there are economies of scale offsetting the costs of increased reservoir depth, and numerous development opportunities are apparent.

Increased Reservoir Depth Target

Most developed geothermal reservoirs in the U.S. are at 1 – 3 km depth. Sanyal and others (2007) highlighted the change in production technology required at a reservoir temperature of about 190 °C between pumps on wells at lower temperatures, and self-discharging wells at higher temperatures (Figure 2). When considering the temperatures in deep basins, there is a pronounced difference between the temperature – depth charac-

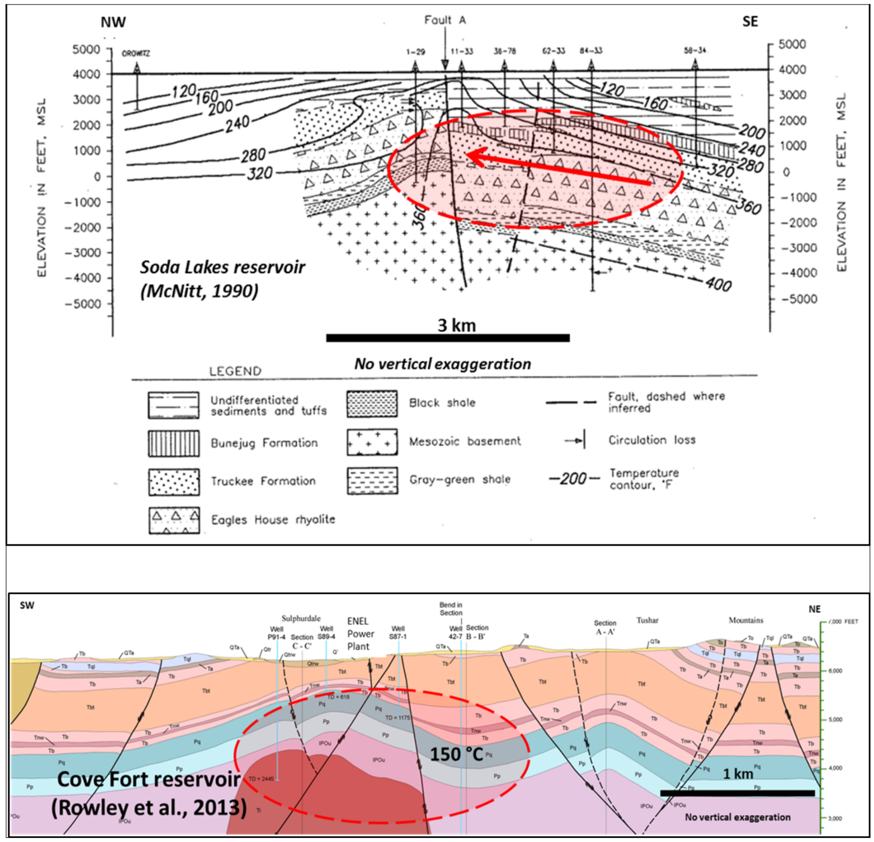

Figure 1. Two cross-section examples (reproduced from the original publications with minor modifications) of developed hydrothermal reservoirs where there is strong stratigraphic control to the permeability. In the case of Soda Lakes, the main permeability is relatively shallow at the base of the Truckee Formation, and lateral flow into the structural high from beneath the adjacent Carson Sink is suspected (McNitt, 1990; 400 °F is close to 200 °C). At Cove Fort, numerous wells have confirmed high permeability within Paleozoic carbonate units (labelled Pq, Pp and IPOu). Overlying Tertiary volcanic units (labelled Ta, Tb, etc.) act as a cap separating groundwater from the reservoir. In both cases, faults locally allow hot fluids to leak to the surface, and there are intrusive rocks at depth beneath the main reservoir.

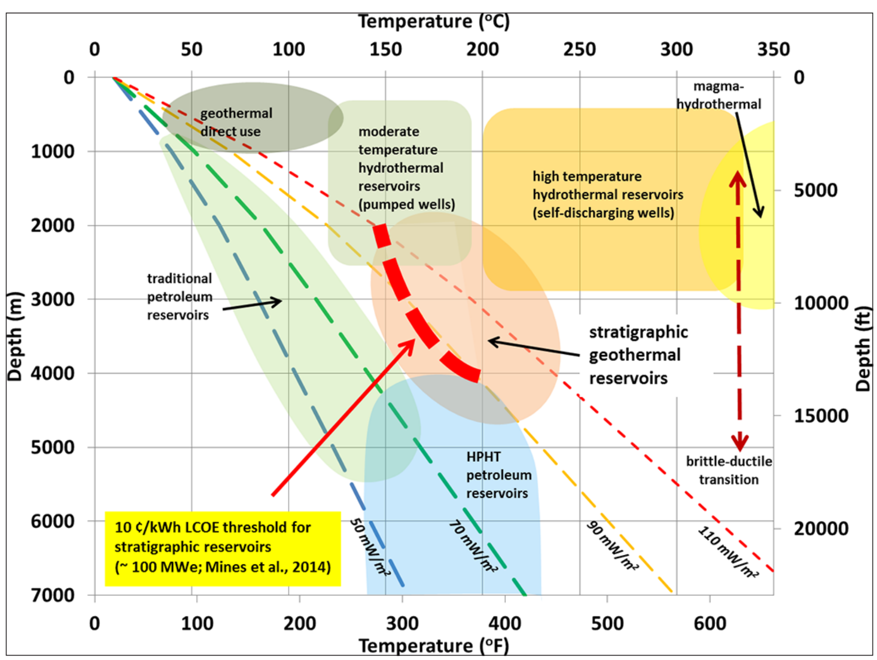

Figure 2. Contrast in thermal regimes of typical petroleum reservoirs and geothermal reservoirs. A levelized cost of electricity (LCOE) threshold derived from economic modeling provides a temperature-depth guide to the more attractive stratigraphic geothermal reservoirs (derived from Mines and others, 2014). If development of geothermal reservoirs at 3 – 4 km depth is economically viable, then there are many stratigraphic reservoir targets in the northern Great Basin where the heat flow is about 90 mW/m^2. The economic models do not include any subsidies.

teristics of most petroleum reservoirs, and those of most hydrothermal reservoirs. In high heat-flow settings, especially if there is a significant thickness of low thermal conductivity rocks (such as basin fill or shale), temperatures of about 200 °C can be found at 3 – 4 km depth where the heat flow is more than 90 mW/m^2. There are large areas in the western U.S. where such heat flows are common, especially in the Great Basin (Blackwell and others, 2011; Williams and DeAngelo, 2011). The high heat flow areas in the Great Basin are one of the largest, if not the largest, high heat-flow land areas in the world (30% of 500 x 500 km area at > 200 °C at 4 km depth; MIT, 2006). The 3 – 4 km depth range is an obvious target for the next generation of geothermal power developments in the U.S.

Can We Find Adequate Permeability at 3 – 4 km Depth?

Evidence from permeability tests in petroleum reservoirs confirms that permeabilities in the range of 30 – 100 mD are not uncommon at depths greater than 3 km (Figure 3). Kirby (2012) compiled permeability measurements from the western U.S. and found the geometric mean permeability between 3 and 5 km depth is 75 mD for carbonates and 30 mD for siliciclastics. There is no evidence in this dataset that permeability decreases with depth between 1 and 6 km depth with these two lithologies. However, there is a strong trend of decreasing permeability with depth in igneous rocks (volcanics and intrusives; most data is less than 2.5 km depth), probably due to the mixed mineralogy of igneous rock and their sensitivity to alteration and plugging of permeability with increasing temperature. Clean sandstones and carbonates appear to be the lithologies most likely to sustain permeability at depth and are an obvious target as possible reservoir rocks.

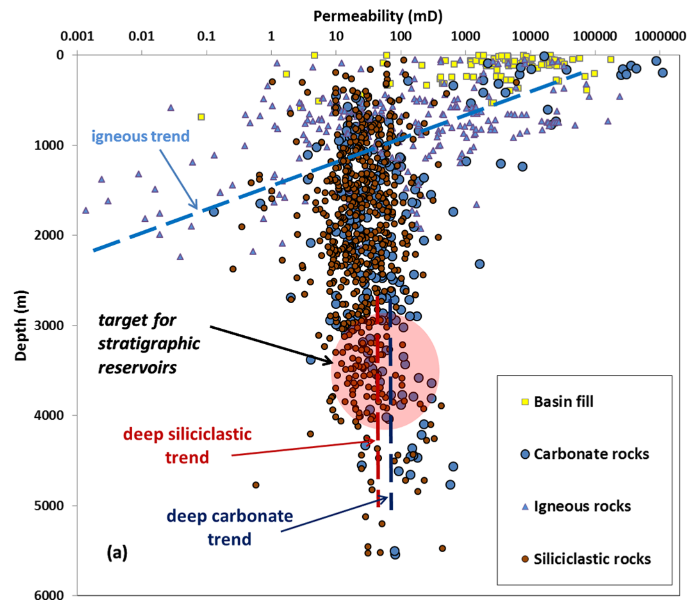

Figure 3. Compilation of permeability measurements documented in oil exploration (Dept. of Energy Gas Information System - GASIS) and groundwater databases for the Great Basin and Rocky Mountain regions (Kirby, 2012), split by lithology. The red zone highlights the measurements in the depth range of interest (3 - 4 km) for stratigraphic geothermal reservoirs.

The effective reservoir thickness with a target permeability of 10 – 100 mD is another important factor influencing the heat sweep efficiency (heat recovery factor) within a reservoir. Modeling of different reservoir-seal "sandwiches" comprising four 25-m-thick horizontal layers with permeabilities of 100 mD within a 300-m-thick host rock of 1 mD showed very different thermal responses over 50 years of production and injection (Roehner and others, 2014). The models utilized a five spot pattern with a 500 m well spacing, with flow rates in producer and injector wells of 63 L/s (1000 gallons per minute). The sandwich model with a cumulative reservoir "pay zone" transmissivity of 10 D-m, had a power density declining from 10 to 4 MWe/km^2 after 30 years of production, with the thermal rundown starting after about 10 years. Not surprisingly, the more dispersed the flow regime in multiple layers, the better the heat sweep efficiency and the slower the thermal decline. However, when the transmissivity of the reservoir decreases to 3 D-m, the improved heat sweep efficiency is compromised by excessive pressure decline in the production wells. Modeling including the parasitic loads of pumps, and investigating the impacts of varying production flow rate, well spacing and configuration, and reservoir permeability characteristics are continuing.

An important difference between stratigraphic reservoirs and faulted hydrothermal reservoirs commonly developed to date in the Great Basin is reservoir volume and the scale of developments. Reservoir areas of less than several square kilometers for hydrothermal systems in the Great Basin (Blackwell and others, 2012) mean modest sustainable power generation levels, typically less than 50 MWe. With stratigraphic reservoirs, the potential area of the reservoir can be almost basin scale, and therefore hundreds of square kilometers. Once a discovery well verifies the thermal regime, permeability characteristics, and their relationship to the stratigraphy, subsequent step-out wells have much lower risk. Although the main permeability is sub-horizontal, if faults are also present, they may be zones of enhanced permeability that become important targets for wells.

The possibility of laterally extensive, high permeability carbonate units at depth beneath the eastern Great Basin having an effect on regional heat flow has long been recognized (Sass and others, 1971; Lachenbruch and Sass, 1977; Blackwell, 1983). Recent work by the USGS reassessing the hydrogeology of the Great Basin carbonate system has characterized the key hydrological units (Heilweil and Brooks, 2011; Figures 4, 5). Of greatest interest for the geothermal reservoir potential is the "lower carbonate aquifer unit" which comprises mainly Cambrian through Devonian limestone and dolomite, and is prominently exposed in the mountain ranges. The USGS compilation of hydraulic property measurements indicates it has a geometric mean hydraulic conductivity of 4 feet per day (about 150 mD; the average depth of these measurements not stated), and a maximum thickness of 5 km. The cross sections in Figure 5 show there is good connectivity in a north-south direction, but early compressional faulting, followed by extensional faulting in the Cenozoic, has dissected the unit in an east-west direction. Masbruch and others (2012) confirmed that lower heat flow in the southern sector of the carbonate system is due to groundwater recharge and lateral (mostly southern) drainage of cool groundwater at depth. The large "Eureka heat flow" in the southern Great Basin is attributed to this effect (Sass and others, 1971). More important for preserving high temperatures within permeable carbonate units will be the areas of the Great Basin where interbasin flow is more subtle and perhaps directed inwards to hydrologic sinks with no, or minimal, lateral outflow. Numerous examples exist in the northern half of the Great Basin carbonate system.

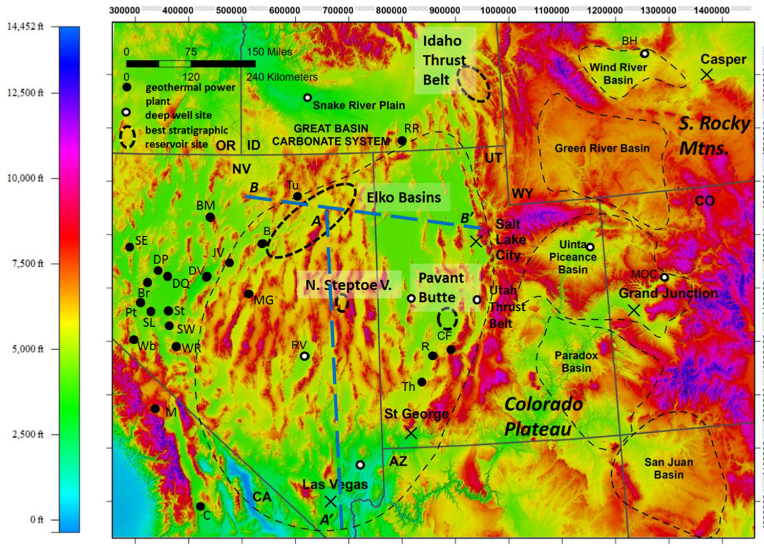

Figure 4. Shaded relief map (feet above sea level) of the eastern Great Basin and western Colorado Plateau. The Great Basin Carbonate System (Heilweil and Brooks, 2012) occupying the eastern half of the Great Basin is dashed. The hydrogeology beneath two cross sections labeled as A-A', B-B' (heavy blue dashes) is shown in Figure 5. Geothermal power plants, and wells referred to in the text, are also highlighted. The four areas promoted here as having the best proven stratigraphic geothermal reservoir potential are Pavant Butte, North Steptoe Valley, the Elko basins, and the Idaho Thrust Belt (black dashed ellipses). Power plant abbreviations are: B, Beowawe; BM, Blue Mountains; Br, Brady; C, Coso; CF, Cove Fort; DP, Desert Peak; DQ, Desert Queen; DV, Dixie Valley; M, Mammoth; MG, McGuinness; Pt, Patua; R, Roosevelt, RR, Raft River; SE, San Emidio; SL, Soda Lakes; St, Stillwater; SW, Salt Wells; Th, Thermo; Tu, Tuscarora; W, Wabuska; WR, Wild Rose. Deep well abbreviations are: BH, Bighorn #2-3 in Wind River Basin; MOC, Mobil O'Connell well in eastern Piceance Basin; RV, Railroad Valley.

Levelized Cost of Electricity (LCOE) With Reservoirs at 3 – 4 km Depth

The greater depth of these reservoirs raises questions about whether the extra drilling costs still allow a viable project. The effects of many factors were investigated by Mines and others (2014) using the GETEM modeling tool. An important difference from many recent hydrothermal developments in the Great Basin is the scale of development for stratigraphic reservoirs. With potential areas of 100's to 1000's km^2 within basins, rather than 1 – 10 km^2 for fault-bounded systems, 100+ MW power plants are feasible, and significant economies of scale are possible (for example, drilling costs). The drilling costs assumed by Mines and others (2014) were based on 2013 prices, and the cost of a 3 – 4 km deep well ranged between $5 - $10 million depending on assumptions of "smaller" diameter (7 inch perforated inside 8.5 inch casing) or "larger" diameter (9.625/12.25 inch). Another critical variable was the reservoir productivity/injectivity index (PI/II), which ranged from the GETEM default of 52

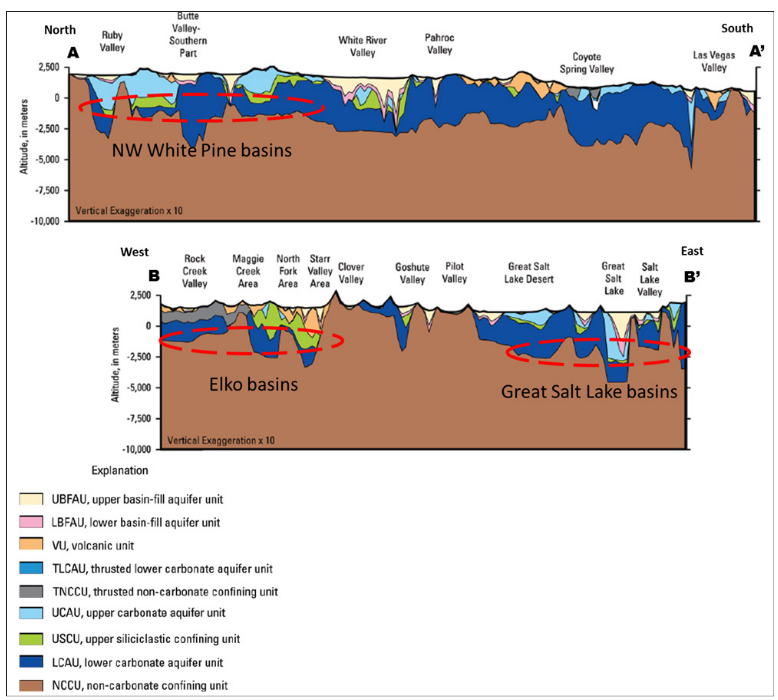

Figure 5. Cross sections illustrating the three-dimensional hydrogeological framework developed by the USGS for the Great Basin carbonate and alluvial aquifer system (Sweetkind and others, 2011; Masbruch and others, 2012). The deep blue lower carbonate aquifer unit represents potential stratigraphic geothermal reservoirs wherever the temperature is in the range of 150 - 200 °C. The cross-section lines are shown on Figure 4. The red ellipses highlight zones where stratigraphic geothermal reservoir targets have been identified by this project. The volcanic and basin-fill units are Tertiary and younger. Remaining units are Paleozoic and older. There is no TLCAU on these two cross sections.

L/s/bar (mod PI/II) to 104 L/s/bar (Hi PI/II). Although initial modeling runs assumed a reservoir decline rate of 1% per year, based on the reservoir modeling discussed above, the positive cash-flow effect on the LCOE of delayed thermal decline by a decade was also considered. Examples of some of these variables are shown in Figure 6.

The effects on the LCOE from the interplay between the various factors are discussed by Mines and others (2014). Perhaps the most useful guideline for this paper is that if the LCOE is to be close to 10¢/kWh, then reservoir temperature has to increase from about 150 °C for a reservoir depth of 2 km, to about 200 °C when the reservoir depth is 4 km (LCOE "threshold" shown on Figure 2). The increasing efficiency of the power conversion with increasing temperature compensates for the increased cost of deeper wells. At 4 km depth all the variables need to be favorable, so a reservoir target not significantly deeper than 3 km and close to the maximum temperature of pumps (~ 190 °C) is considered optimal for a stratigraphic reservoir. Once the viability of these reservoirs is demonstrated, a greater range of reservoir conditions should be a target. A characteristic heat flow geotherm for the northern Great Basin of 90 mW/m^2 grazes the 10¢/kWh LCOE threshold at reservoir depths between 3 and 4 km (Figure 2).

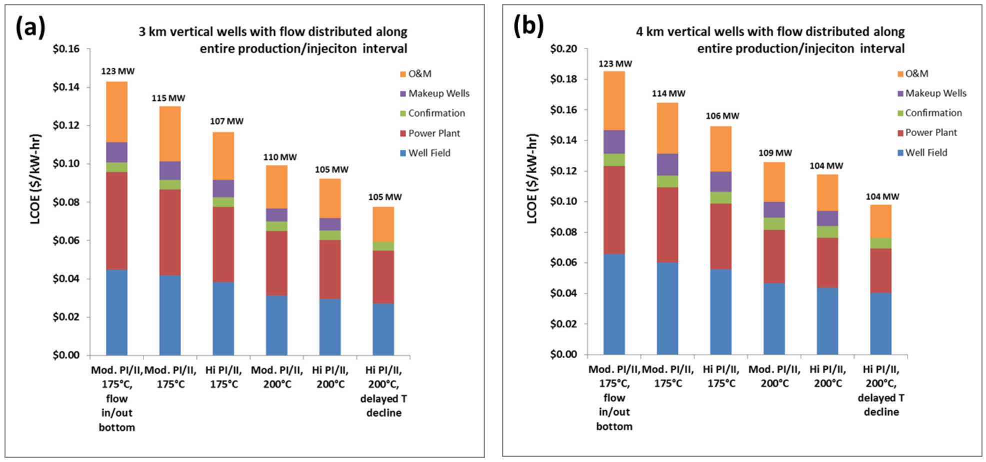

Figure 6. Variations in LCOE and the cost components contributing to the total cost estimate (Mines and others, 2014). (a) is for 3 km-depth vertical wells, (b) is for 4 km-depth vertical wells. The models shown here tested varying reservoir temperature and depth, moderate and high productivity/injectivity indices, distributed and dispersed inflow to wells, and a 10-year delay in the temperature decline curve.

Four Attractive, Undeveloped Reservoir Prospects

Four areas in the eastern Great Basin are attractive prospects because of evidence for reservoirs having both the required temperature and a stratigraphic, high-permeability target. These are the Elko basins (Nevada), North Steptoe Valley (Nevada), Pavant Butte (Utah), and the Idaho Thrust Belt (Figures 4, 7). Details of the thermal characteristics of each of these can be found in: Elko basins (Gwynn and others, 2014; Kirby and others, 2015); N. Steptoe Valley (Allis and others, 2012; Gwynn, 2015); Pavant Butte (Gwynn and others, 2013; Hardwick and others, 2014; Allis and others, 2015); and the Idaho Thrust Belt (Welhan and others, 2014; Welhan and Gwynn, 2014). Here we summarize the key features that make these prospects attractive. Characteristic cross sections are shown in Figure 8.

The Elko basins comprise the following basins from northeast to southwest: Toano, Marys River, Huntington, and Pine Valley. We suspect Crescent Valley may also be included, but there is insufficient deep well data. On the basis of a small amount of deep well data, the Ruby-Goshute Valleys appear to be significantly cooler. However, in this case, very shallow (typically less than 150 m depth) thermal gradient data in central Ruby Valley (Phillips Geothermal data documented in Sass and others, 1999) suggest the possibility of gradients of 70 – 100 °C/km, so additional thermal information is

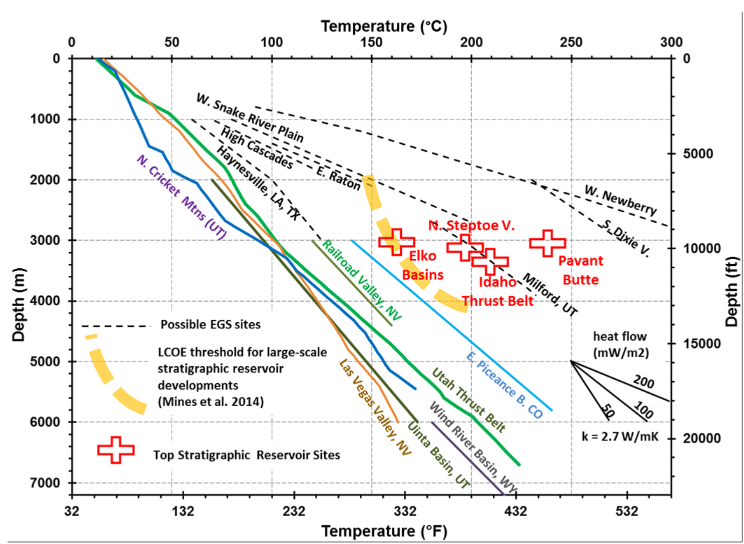

Figure 7. Thermal characteristics of the four most attractive stratigraphic reservoir prospects identified so far by this project (red crosses). Conductive thermal regimes overlie these prospects but for simplicity, the temperature-depth trends are not shown. As background, the geotherms from several basins with very deep oil exploration wells within and east of to the Great Basin are shown as colored lines. Also shown are geotherms from several sites recommended for enhanced geothermal system (EGS) projects, which typically are in volcanic or intrusive rock at depth (black dashed lines; examples from Blackwell and others, 2013).

needed to resolve the uncertainties. A very simple cross section is shown in Figure 5 (A-A'), but the geological setting is complex. Lower Paleozoic carbonates form a thick section at depth in the east, but in the west this carbonate platform has been overridden from the west by typically more siliciclastic, deep-water marine rocks of the Roberts Mountain thrust belt. At Beowawe geothermal field on the west edge of these basins there is a thick sequence of low-permeability, shale-rich Ordovician rock which is inferred to overlie carbonate units at greater depth (Zoback, 1979; Kirby and others, 2015). In Blackburn oilfield (Pine Valley), the oil reservoir is in Devonian dolomite and this is overlain by 2 km of Tertiary volcanics and younger basin fill. A substantial gravity low in Marys River Basin suggests over 3 km of basin fill (Heilweil and Brooks, 2011). The reservoir target for geothermal development is the lower Paleozoic carbonate unit (LCAU of Sweetkind and others, 2011), but an integration of the geology with reinterpreted seismic lines and a 3-D gravity survey are needed before deep drilling is justified. There appear to be lateral variations in the thermal regime within and between the basins, so confirmation with some new heat-flow holes is also required. The most attractive area within the Elko basins at the moment is the Marys River Basin. The One Nevada transmission line that is planned to connect renewable energy power projects in northeast Nevada and southern Idaho with southwest Nevada and California was completed as far north as Ely in 2013. The planned route further north passes through the Elko basins, and may be important if large-scale geothermal power generation is viable here.

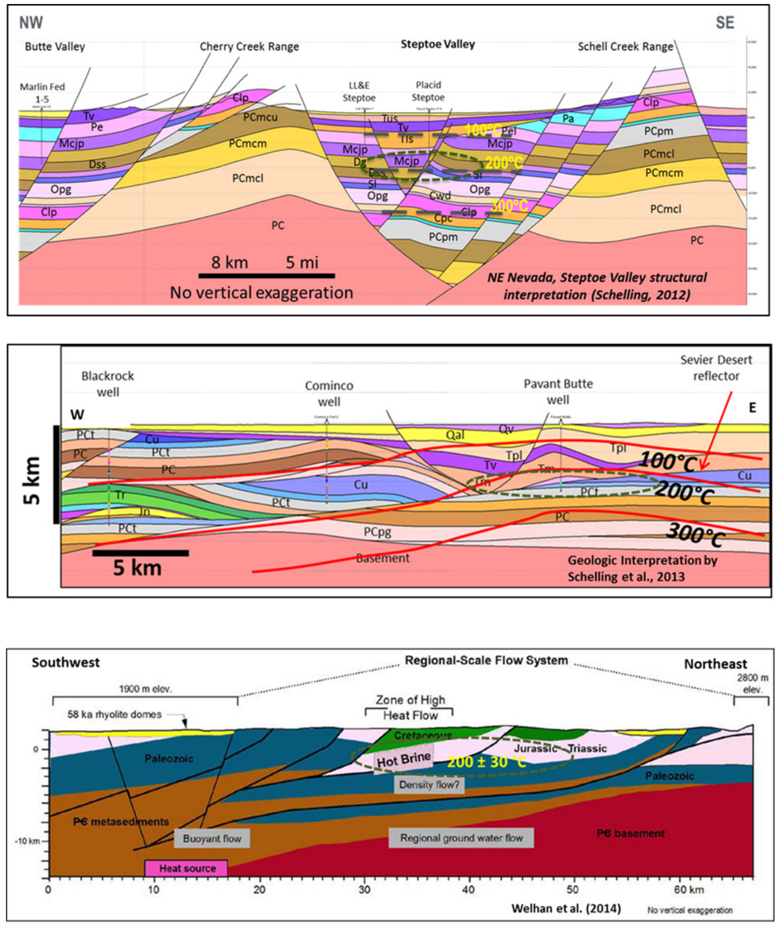

Figure 8. Characteristic cross-sections of three of the areas identified as the best prospects for large-scale geothermal development: North Steptoe Valley, Nevada (upper), Pavant Butte, Utah (middle) and Idaho Thrust Belt (lower). A simple section through the Elko basins is shown in Figure 5 (A – A'). The dashed green ellipses highlight reservoir targets. The geologic units in the upper two sections are: PC, Precambrian; C, O, S, D, M, and P are Paleozoic subdivisions; J, T are Mesozoic subdivisions, T is Tertiary and Q is Quaternary. For more explanation refer to the original references.

North Steptoe Valley has both the thermal regime and the reservoir target relatively well-determined. Shell Oil (Shell-1) and Placid Oil (well 17-14) drilled in the center of the valley, and confirmed 2 km of valley fill and predominantly Paleozoic carbonates and shale to at least 3566 m depth. The temperature between 3 and 3.5 km depth ranges between 170 and 200°C. Four carbonate units, the Guilmette Formation, Simonson Dolomite, Sevy Dolomite, and Ely Springs Dolomite, are known elsewhere to have characteristically high permeability. These units represent a potential reservoir section more than 500 m thick. In addition, faults may enhance the permeability in this section of the Placid Oil well. About 20 km to the south, Hunt Energy Corp. conducted some temperature-gradient drilling in the late 1970s and then drilled two geothermal exploration wells (Chovanec, 2003). The deepest well (74-23) had a temperature of 198°C at its total depth of 3308 m. The continuous temperature profile in this well is remarkably similar to the trend of corrected bottom hole temperatures (BHTs) in the two wells in the center of the valley to the north. Well 74-23 penetrated a quartz monzonite intrusion below about 1700 m depth, which confirms the gravity anomalies and suggests the basin is slightly deeper, extending at least 20 km farther north. Based on the present information, the prospective area with attractive temperatures at about 3 km depth extends over at least 200 km^2. More detailed gravity data is required to better define the base of the surface fill, and some modern seismic reflection surveying is also required to image the lower Paleozoic carbonate section (i.e., beneath the Chainman Shale) and faults such as the one suspected at 3200 m in the Placid Steptoe well 17-14 (Figure 8). Some oil industry seismic lines have been collected in this valley, but unfortunately the quality of the reflections from beneath the valley fill is poor (Schelling and others, 2013). Based on the known potential reservoir section at 3 km depth in the middle of the valley, and the apparent uniformity of the thermal regime across the basin, even with a conservative power density of 3 MWe/km^2, Allis and Moore (2014) suggest this basin should support a power plant of several hundred MWe. Connection to the present northern terminus (Robinson sub-station) of the new One Nevada line is 30 miles from North Steptoe Basin.

Pavant Butte has a well-determined thermal regime based on the Pavant Butte oil exploration well and its re-entry by Phillips Geothermal two years after being plugged and abandoned by Arco. The best-fit geotherm using thermal conductivities measured on cuttings from Pavant Butte 1 (Edwards, 2013) has a heat flow of 140 ± 20 mW/m^2, and predicts a temperature of 238 °C at 3 km, and 281 °C at 4 km depth. These results suggest some of the highest temperatures in Utah at these depths may exist near Pavant Butte volcano. High-permeability characteristics that could be geothermal reservoir targets are the Quaternary fault zone that traverses the graben, and stratigraphic permeability such as that described by Allis and others (2012) and Allis and Moore (2014). The Pavant Butte 1 well drilled a 400 m section of Lower Cambrian bedrock at the bottom of the well, which is known to be permeable where it outcrops around the basin, but there were no strong indicators of high permeability within the well. The Lower Cambrian section included limestone, phyllite and quartzite (Hintze and Davis, 2003). Allis and others (2012) noted fractures at 3040 m (mud loss of 15 barrels) and possible fractures from 3064 to 3069 m, and from 3266 to 3274 m. Reinterpretation of existing seismic lines (1980s vintage), and some additional shallow heat-flow holes are needed to refine the reservoir target and establish whether the thermal anomaly is centered beneath the axis of the basin, or beneath Pavant Butte volcano. There are several transmission line options close to Pavant Butte that allow easy connection to the California power market.

The Idaho Thrust Belt has the least amount of thermal data of the four prospects, but three deep oil exploration wells have temperatures of 160 to 230 °C at about 3 km depth, suggesting a substantial resource in a 300 km^2 area. At this stage it is unclear whether the high heat flow is associated with the late Quaternary Blackfoot volcanic field to the southwest, or whether the thermal anomaly is a flank effect of the high heat-flow Snake River Plain to the north. Welhan and others (2014) suggest that limestone and sandstone of Pennsylvanian to Jurassic age at 3 – 5 km depth represent target reservoir rocks (Figure 8). The Jurassic Nugget sandstone is a prolific oil producer further south in the thrust belt; it is known to have permeabilities of about 100 mD (Lindquist, 1988), sufficient for a geothermal reservoir, and occurs at about 3 km depth in the thrust belt. There is some evidence for brines in deeper parts of the thrust belt, and Welhan and others (2014) also suggest that lateral (stratigraphic) movement of pore fluid could be influencing the thermal regime. Additional heat-flow measurements are needed to better delineate the resource before deep drilling is attempted. A high-voltage transmission line runs northwest from Soda Springs and is about 30 km from the high heat flow area (Welhan, pers. comm., 3/30/2015).

Conclusions

The thick, shallow-marine carbonate platform that developed during the early Paleozoic and is now at varying depths below the ground surface of the eastern Great Basin is considered by hydrologists to be an important aquifer contributing to interbasin flow. This aquifer is also a natural geothermal reservoir target where it has the optimal temperature (150 – 200 °C) and depth (3 – 4 km) for economic power generation. The sub-horizontal characteristics of stratigraphic units mean that these reservoirs can have areas of hundreds of square kilometers, and the potential to support power plants of hundreds of MWe. Where these aquifer/reservoir units outcrop or have been used for groundwater developments, their high permeability has been proven. Permeability measurements from drill stem tests in oil reservoir exploration in the western U.S. confirm that clean carbonates and sandstones can have the required high permeability for geothermal wells at depths to at least 5 km.

Four examples of potential stratigraphic geothermal reservoirs at about 3 km depth are identified in this paper. At Pavant Butte the reservoir is Cambrian carbonate, in the Elko basins it is Devonian dolomite, in North Steptoe Valley it is Mississippian carbonate, and in the Idaho Thrust Belt it is Jurassic sandstone and limestone. In all four cases the thermal regime is reasonably well determined, although additional heat-flow measurements are recommended. The greatest risk for development is proving that the necessary permeability is actually present. An exploration well to reservoir depth is still required before planning and scaling up for a power project in these prospects. With tight oil and gas exploration in a new play, a "stiletto" strategy is sometimes used, with the first deep well being near-vertical and used for intensive downhole investigations prior to a program of horizontal drilling. Seismic reflection surveying, which has been of limited value for developing fault-hosted hydrothermal systems in the Great Basin, is considered an essential exploration technique in defining both structure and stratigraphy prior to deep drilling of stratigraphic reservoirs. One advantage of developing these reservoirs is once the optimal drilling and stimulation technique has been established, the rest of the well field should be simple step-out grid drilling, and economies of scale should reduce the cost per MWh. Recent technological advantages in drilling in tight oil and gas fields in the U.S. have shown significant savings with centralized drill pads accommodating more than 20 wells, and skid-mounted rigs that can be slid several meters to their next well head position without dismantling. Acid stimulation techniques, which are common in carbonate oil reservoirs, are also likely to be applicable in these geothermal reservoirs.

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References

Allis, R., Blackett, R., Gwynn, M., Hardwick, C., Moore, J. N., Morgan, C., Schelling, D., and Sprinkel, D. 2012. Stratigraphic reservoirs in the Great Basin – the bridge to Enhanced Geothermal Systems in the U.S., Geothermal Resources Council Transactions, 36, p. 351-357.

Allis, R., Moore, J.N., Kirby, S., Anderson, T., and Spencer, T. 2013. Characterizing the power potential of hot stratigraphic reservoirs in the Great Basin, U.S. Proccedings, 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, Feb 11-13, 2013, pp. 11, SGP-TR-198.

Allis, R., and Moore J. 2014, Can deep stratigraphic reservoirs sustain 100 MW power plants: GRC Transactions, Vol. 38, 1009-1016.

Allis, R., Hardwick, C., Gwynn, M., and Johnson, S., 2015. Pavant Butte geothermal prospect revisited. Submitted to Geothermal Resources Council Transactions, April 2015.

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., and others, 2011 Heat flow map of the conterminous United States, Google.org/egs, 2011.

Blackwell, D.D., Waibel, A.F., and Richards, M., 2012. Why Basin and Range systems are hard to find: The moral of the story is they get smaller with depth! Transactions, Geothermal Resources Council, 36, 1321-1326.

Blackwell, D.D., Frone, Z., and Richards, M., 2013. The future of geothermal energy: the shale gas analogy. Significant electrical EGS resource areas in the U.S. Transactions, Geothermal Resources Council, 37, 117 – 122.

Chovanec, Y.M., 2003. Geothermal analysis of Schellbourne, east-central Nevada. MS thesis, University of Texas at Arlington, pp. 124.

Edwards, M.C., 2013. Geothermal resource assessment of the Basin and Range Province in western Utah. M.S. thesis, Departtment of Geology and Geophysics, University of Utah. pp.111.

Faulds, J. E., Hinz, N.H., Dering, G.M., and Siler, D.L., 2013. The hybrid model – the most accommodating structural setting for geothermal power generation in the Great Basin, western U.S. Geothermal Resources Council Transactions, Vol. 37, 3-10.

GEA 2015. 2015 Annual U.S. & global geothermal power production report. Geothermal Energy Association Report. Online: http://geo-energy.org/reports/2015/2015%20Annual%20US%20%20Global%20Geothermal%20Power%20Production%20Report%20Draft%20final.pdf.

Gwynn, M., Blackett, R., Allis, R. and Hardwick, C. L., 2013. New geothermal resource delineated beneath Black Rock Desert, Utah. Proceedings, 38th Workshop on Geothermal Reservoir Engineering, Stanford University, 1511-1519, SGP-TR-198.

Gwynn, M., Allis, R., Sprinkel, D., Blackett, R., and Hardwick, C., 2014. Geothermal potential in the basins of northeastern Nevada, Geothermal Resources Council Transactions, Vol. 38, p. 1029-1039.

Gwynn, M.L., 2015. Geothermal Potential in the Basins of East-Central and Southeastern Nevada. Submitted to Geothermal Resources Council Transactions, April 2015.

Hardwick, C. L., Kirby, S., and Gwynn, M., 2014. Geothermal prospecting in Utah: A new thermal model of the Black Rock Desert, Geothermal Resources Council Transactions, Vol. 38, p. 1041-1045.

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.

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

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

Kirby, S. M. 2012. Summary of compiled permeability with depth measurements for basin, igneous, carbonate, and siliciclastic rocks in the Great Basin and adjoining regions. Open File Report 602, Utah Geological Survey, pp. 12.

Kirby, S., Simmons, S., Gwynn, M., and Moore, J., 2015. Comparisons of geothermal systems in central Nevada: Evidence for deep regional geothermal potential based on heat flow, geology, and fluid chemistry. Submitted to Geothermal Resources Council Transactions, April 2015.

Lachenbruch, A.H., and Sass, J.H., 1977. Heat flow in the United States and the thermal regime of the crust. In: Heacock, J.G. (ed.) The Earth's Crust, Geophys. Mono. Ser. 20, American Geophysical Union, 626 – 675.

Lindquist, S.J., 1988, Practical characterization of eolian reservoirs for development-Nugget Sandstone, Utah-Wyoming thrust belt: Sedimentary Geology, 56, 1-4, 315-339.

Masbruch, M.D., Heilweil, V.M., and Brooks, L.E., 2012. Using hydrological data to evaluate geothermal potential in the eastern Great Basin. GRC Transactions, Vol. 36, 47-52.

McNitt, J.R., 1990. Stratigraphic and structural controls of the occurrence of thermal fluid at the Soda Lakes geothermal field, Nevada. Transactions, Geothermal Resources Council, 14, Part II, 1507 – 1512.

McNitt, J.R., 1995. A new model for geothermal exploration of non-volcanic systems in extended terrains. Proceedings, World Geothermal Congress, Bali, 1115 – 1118.

Mines, G. Allis, R., Moore, J., and Hanson, H., 2014, Economics of developing hot stratigraphic reservoirs: GRC Transactions, v. 38, p. 1047-1054.

MIT, 2006. "The Future of Geothermal Energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century, "Massachusetts Institute of Technology and U.S. Department of Energy Report, Idaho National Laboratory, INL/EXT-06-11746.

Roehner, R., Deo, M., Moore, J., and Allis, R., 2014, Modeling geothermal energy production from stratigraphic reservoirs in the Great Basin: Geothermics, v. 51, p. 38-55.

Rowley, P.D., Rutledge, E.F., Maxwell, D.J., Dixon, G.L., and Wallace, C.A., 2013. Geology of the Sulphurdale geothermal resource area, Beaver and Millard Counties, Utah. Utah Geological Survey Open File Report 609, pp. 27 and 2 plates.

Sanyal, S.K., Morrow, J.W., and Butler, S.J., 2007. Geothermal well productivity: why hotter is not always better. Transactions, Geothermal Resources Council, 31, 573 - 579.

Sass, J.H., Lachenbruch, A.H., Munroe, R.J., Green, G.W., and Moses, T.H., 1971. Heat flow in the western United States, Journal of Geophysical Research, 76, 6358-6431.

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

Schelling, D., 2012. Results of an evaluation of 2D seismic data from the Basin and Range tectonic province of western Nevada and Utah. Unpublished report submitted to Utah Geological Survey, p. 10.

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

Sweetkind, D.S., Cederberg, J.R., Masbruch, M.D., and Buto, S.G., 2011. Hydrogeologic framework. Chapter B in Heilweil, V.M., and Brooks, L.E., eds., Conceptual model of the Great Basin carbonate and alluvial aquifer system. U.S. Geological Survey Scientific Investigations Report 2010-5193, 15-50.

Welhan, J. and Gwynn, M., 2014. High heat flow in the Idaho thrust belt: A Hot Sedimentary Geothermal Prospect. GRC Transactions, Vol. 38, 1055-1066.

Welhan, J., Gwynn, M., Payne, S., McCurry, M., Plummer, M., and Wood, T. 2014. The Blackfoot Volcanic Field, southeastern Idaho: A hidden high-temperature geothermal resource in the Idaho Thrust Belt. Proceedings, 39th Workshop on Geothermal Reservoir Engineering, Feb. 24-26, 2014, pp. 9. SGP-TR-202.

Williams, C.F., and DeAngelo, J., 2011. Evaluation of approaches and associated uncertainties in the estimation of temperatures in the upper crust of the western United States. Transactions, Geothermal Resources Council, 35, 1599 – 1605.

Zoback, M. L., 1979, Geologic and geophysical investigation of the Beowawe geothermal area, north-central Nevada: Stanford Univ. Pub. Geol. Sci., vol. XVI, 79 pp.

2011

Allis, R., Moore, J. N., Blackett, B., Gwynn, M., Kirby, S., Sprinkel, D., 2011, The Potential for Basin-Centered Geothermal Resources in the Great Basin, GRC *Transactions,* Vol. 35

Hardwick, C. L., Chapman, D. S. 2011, Geophysical Delineation of the Crater Bench, Utah, Geothermal System, GRC *Transactions*, Vol. 35

2012

Allis, R, Blackett, B., Gwynn, M., Hardwick, C., Moore, J.N., Morgan, C., Schelling, D., Sprinkel, D. A., 2012, Stratigraphic Reservoirs in the Great Basin — The Bridge to Development of Enhanced Geothermal Systems in the U.S., GRC *Transactions*, Vol. 36

Hardwick, C. L., Chapman, D., 2012, Geothermal Resources in the Black Rock Desert, Utah: MT and Gravity Surveys, GRC *Transactions*, Vol. 36

Kirby, S. M., 2012, Summary of compiled permeability with depth measurements for basin fill, igneous, carbonate, and siliciclastic rocks in the Great Basin and adjoining regions, Open-File report 602, Utah Geological Survey, Division of Utah Department of Natural Resources

Kirby, S. M., 2012, Summary of compiled fluid geochemistry with depth analyses in the Great Basin and adjoining regions, Open-File report 603, Utah Geological Survey, Division of Utah Department of Natural Resources

Masbruch, M. D., Heilweil, V. M., Brooks, L. E., 2012, Using Hydrogeologic Data to Evaluate Geothermal Potential in the Eastern Great Basin, GRC *Transactions*, Vol. 36

2013

Allis, R., Moore, J. N., Anderson, T., Deo, M., Kirby, S., Roehner, R., Spencer, T., 2013, Characterizing the Power Potential of Hot Stratigraphic Reservoirs in the Western U.S., PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198

Anderson, T. C., 2013, Geothermal Potential of Deep Sedimentary Basins in the United States, GRC *Transactions*, Vol. 37

Deo, M., Roehner, R., Allis, R., Moore, J. N., 2013, Reservoir Modeling of Geothermal Energy Production from Stratigraphic Reservoirs in the Great Basin, PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013 SGP-TR-198

Gwynn, M., Blackett, B., Allis, R., Hardwick, C., 2013, New Geothermal Resource Delineated Beneath Black Rock Desert, Utah, PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198

Hardwick, C. L., 2013, Geothermal Resources in Southwestern Utah: Gravity and Magnetotelluric investigations, Thesis submitted to the faculty of The University of Utah, Master of Science in Geophysics Department of Geology and Geophysics, The University of Utah, August 2013

Holbrook, J., Moore, J., Snyder, W., 2013, The Promise of geothermal energy, in: Tracking the Energy Elephant, ed. Holbrook, J., NSF-SEES Workshop Report, pp. 10-11.

Schelling, D., Allis, R., Sprinkel, D., 2013, Role of Seismic Reflection Profiles in Delineating Basin-Centered Geothermal Reservoirs, GRC Transactions, Vol. 37

Wannamaker, P. E., Maris, V., Hardwick, C. L., 2013, Basin and Rift Structure of the Central Black Rock Desert, Utah, and Initial Thermal Implications, From 3D Magnetotellurics, GRC *Transactions*, Vol. 37

2014

Allis, R., 2014, Formation Pressure as a Potential Indicator of High Stratigraphic Permeability PROCEEDINGS, Thirty-Ninth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 24-26, 2014, SGP-TR-202

Allis, R., Moore, J. N., 2014, Can Deep Stratigraphic Reservoirs Sustain 100 MW Power Plants?, GRC *Transactions*, Vol. 38

Preliminary Studies of Geothermal Resources — Northern Great Salt Lake Region, Utah Robert E. Blackett, Mark L. Gwynn, Christian L. Hardwick, and Richard G. Allis, GRC *Transactions*, Vol. 38, 2014

Gwynn, M., Allis, R., Sprinkel, D., Blackett, R., Hardwick, C., 2014, Geothermal Potential in the Basins of Northeastern Nevada, GRC *Transactions*, Vol. 38

Hardwick, C. L., Kirby, S., Gwynn, M., 2014, Geothermal Prospecting in Utah: A New Thermal Model of the Black Rock Desert, GRC *Transactions*, Vol. 38

Mines, G., Allis, R., Moore, J., Hanson, H., 2014, Economics of Developing Hot Stratigraphic Reservoirs, GRC *Transactions*, Vol. 38

Simmons, S. F., Moore, J. N., 2014, Preliminary Assessment of Fluid-Mineral Equilibria in Dilute Thermal Waters from Sedimentary Aquifers: Implications for Geothermal Resources, PROCEEDINGS, Thirty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 24-26, 2014, SGP-TR-202

Welhan, J., Gwynn, M., 2014, High Heat Flow in the Idaho Thrust Belt: A Hot Sedimentary Geothermal Prospect, GRC *Transactions*, Vol. 38

Welhan, J., Gwynn, M., Payne, S., McCurry, M., Plummer, M., Wood, T., 2014, The Blackfoot Volcanic Field, Southeast Idaho: A Hidden High-Temperature Geothermal Resource in the Idaho

Thrust Belt, PROCEEDINGS, Thirty-Ninth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 24-26, 2014, SGP-TR-202

2015

Allis, R., Gwynn, M., Hardwick, C., Mines, G., Moore, J., 2015, Will Stratigraphic Reservoirs Provide the Next Big Increase in U.S. Geothermal Power Generation?, GRC *Transactions,* Vol. 39, 2015

Allis, R., Hardwick, C., Mark Gwynn, M., Johnson, S., 2015, Pavant Butte, Utah Geothermal Prospect Revisited, GRC *Transactions*, Vol. 39, 2015

Allis, R., Gwynn, M., Hardwick, C., Kirby, S., Moore, J., Chapman, D., 2015, Re-evaluation of the Pre-Development Thermal Regime of Roosevelt Hydrothermal System, Utah, PROCEEDINGS, Fourtieth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 26-28, 2015, SGP-TR-204

Gwynn, M., 2015, Geothermal Potential in the Basins of East-Central and Southeastern Nevada, GRC *Transactions*, Vol. 39

Hardwick, C. L., Allis, R., Wannamaker, P. E., 2015, Observations and Implications of Magnetotelluric Data for Resolving Stratigraphic Reservoirs Beneath the Black Rock Desert, Utah, USA, GRC *Transactions,* Vol. 39

Hardwick, C. L., Willis, H. W., Gwynn, M. L., 2015, A Basin-Scale Geothermal Assessment of Co-Produced Waters in Oil and Gas Fields: Uinta Basin, Utah, USA
GRC *Transactions*, Vol. 39

Hardwick, C. L., Willis, H. W., Gwynn, M. L., 2015, Geothermal Assessment and Modeling of the Uinta Basin, Utah, Geothermal Assessment and Modeling of the Uinta Basin, Utah, *in* Vanden Berg, M.D., Ressetar, R., and Birgenheier, L.P., editors, Geology of Utah's Uinta Basin and Uinta Mountains: Utah Geological Association Publication 45

Kirby, S., Simmons, S., Gwynn, M., Allis, R., Moore, J., 2015, Comparisons of Geothermal Systems in Central Nevada: Evidence for Deep Regional Geothermal Potential Based on Heat Flow, Geology, and Fluid Chemistry GRC *Transactions*, Vol. 39

Simmons, S., Kirby, S., Moore, J., Wannamaker, P., Allis, R., 2015, Comparative Analysis of Fluid Chemistry from Cove Fort, Roosevelt and Thermo: Implications for Geothermal Resources and Hydrothermal Systems on the East Edge of the Great Basin, GRC *Transactions*, Vol. 39

2016

Blackett, R., Gwynn, M., Hardwick, C., Allis, R., 2016, Stratigraphic Geothermal Resources in Deep Sedimentary Basins, Northeastern Great Basin, Utah, Utah Geological Survey Publication *in press*, Salt Lake City, Utah