STRATIGRAPHIC RESERVOIRS: A SIGNIFICANT FUTURE RESOURCE IN THE U.S.

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ABSTRACT

If there is to be renewed growth in geothermal power generation in the U.S. that competes with the growth in wind and solar photovoltaic (PV) power, developments need to be on a scale of ~100 MW. Stratigraphic reservoirs are scalable because of the conductive thermal regime, and the predictable characteristics of the reservoir units on a basin scale once a successful confirmation well has been drilled. However, based on economic modelling by Mines et al. (2014), the target depth range for these reservoirs is 2 – 4 km and temperatures need to be at least 150°C to 200°C. Reasonable assumptions for reservoir and power station characteristics yield a levelized cost of electricity of 10c/kWh. If recent technological advances in drilling for tight oil and gas can be adapted then it should be possible to significantly reduce the cost and make geothermal more competitive. Deep, lateral groundwater flow in high-permeability stratigraphic units in the eastern Basin and Range Province has swept heat and lowered basin temperatures. Two examples from Utah are examined and demonstrate exploration strategies need to integrate subtle basin-scale groundwater movement with the thermal regime in order to identify the best regions for locating viable stratigraphic reservoirs. In view of the challenging time for new geothermal projects in the U.S, it is essential that government-funded research focus on development issues for both enhanced geothermal systems and stratigraphic reservoirs.

1. INTRODUCTION

1.1 Subheading

Relatively low power prices in the U.S. for new natural gas coupled with? wind and solar photovoltaic (PV) generation are making it difficult for new geothermal power plants to compete. The transition away from coal-fired generation has also made it difficult for expensive nuclear generation to fill the void. The Energy Information Agency reported that 74 GW of new power projects are scheduled over the next 3 years (2019-2021) in the U.S.; 42% of the projects are from natural gas, 33% from wind, and 21% are from solar PV. Other power projects include nuclear (1.5%) batteries (1.4%) and geothermal (0.2%). Of the three geothermal projects, two are still working through permitting issues. The net summer capacity of geothermal plants in the U.S. has remained in the range of 2.5 – 3 GW since the late 1980s with retirements in recent years offsetting new capacity additions (Augustine et al., 2019).

The U.S. Department of Energy (DOE) has just completed an assessment of the future of geothermal energy in the U.S. (Geovision, 2019). This report concludes that there is potential for over 50 GW of power growth from geothermal energy by 2050 stimulated by improved regulatory oversight and technology improvements. Most of the growth comes from development of enhanced geothermal systems (EGS) and a smaller fraction coming from development of presently undiscovered hydrothermal resources. Although the Geovision recognizes the large, direct-heat potential in the U.S for low temperature "sedimentary resources" (< 150°C; 7.5 million GWh_{th}, Geovision 2019, Appendix C) it does not identify the potential of hotter, sedimentary resources for future power generation. These resources are typically in basins where the permeability is stratigraphically controlled in contrast to the fault control typical of most hydrothermal resources. Examples of geothermal development of stratigraphic reservoirs are in the Imperial Valley (U.S.), the Paris Basin (France), and the Molasse Basin (southern Germany).

Recent studies of the potential of stratigraphic reservoirs in the U.S. include Porro et al. (2012), Anderson (2013), Allis and Moore (2014), Allis et al. (2015) and Dobson (2016). In particular, the high heat flow terrain of the western U.S. (the Basin and Range physiographic province) has been recognized as having the greatest potential. A critical difference to fault-controlled hydrothermal systems in the Basin and Range is the horizontal scale of stratigraphic reservoirs. The high permeability stratigraphic unit(s) may extend across a large part of the basin, that is many hundreds of square km, whereas fault-controlled high permeability zones in many cases appear to have a relatively small volume (Blackwell et al., 2012). It is possible that fault-controlled hydrothermal resources tap into stratigraphic resources at depth. High stratigraphic permeability in mineralogically "clean" sediments has been shown to extend to at least 5 km (Figure 1) and oil and gas wells commonly produce economic flowrates at these depths.

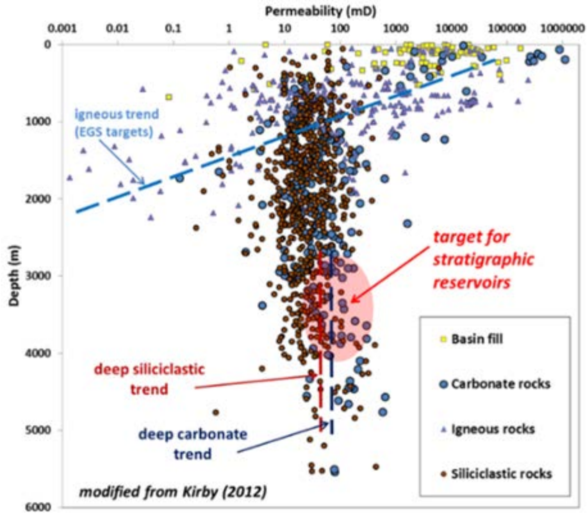

Figure 1: Compilation of permeability measurements documented in oil exploration (Dept. of Energy Gas Information System - GASIS) and groundwater databases for the Great Basin and Rocky Mountain regions (modified from Kirby, 2012a), split by lithology.

In addition to permeability, the key to locating prospective stratigraphic reservoirs is finding temperature-depth characteristics that are economically viable. The conductive thermal regime that is present in most basins is controlled by the underlying bedrock heat flow and the thermal conductivity of sedimentary fill. Having 1 – 2 km of fill with a high clay content (low thermal conductivity) can raise deeper temperatures in a basin by more than 50°C for a given heat flow (Allis et al., 2011). Mines et al. (2014) used GETEM software to model the balance between the increased power conversion efficiency of drillling deeper for higher temperature, and the higher drilling costs this causes. Using realistic assumptions for drilling costs, well productivity, and power plant design, Mines et al. (2014) found that temperatures had to exceed about 150°C at 2 km depth and 200°C at 4 km depth for a levelized cost of electricity of 10c/kWh from a 100 MW power plant. Drilling costs in this study, including make-up wells as temperature declined with heat sweep in the reservoir, amounted to nearly half the total project costs. Significant cost reductions are possible if some of the drilling techniques now used in tight oil reservoirs can be adapted to stratigraphic geothermal reservoirs. Hicks, (2013) states that wells in the Bakken tight oil play, North Dakota are $5 - $6 million for 6 km drillholes (3km vertical, 3 km horizontal ; grid drilling with skid-mounted rigs). Although these costs are less than half the drilling cost curve used by Mines et al. (2014), the diameter of the wells (and flow rates) are much smaller than those required for geothermal wells. Geovision (2019) predicts significant drilling cost reductions for geothermal projects due to technology improvements in the coming decades.

The purpose of this paper is to review the best stratigraphic prospects in the Paleozoic carbonate system that underlies the eastern half of the Basin and Range (sometimes referred to as the Great Basin). The average heat flow of the Basin and Range is about 85 ± 10 mW/m^2 (Blackwell, 1983) and there are widespread, high-permeability carbonate units at depth in the basins. High-permeability carbonate reservoirs are an attractive reservoir target, but may also reduce observed heat flow as lateral movement of water on a thousand-year time scale and flushes heat from the basins, degrading the thermal resource. Two examples from Utah (Snake Valley-Fish Springs and Cove Fort-Black Rock Desert), will be used to demonstrate the thermal effects of basin flushing. Geothermal exploration strategies need to integrate subtle basin-scale groundwater movement with the thermal regime in order to narrow down the best regions for locating stratigraphic reservoirs.

2. THERMAL TARGET

The numerous oil exploration wells drilled into the Paleozoic carbonate system provide insight to both the deep thermal regime and the stratigraphy of the region (Gwynn et al., 2014; Gwynn, 2015). Of the top four undeveloped stratigraphic prospects in the Basin and Range province identified by Allis et al. (2015), two are carbonate reservoirs (Elko basins and North Steptoe valley), the Idaho thrust belt is a sandstone reservoir, and Pavant Butte has mixed lithology in Cambrian metasedimentary units. The four prospects are located on a heat flow map (Figure 2; modified from Blackwell et al., 2011), and their thermal characteristics are shown in Figure 3. All four have temperatures (160°C - 240°C) exceeding the minimum thermal threshold identified by Mines et al. (2014). All four basins have conductive heat flows that range from 90 to 150 mW/m^2 over an area of at least 100 km^2. Figure 3 also includes typical conductive 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 et al. 2013) and includes the Milford FORGE project presently being carried out adjacent to the Roosevelt hydrothermal system in Utah. Many of these sites are in higher heat flow terrain but with low permeability at potential reservoir depth.

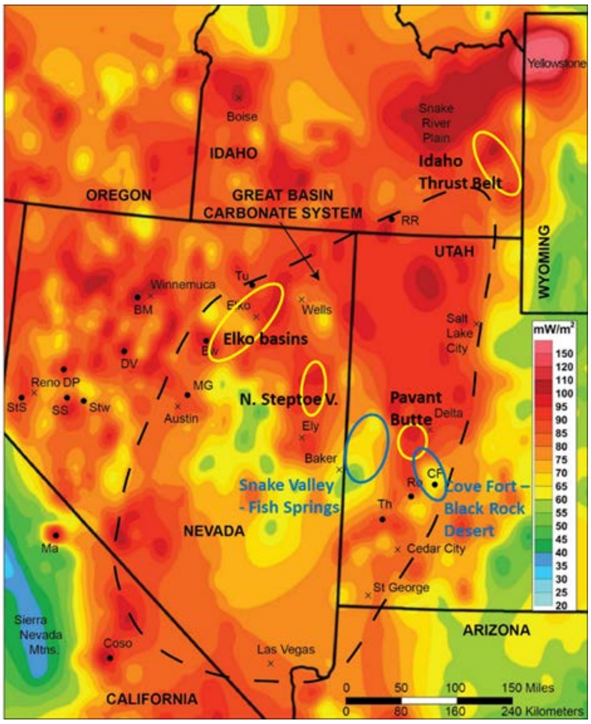

Figure 2. Four stratigraphic geothermal prospects with development potential (yellow outlines, Allis et al., 2015). The background contours are from the regional heat flow map of the U.S. compiled by Blackwell et al. (2011). The two blue ellipses are regions where basin-scale lateral groundwater flow has modified the thermal regime (discussed below). Geothermal power plant abbreviations are: Ro Roosevelt Hot Springs, CF Cove Fort, Th Thermo, StS Steamboat Springs, SS Soda Springs, Slw Stillwater, MG McGuiness, DP Desert Peak, DV Dixie Valley, Bw Beowawe, BM Blue Mountain, Tu Tuscarora, RR Raft River.

Figure 3 includes typical geotherms from major basins in the western U.S. The temperatures are significantly cooler than the Mines threshold and are not attractive for power development based on that criterion. However, caution is needed in using the threshold because of the assumptions in the GETEM modelling. Factors such as proximity to transmission lines, the local power price, and reservoir characteristics such as well productivity and thermal decline rate can greatly affect the economics of a prospect. For example, several successful power developments in the Molasse Basin of SW Germany have targeted the Malm carbonate aquifer where temperatures range from 80°C to 130°C between 1.5 and 3.3 km depth (Rioseco et al., 2018). On Figure 3 these temperatures plot close to the Haynesville – Railroad Valley geotherms and they are 40°C less than the Mines threshold.

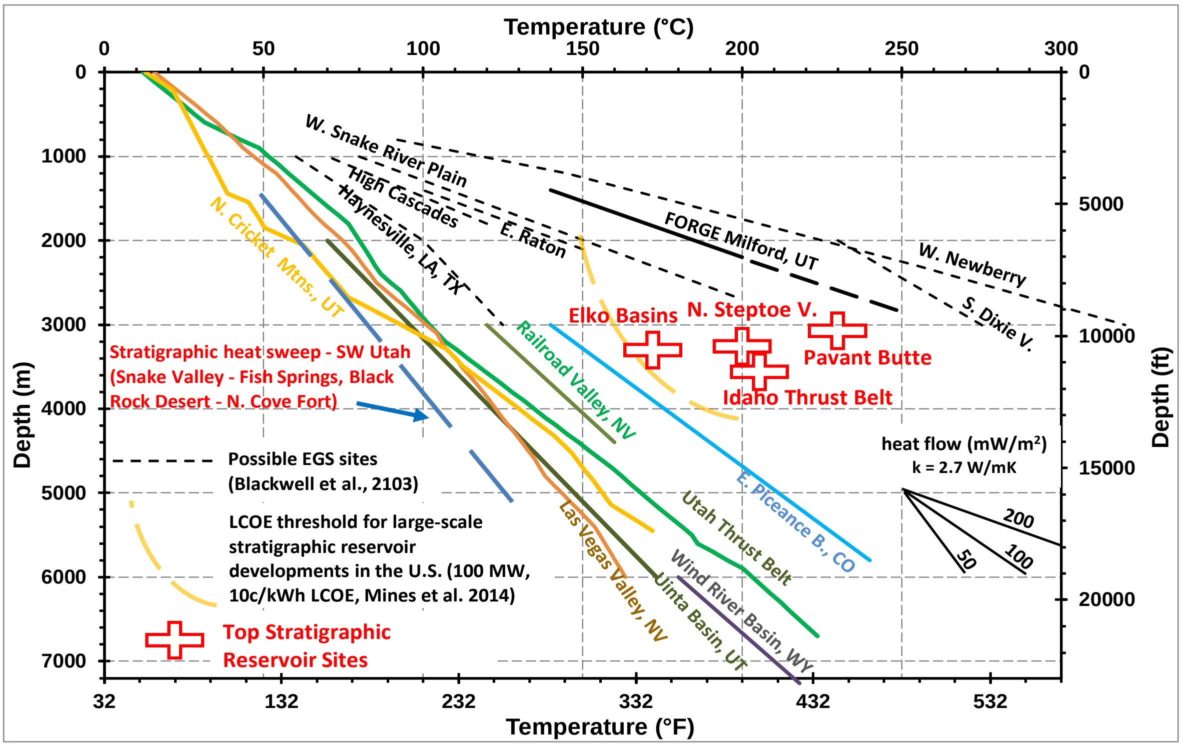

Figure 3. Thermal characteristics of the four most attractive stratigraphic reservoir prospects identified by Allis et al. (2015; red crosses). Conductive thermal regimes overlie these reservoirs but for simplicity are not shown here. For comparison, typical geotherms from major basins adjacent to the high heat flow areas of the Basin and Range are shown (colored lines), along with geotherms from EGS sites proposed by Blackwell et al. (2013; dashed black lines). The active EGS project is labelled FORGE Milford, UT.

3. EFFECT OF GROUNDWATER MOVEMENT

Despite the characteristically high heat flow of the Basin and Range province, there are also large areas of lower heat flow (yellow contours on Figure 2). Sass et al. (1971) attributed the depressed heat flow in southern Nevada to lateral flow (mostly southward) of groundwater in carbonate units underlying the region. USGS studies have confirmed the presence of interbasin flow in the carbonate system (Heilweil and Brooks, 2011; Masbruch et al., 2012). In addition to depressing the basin heat flow, the lateral flow can smear out thermal anomalies and mask the deeper hot upflows. Two examples from western Utah are discussed.

3.1 Snake Valley – Fish Springs

In a very detailed groundwater study involving over 60 new wells, Hurlow (2014) documented lateral flow northward from the Snake Range and adjacent Snake Valley towards Fish Springs (Figure 4; location on Figure 2). The outflow at Fish Springs is about 1000 L/s at temperatures of 20 – 27°C indicating a heat output of 40 MW (relative to mean annual ground temperature of 15°C). The desert climate here means there is minimal local recharge. Age dating of the groundwater indicates older water northwards towards Fish Springs and a time scale for flow of several thousand years (Hurlow and Kirby, 2014). The most likely flow paths range between 50 and 100 km in length, and the piezometric head difference beneath the valley floors is less than 200 m along the paths. Oil exploration wells in the Snake Valley and adjacent valleys indicate a range of temperatures (20 – 70°C) at about 1 km depth, but between 2 and 5 km depth the temperature follows a geotherm with a gradient of 25°C/km indicating depressed heat flow (Figure 3). However, on the west side of the range at Fish Springs, 15 drillholes from the Crypto zinc prospect range up to 800 m depth and confirm a gradient of 35°C/km (heat flow of 100 mW/m^2; Gwynn et al., 2017). At the north end of the Fish Springs Range, the Wilson hot springs are 60 – 80°C. Although complicated, the lateral flow of groundwater in subsurface carbonate units has caused a major redistribution of the heat on a basin scale.

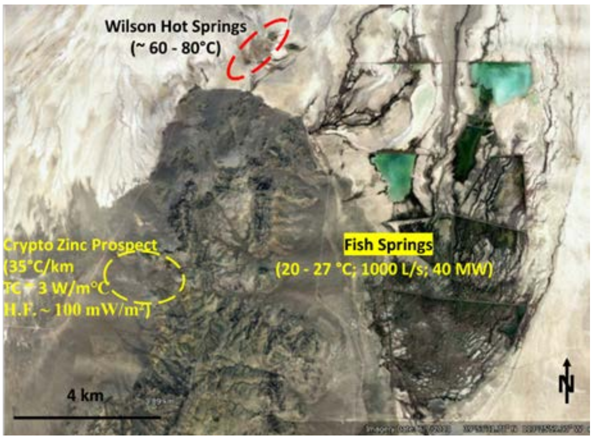

Figure 4. Aerial photograph of the northern end of the Fish Springs Range where a large outflow of warm water occurs at Fish Springs, and Wilson hot springs are located several km to the north. The water at Fish Springs is recharged at 50 – 100 km depth and has ages of several thousand years (Hurlow and Kirby, 2014). T.C is thermal conductivity; H.F. is heat flow.

3.2 Cove Fort – Southern Black Rock Desert

The geothermal system beneath Cove Fort–Sulphurdale (CF on Figure 2) has intrigued developers since exploration by many companies in the late 1970s and the drilling of deep wells (Union Oil, 1979). ENEL is the present operator of a 25 MW (gross) power plant tapping a 150°C liquid reservoir in fractured carbonate locally intruded by quartz monzonite (Huttrer, 1992; Ross and Moore, 1994; Rowley et al., 2013; Allis et al., 2017). One exploration well (42-7) showed evidence of higher temperatures above and below the main reservoir section, but the source of the higher temperatures has never been proven.

Numerous ~150-m-deep temperature gradient wells around Cove Fort reveal a thermal anomaly far larger than the equivalent anomaly at Roosevelt Hot Springs (RHS; Allis et al., 2017; Figure 5). Integration of the thermal anomaly at 100 m depth and assuming an average thermal conductivity of 1.5 W/m°C shows a conductive heat loss of 110 MW north and west of Cove Fort, compared to a heat loss of 50 MW at the RHS system (calculated for regions where the temperature is more than 20°C; Figure 5). The key difference is the area of the Cove Fort anomaly of 500 km^2 compared to 140 km^2 at RHS. However, pre-development RHS had a boiling spring and silica deposits at the surface, whereas at Cove Fort there is no thermal ground, although there are areas of active gas outflow (especially CO_2 and H_2S) and extensive hydrothermal alteration that was a focus of sulfur mining between the late 1800s and 1952 (Callaghan, 1973; Ross and Moore, 1994; Klusman et al., 2000.)

The geothermal reservoir beneath Cove Fort is significantly under-pressured relative to the ground surface and requires submersible pumps on the production wells that incur a 20% parasitic load on total generation. The high permeability in the carbonate units control the geothermal potentiometric surface and cause the undisturbed head at Cove Fort-Sulphurdale to be 300 to 400 m below the ground surface (Allis et al., 2017). The high permeability allows downhole generators to be installed in injection wells to generate power from the downflow and also prevent two-phase conditions in the wellbore (ENEL, 2016). The potentiometric head at Cove Fort reservoir is about 1550 m above sea level (asl), and is similar to that in deep wells in Dog Valley 10 km to the north, and to springs and wells in the southern Black Rock Desert 20 to 30 km to the north (Twin Peaks spring is at about 1450 m asl ; Figure 6 ; Allis et al., 2017). The pressure regime is consistent with a mainly northwestward flow of groundwater, and based on the large thermal anomaly area at 100 m depth, this flow is a characteristic of most of the basin between the Tushars Mountains on the east and the Mineral Mountains on the west.

Five deep oil exploration wells were drilled within 35 km of of Cove Fort. Two were in the southern Black Rock Desert, two were east and northeast of the Tushar Mountains, and one was 15 km south of Cove Fort near I-15. The bottom-hole temperatures recorded in all five wells are consistent with a regional gradient depth of 25°C/km extending to at least 5 km. This temperature profile is the same as that found in oil exploration wells in the basins surrounding Snake Valley-Fish Springs, and it is plotted on Figure 3 as the blue dashed line. The anomalously low heat flow here (about 60 mW/m^2) indicates a deeply flushed upper crust similar to southeast-central Nevada and western Utah where there has been large-scale lateral movement of water in underlying Paleozoic carbonate units (Sass et al., 1971; Heilweil and Brooks, 2011; Masbruch et al., 2012).

A lingering issue is the source of hot water in the Cove Fort reservoir. The review by Union Oil (1979) of their exploration drilling at Cove Fort commented that the geochemical characteristics of the reservoir fluids were complex and variable despite the relatively high permeability. Silica geothermometers were considered the most reliable, indicating a temperature in well 31-33 of 178°C, which is the same as the maximum temperature measured at the total depth of well 42-7. The most reliable Na-K-Ca deep-temperature estimate collected from Cove Fort wells was considered by Union Oil to be 257°C. Later analyses from two production wells at Sulphurdale yielded Na-K-Ca geothermometer estimates of close to 250°C (Moore et al., 2000). If this is representative of a hydrothermal upflow temperature at Cove Fort, then an inferred 10 km circulation depth based on the 25°C/km found by the surrounding deep oil exploration wells seems unlikely.

The evidence for northward movement of thermal groundwater may provide insight to the source of the Cove geothermal reservoir water beneath Cove Fort. When the groundwater chemistry is overlain on the topography, groundwater levels, and the 100-m-depth temperature contours, there is a contrast between the traditional relationships seen at the RHS on the west flank of the Mineral Mountains, and those east of the Mineral Mountains (Figure 7). At RHS the upflow of the geothermal fluid is known to occur on faults adjacent to the Mineral Mountains which are the focus of production wells for the Blundell Power plant (Allis and Larsen, 2012). The westward outflow of thermal groundwater from the range front is delineated by the NaCl and temperature contours in Figure 7. In contrast, the geothermal anomalies associated with Cove Fort are displaced and enlarged by the regional scale groundwater flow. The main geochemical anomaly surfaces in the southern Black Rock Desert where there is a cool NaCl plume which merges northwards with groundwater having a higher sulfate content (Holmes and Thiros, 1990). Both the Cove Fort and RHS systems have sulfate/chloride ratios that are similar to the southern Black Rock Desert groundwater (Simmons et al., 2015). The large thermal anomaly north and west of Cove Fort depicts the conductive gradient overlying the thermal groundwater and suggests an equally large (500 km^2) thermal outflow. This flow pattern in consistent with the deep heat source for the Cove Fort reservoir being farther south or southwest and possibly related to the mid-crustal partial melt inferred to exist beneath the Mineral Mountains (Robinson and Iyer, 1981; Trow et al., 2019).

4. CONCLUSIONS

The usual challenges for locating viable geothermal reservoirs start with permeability and temperature. Stratigraphic reservoirs in high heat flow basins offer the advantage that the potential reservoir area (and volume) is large (> 100 km^2) and once the basin geology is confirmed as having suitable characteristics, it should be predictable and low-risk for step-out drilling. The power generation would be scalable. For significant growth in geothermal power production in the U.S. to resume after almost 30 years of capacity stagnation, new projects need to be hundreds of MW in scale. Stratigraphic reservoirs are capable of attaining that scale.

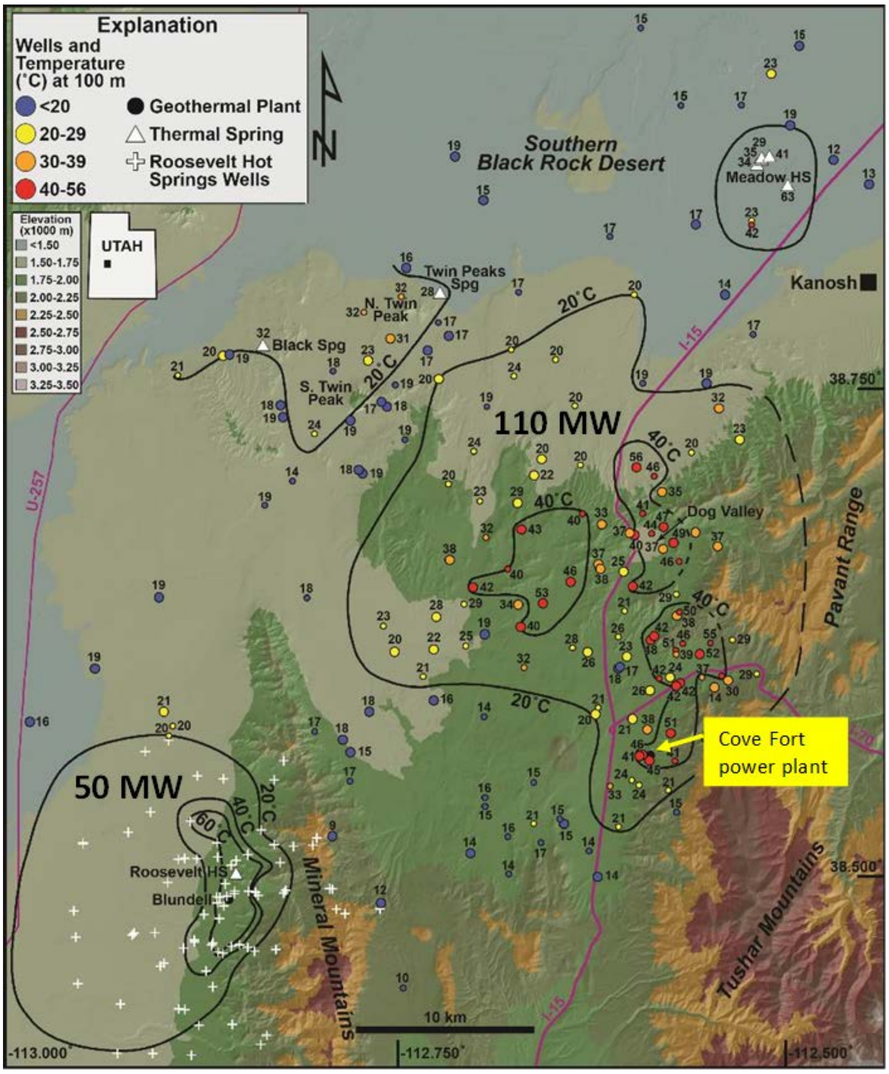

Figure 5. Temperature at 100 m depth derived from 169 thermal gradient wells drilled during the exploration for geothermal resources in the late 1970s and early 1980s. The Roosevelt Hot Spring and Cove Fort geothermal systems are located on Figure 2 as Ro and CF. Colors are topography which ranges between 1500 and over 3000 m above sea level. The heat output from the two main thermal anomalies are shown in MW based on temperature above 20°C.

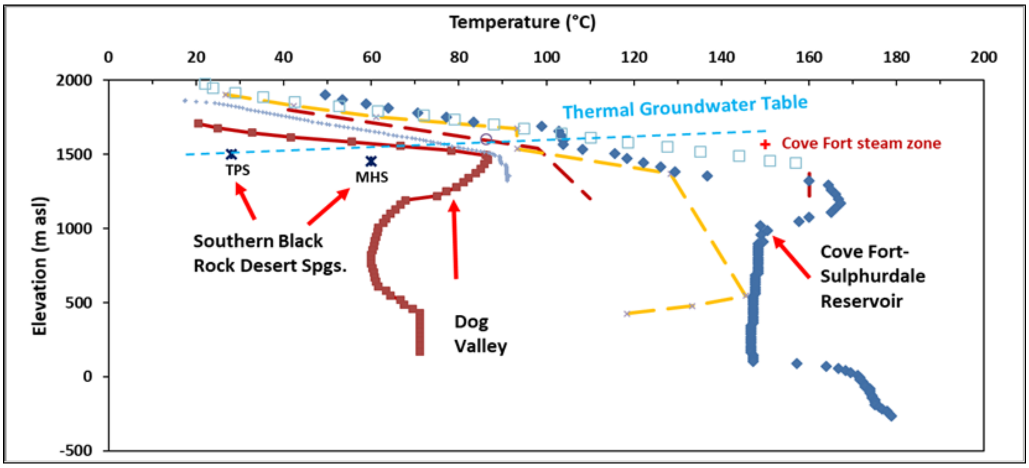

Figure 6. Temperature profiles in wells at the Cove Fort – Sulphurdale reservoir, Dog Valley 10 km to the north, and in the southern Black Rock Desert 20 – 30 km to the north (locations on Figure 5). Fractured carbonate is found at depth in all three areas, and the piezometric head varies from 1500 m above sea level to about 1600 m asl at Cove Fort. There is a northward TPS is Twin Peaks spring and MHS is Meadow-Hatton spring.

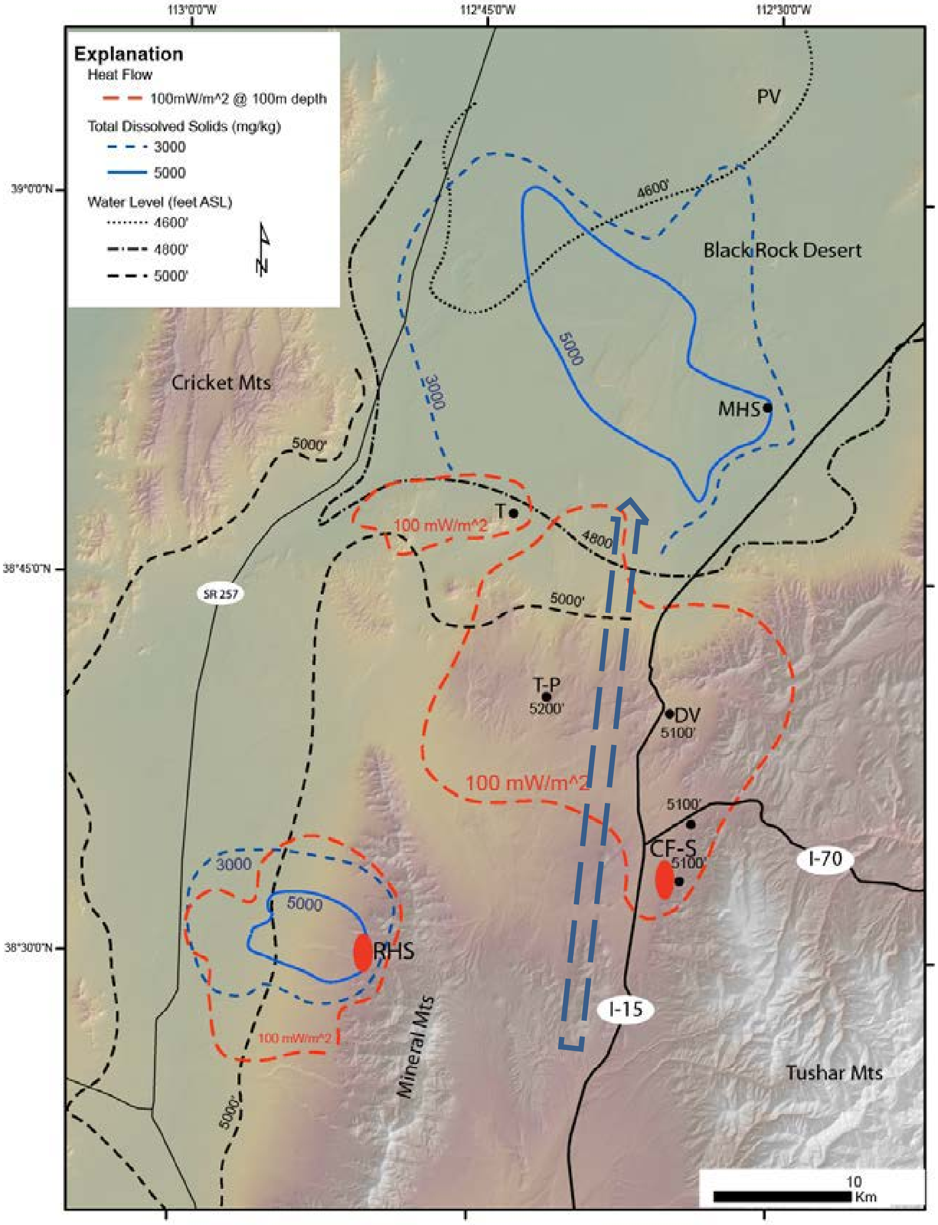

Figure 7. Overlay of heat flow derived from temperature at 100 m depth (from Allis et al., 2017), groundwater chemistry expressed as total dissolved solid concentration (mg/kg) and groundwater level (in feet above sea level; Holmes and Thiros, 1990; Kirby, 2012b). The large blue arrow is the inferred northward flow of hot groundwater. T is Twin Peaks spring, MHS is Meadow-Hatton spring, DV is Dog Valley, red ellipse labelled CG-S is the Cove Fort-Sulphurdale reservoir, similarly RHS is the Roosevelt Hot Spring reservoir, T-P is a groundwater well. 4600' is 1402 m asl; 4800' is 1463 m asl; 5000' is 1524 m asl.

Data from oil exploration wells indicate that permeability in the range of 50 – 100 mD can be found down to at least 5 km depth. Although the effects of diagenesis at prospective temperatures (>150°C) are less well understood, clean carbonate and sandstone appear to be the preferred lithologies. Because of the conduction-dominated thermal regime, startigraphic reservoir temperatures are determined by the basin heat flow. The threshold reservoir temperature required for economic viability identified by Mines et al., (2014; 150°C at 2 km depth rising to 200°C at 4 km depth) is sensitive to many factors such as drilling costs, production (pump rate), casing configuration, thermal decline rate, and power plant specifics. The large variability offers opportunities for improving the economics, particularly if the recent technological improvements in tight oil and gas productivity can be adapted to stratigraphic hot water production.

The critical exploration tool is identification of basins where the conductive temperature profile (geotherm) exceeds the Mines et al. (2014) threshold. This should occur in many basins with a heat flow of 100 mW/m^2 and with 1 – 2 km of poorly consolidated basin fill over bedrock units and numerous basins in the northern Basin and Range Province have these conditions. The southern Basin and Range has relatively low heat flow over large areas attributed to flushing of heat by southward directed inter-basin groundwater flow in high-permeability carbonates (Sass et al., 1971; Heilweil and Brooks, 2011; Masbruch et al., 2012). Those basins with internal drainage, which tend to be in the northern Basin and Range, have a greater chance of having the necessary heat flow. The two basins in southwestern Utah examined in this paper have northward drainage towards internal basins (Great Salt Lake north of Snake Valley, and the Sevier Desert north of Cove Fort). In both cases, oil exploration wells across this part of Utah (20 in all) show a relatively low regional heat flow (about 60 mW/m^2) atypical of average Basin and Range heat flow (90 mW/m2; Blackwell et al., 2013). The upper crust here presumably has relatively low heat flow due to deep, groundwater movement.

Based on the groundwater and reservoir pressure and temperature trends discussed here and in Allis et al. (2017), the source of the hot water in the Cove Fort reservoir is likely to be beneath the higher topography to the south or southwest. The young rhyolites (< 1 million year ages) and geophysical evidence for partial melt at mid crustal depth beneath the central Mineral Mountains is an obvious indicator of high temperatures in the shallow crust. Thermal models of the conductive temperature profiles in two impermeable wells in the RHS system suggest partial melt below about 8 km depth (Allis et al., 2019). In contrast, the depressed thermal regime adjacent to the Tushar Mountains and the lack of Quaternary igneous activity in these mountains is inconsistent with the 250°C geothermometry of the Cove Fort reservoir water.

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