The Potential for Basin-Centered Geothermal Resources in the Great Basin

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ABSTRACT

Most geothermal power production from the Great Basin of the western U.S. is located near extensional faults that allow upflow of geothermal fluids to near-surface. However, improved drilling technologies, and the prospect of rising power prices raises the possibility of economically viable large-scale power production from the centers of the basins. Oil and gas exploration wells, and water wells in the Great Basin have proven the existence of laterally extensive, high permeability within Paleozoic carbonates. In the southern Great Basin, regional scale ground water flow towards the Colorado River in these carbonates has depressed the heat flow. However, in general the northern Great Basin has not been flushed by ground water, and the heat flow is about 80 – 100 mW/m^2. This equates to gradients of about 30 – 40 ºC/km in bedrock formations (e.g. beneath the ranges), and about 55 – 75 ºC/km within unconsolidated sediments and shale sequences due to the effects of thermal conductivity. There is the potential for temperatures of 150 – 300 ºC at 3 – 5 km depth in basins with thick basin fill, as supported by several oil exploration wells in the eastern Great Basin where the temperatures are > 200 ºC at 3 km depth. In addition, several shallow wells near one of these deep wells confirm regionally extensive gradients of 65 ºC/km. The critical issue for the geothermal potential is whether there is laterally extensive permeability in the 3 – 5 km depth range. The geologic evidence for near-horizontal Paleozoic formations at depth across much of the Great Basin, some of which are known to have characteristically high permeability, suggests the geothermal resource potential beneath the basins could be significant.

Introduction

The geothermal potential of reservoirs within deep sedimentary basins has been known for many years. Many examples of high-temperature sediment-hosted systems are located in the Imperial Valley-Mexicalli rift basin (temperatures to > 300 ºC), and lower temperature aquifers (< 150 ºC) have been tapped in many basins round the world. A subset of sedimentary-hosted geothermal systems are those associated with oil and gas producing basins, some of which may be geopressured, and most having temperatures < 150 ºC (MIT, 2006; Sanyal and Butler, 2009; Sanyal, 2010).

The purpose of this paper is to take a fresh look at potential geothermal reservoirs in the vast, non-magmatic, high heat flow region of the Great Basin (Blackwell and Richards, 2004). The typical heat flow here is considered to be 85 ± 10 mW/m^2, although the actual average is higher due to possible bias from measurements near hydrothermal systems (Blackwell, 1983). An area of lower heat flow in the south-central part of the Great Basin, sometimes referred to as the "Eureka Low," defines a hydrologic heat sink due to inter-basin flow of water in carbonate rocks in eastern Nevada (Lachenbruch and Sass, 1977).

This paper will show that beneath at least some of the basins outside of the Eureka Low in the eastern Great Basin have temperatures of more than 200 ºC at about 3 km depth, and furthermore the geologic evidence suggests that significant permeability should exist within several Paleozoic formations that underlie the basin fill. Just as the thermal regime of southern Great Basin appears to be depleted because of regional-scale permeability within the Paleozoic sedimentary section, we believe that same permeability may also be present in the same units beneath the rest of the Great Basin. This is the beginning of a multi-year study of the geothermal potential of the Great Basin at depths of 3 – 5 km.

Reservoir Temperature

Many of the obvious hydrothermal systems within the Great Basin, often associated with extensional faults and leakage of hot water at the surface, have already been developed for geothermal power. Factors controlling the locations of these systems and the regional heat flow variations have been known for a long time (e.g. Blackwell, 1983; Koenig and McNitt, 1983; Sass and Walters, 1999; Coolbaugh et al., 2005). In regions where thermal conduction is dominant, the most important factor influencing the temperature at depth is thermal conductivity (Figure 1).

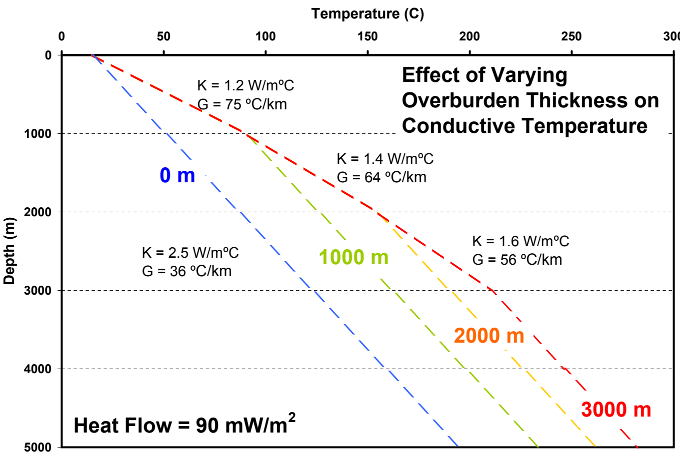

Figure 1. Thermal regime at depth for a Great Basin heat flow of 90 mW/m^2 assuming thermal conduction in bedrock (thermal conductivity K = 2.5 W/mºC) and varying overburden thickness (high clay content; overburden thickness labeled). Note that thermal conductivity increases with depth due to the effects of compaction. These assumptions produce a thermal gradient (G) in bedrock of 36 ºC/km and gradients of 56 - 75 ºC/km in the overburden, depending on the thermal conductivity.

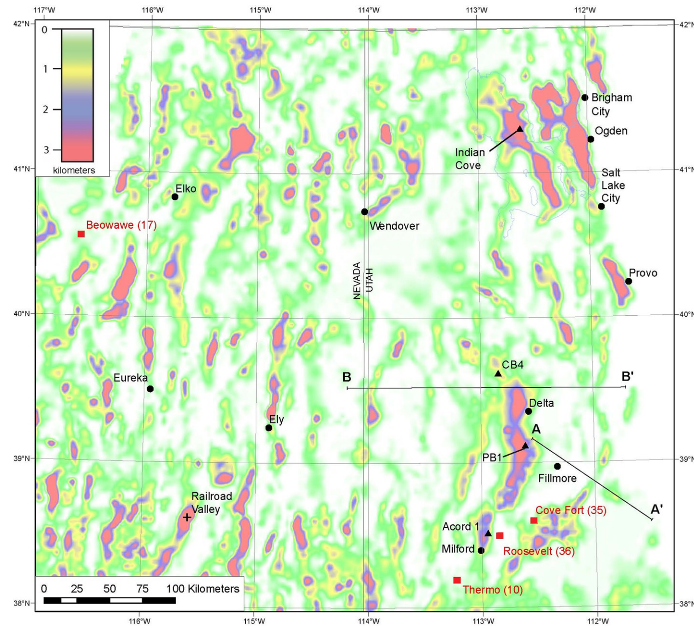

Figure 2. Basin-depth map for eastern Great Basin based on gravity modeling (Saltus and Jachens, 1995). The three deep wells that have bottom-hole temperatures of 220 – 240 ºC are labeled (PB1 is the Pavant Butte – Arco well; also Acord 1 near Milford, and Indian Cove in Great Salt Lake). Geothermal power plants are labeled in red with MW capacity. Lines A-A′ and B-B′ are the sections in Figure 6. Blue outline is Great Salt Lake. A large area between Salt Lake City and Wendover has few gravity measurements.

Figure 1 highlights the challenge with sedimentary-hosted systems summarized by Sanyal and Butler (2009): the cost of power generation is very sensitive to temperature of the reservoir (i.e. well depth and therefore the drilling cost) and well productivity (reservoir transmissivity or permability). In the scenarios they modeled (Gulf Coast thermal regime of 30 ºC/km), the levelized energy cost decreased to 11 – 16 USc/kW-hr (depending on transmissivity) as the reservoir temperature increased to 160 ºC (equivalent to 5 km depth). Figure 1 also shows that where bedrock crops out in the Great Basin (i.e. the ranges of the basin and range topography) the 160 ºC temperature would be reached at about 4 km depth. This would slightly improve the resulting levelized energy cost, but would barely make such a development attractive based on the best wholesale electricity market in the region (i.e. in California). A bedrock section dominated by shale would be an additional help (thermal conductivity of ~ 1.7 W/mºC), but this effect would be negated if there are also sandstone units (3 – 5 W/mºC).

Obviously the assumptions in the paragraph above need further qualification and investigation, but one clear conclusion is that basins with a significant thickness of basin fill with unconsolidated sediment have the greatest potential for having reservoirs in the underlying bedrock at attractive temperatures. Bedrock reservoirs that underlie 3 km of overburden should have temperatures in the range of 210 – 280 ºC for depths of 3 – 5 km where the heat flow is 90 mW/m^2. These reservoir temperatures imply self-discharging wells in a geothermal development. Very few deep wells have been drilled in the deepest parts of basins within the Great Basin. The focus of the geothermal exploration industry has mostly been on hydrothermal systems where a plume of hot water rises on fault(s) near the basin margins or adjacent to horst blocks within the basins. In the Utah sector of the Great Basin we have found three wells greater than 3 km depth that have bottom-hole temperatures between 220 – 240 ºC, but with no obvious relationship to a hydrothermal system. Temperatures have been extracted from the well-log headers, and all information is accessible on the website of the Utah Division of Oil, Gas, and Mining (DOGM). The locations of these wells are superimposed on a basin depth map derived from gravity modeling (Saltus and Jachens, 1995; Figure 2). The basin-depth map is particularly useful for screening areas of interest where several kilometers of unconsolidated sediment infill should have caused higher bedrock temperatures at depth. The apparent lack of basins in a very large area between Salt Lake City and Wendover is because of a lack of gravity measurements on U.S. Department of Defense (DOD) lands. The UGS is currently acquiring gravity data in these areas to better define basin morphology and resource potential.

All three wells lie within prominent, elongate basins parallel to the eastern margin of the Great Basin (Figure 2). The Amoco Production Company “Indian Cove” well had 3.8 km of basin fill over Precambrian bedrock (Bortz, 2002). It has a corrected bottom-hole temperature of 230 ºC at 3.8 km) and a mid-depth temperature of 148 ºC at 2.4 km, which are consistent with a uniform gradient from the surface of 65 ºC/km and an inferred heat flow of 90 – 100 mW/m2. The Arco Oil and Gas Company Pavant Butte 1 well drilled 3 km of basin fill followed by 250 m of Cambrian strata (Hintze and Davis, 2003). It has a corrected bottom-hole temperature of 232 ºC at 3.3 km depth, and a temperature at 2.35 km of 166 ºC. The temperature gradient here is also about 65 ºC/km. The third well is the McCullough Geothermal Acord-1 well which is 10 km west of the Roosevelt geothermal field and the Blundell power plant of Pacificorp. The well drilled 1 km of basin fill followed by volcanic rocks and a monzonite intrusion, both late Tertiary in age, before drilling Precambrian sediments. The bottom-hole temperature is 230 ºC at 3.86 km yielding an average gradient of 60 ºC/km and a heat flow of 145 mW/m^2 based on thermal conductivity measurements on cuttings (Shannon et al., 1983).

The high bottom-hole temperatures in the Indian Cove and Pavant Butte 1 wells are largely due to the thermal insulation effects of 3 km of unconsolidated, fine-grained sediment. Abnormally high background heat flow may also a factor beneath the Acord-1 site.

Our reassessment of bottom-hole temperatures in Great Salt Lake oil exploration wells, and that of Henriksen and Chapman (2002) confirm that the heat flow is 80 – 100 mWm^2, and temperatures of over 200 ºC should be expected along the northwest-trending basin axis beneath the lake. In the Black Rock Desert adjacent to the Pavant Butte well, two temperature gradient wells were drilled by Phillips Geothermal during the early 1980s, and we have recently drilled three additional wells (Figures 3 and 4). The graph in Figure 4 summarizes the temperature data and allows comparison with the temperatures obtained from the deep Pavant Butte well. The shallow temperature gradient data are consistent with those from the deep well although there appear to variations across the basin. The new thermal data and related geophysical survey data are currently being interpreted and will be reported later. Hardwick et al. (this volume) give an initial interpretation of magnetotelluric and gravity signatures of the Crater Bench – Abraham hot springs area at the northern end of the elongate gravity low anomaly encompassing the Pavant Butte well (Figures 3 and 4).

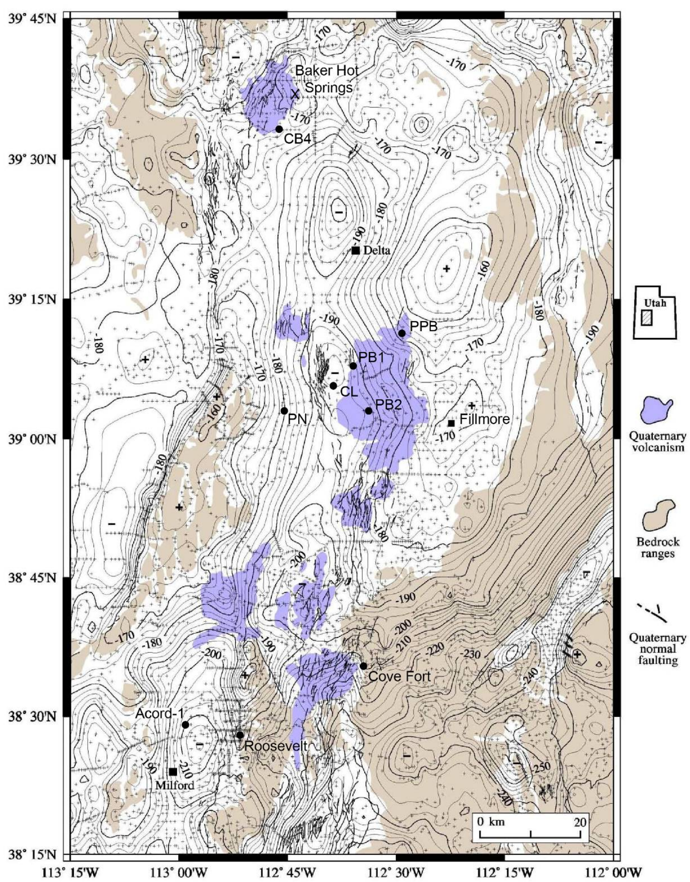

Figure 3. Simplified geologic map with Bouguer gravity anomaly overlay (Wannamaker et al., 2007; contour interval 2 mgals). Locations of wells referred to in text and in Figure 4 are superimposed. PB1 is Pavant Butte-Arco 1, PPB is Phillips-Nth. Pavant, PB2 is Pavant Butte 2, CL is Clear Lake, PN is Phillips Neels, CB4 is Crater Bench.

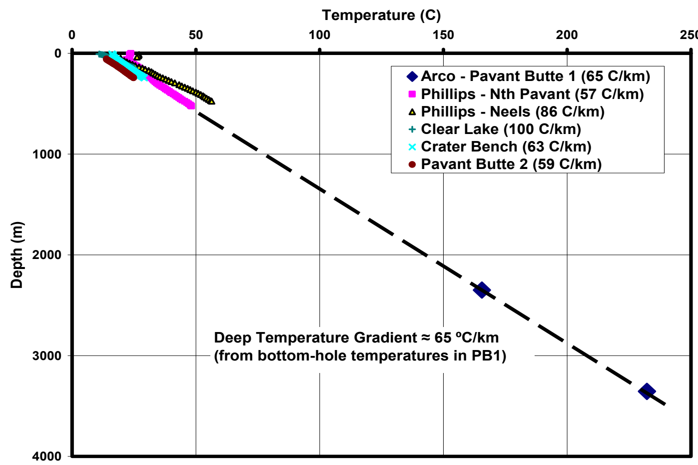

Figure 4. Comparison of temperature gradients in wells around Black Rock Desert. Locations in Figure 3. The Pavant Butte – 2 well was measured soon after completion and may not be at full thermal equilibrium at time of writing.

Permeability

Good permeability (or transmissivity) is essential for a viable geothermal reservoir. The eastern Great Basin contains a thick succession of sedimentary strata that is dominated by carbonate rocks with subordinate amounts of shale, sandstone, quartzite, and conglomerate. Most of the sedimentary section through the central part of the Great Basin is Paleozoic in age with sections in the northern and southern sectors also having Mesozoic rocks. Much less is known about the Proterozoic section in the area because of limited exposures and minimal drilling below the Cambrian section.

Much of the Paleozoic section was deposited in a relatively shallow-water basin that reflects shelf to shelf slope environments where about 30,000 feet of rock accumulated in the central Great Basin (eastern Nevada), thinning to no more than 3,600 feet of rock towards the eastern margin. Of that, most of the section (about 75%) is comprised of carbonate rock (both limestone and dolostone). These rocks range from tight, dense, finely crystalline lime mud to more porous bioclastic and framework lithotypes. These are likely the key reservoirs, especially when enhanced by fractures and dissolution features. In addition, the recent recognition of microbial carbonate reservoirs in many Paleozoic formations in the Rockies may become an important target in this area. The remaining lithotypes in the Paleozoic section for the outlined area includes about 10 percent shale and siltstone and another 15 percent as sedimentary quartzite and sandstone. The percentage of shale and siltstone in the section may be small but is important because they serve as reservoir seals.

A generalized stratigraphic section shows some of the more well-known units with characteristically good permeability highlighted with asterisks (Figure 5). Transmissivity values based on pump tests for Paleozoic carbonate units within several thousand feet of the surface range between 1,000 – 10,000 ft^2/

day, and more typically 2000 – 4000 ft^2/day (USGS and UGS measurements; Halvord 2010). These values are equivalent to permeabilities on the order of a Darcy assuming typical unit thicknesses. Whether these high permeabilities also exist when the formations are at 3 – 5 km depth and at temperatures of 200 – 250 C is a topic we will be researching during the coming year. There are numerous petroleum-producing basins worldwide that have proven permeability at 6 – 10 km depth (Dyman, 1998). Of the 52 wells drilled to more than 7.6 km depth in the U.S. up to 1998, half were productive. Most of these have deep temperatures less than about 200 ºC. One example of a deep, hot carbonate (dolomite) reservoir is in Madison formation dolomite in the Madden gas field of central Wyoming, where productive wells range up to 7.6 km in depth, and temperatures reach 225 ºC (Williams 2000).

Two cross-sections in Figure 6 illustrate the structural geometries across the eastern (Utah) half of the Great Basin. They are based on interpretations from seismic profiles (Allmendinger and Sharp, 1992; Hintze and Davis, 2003; Schelling et al., 2007). Sevier thrust faults are important because they may become sub-horizontal detachments once extension began to form the Great Basin. Shallow, steeply-dipping normal faults are interpreted to flatten into the detachment faults at depth. This interpretation has been challenged and specifically the nature of detachment faults beneath the Sevier-Black Rock Desert area remains controversial (Wills et al., 2005). Despite the uncertain Tertiary kinematic history, the two sections in Figure 6 suggest many stratigraphic reservoir targets exist beneath the region. In contrast to hydrothermal systems controlled by steeply-dipping fault zones, these reservoirs will be sub-horizontal and stratigraphically controlled. Once a reservoir unit is confirmed, the size of the reservoir could be very large (~ 100 km^2).

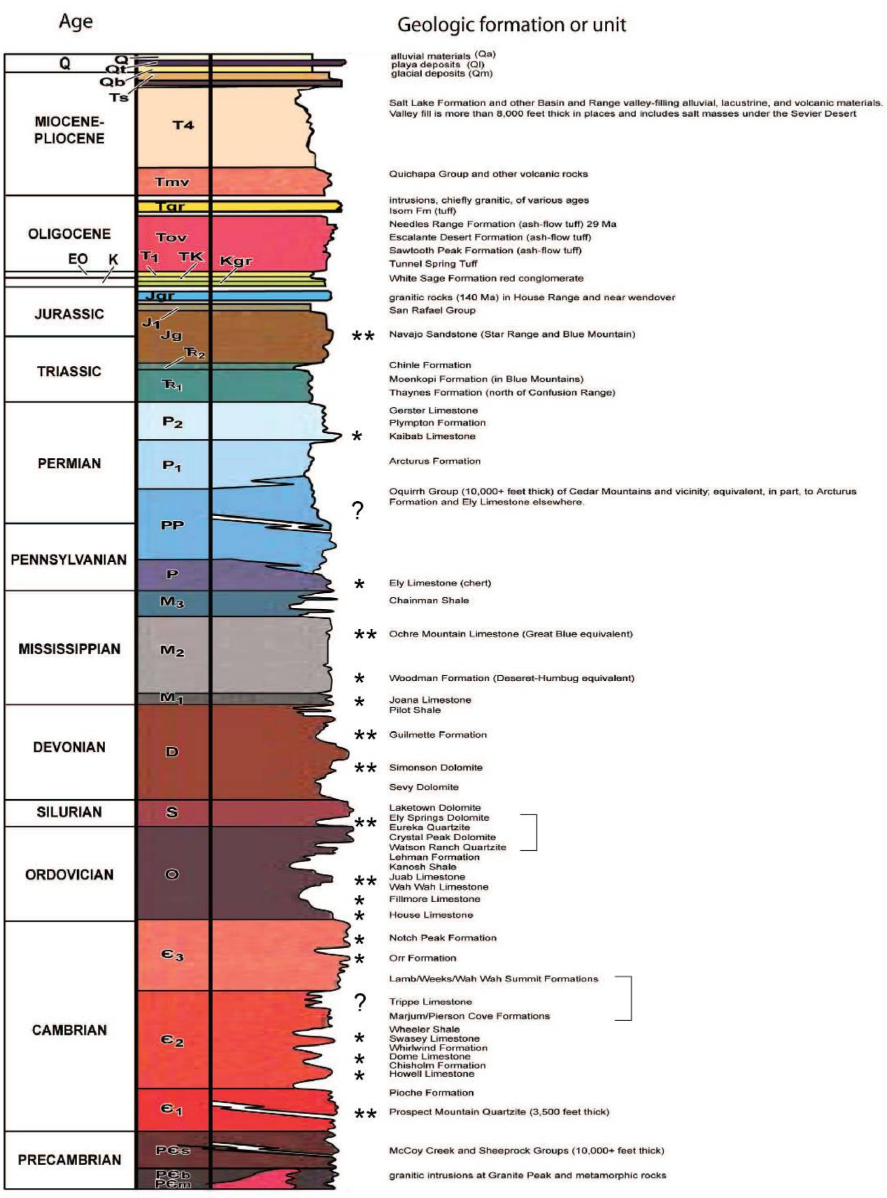

Figure 5. Generalized stratigraphy for west-central Utah (from Kirby and Hurlow, 2005, modified from Hintze et al., 2000). The total stratigraphic thickness is 10 km. Units known to have significant permeability have two asterisks; those with "probable" permeability have one asterisk.

Conclusions

Even with the high heat flow of the Great Basin (85 ± 10 mW/m^2), if thermal conduction is dominant, then temperatures of 200 ºC will typically be at more than 5 km depth in areas where bedrock extends to near the surface. Such depths will require an expensive well-field and will be economically challenging. If the exploration target is sub-horizontal, stratigraphic units known to have high permeability, exploring for these units beneath 2 – 3 km of unconsolidated sediments will ensure temperatures of at least 200 ºC below about 3 km depth. Horizontal drilling with multi-stage hydrofracturing is now a mature technology and appears to be ideal for developing these sub-horizontal reservoirs. Today, more than half of all oil and gas wells drilled in North America have horizontal legs to optimize reservoir productivity (Baker-Hughes, 2011). Similarly, another essential exploration technology to the petroleum industry, seismic reflection imaging, should also have direct application to developing these sedimentary-hosted geothermal reservoirs. Although the application of seismic imaging of near-vertical, range-bounding faults characteristic of hydrothermal systems has been problematic (e.g. Blackwell et al., 2007), the value of seismic imaging of the underlying basin structure in the Great Basin has been proven (Allmendinger, 1992; Wills et al., 2005).

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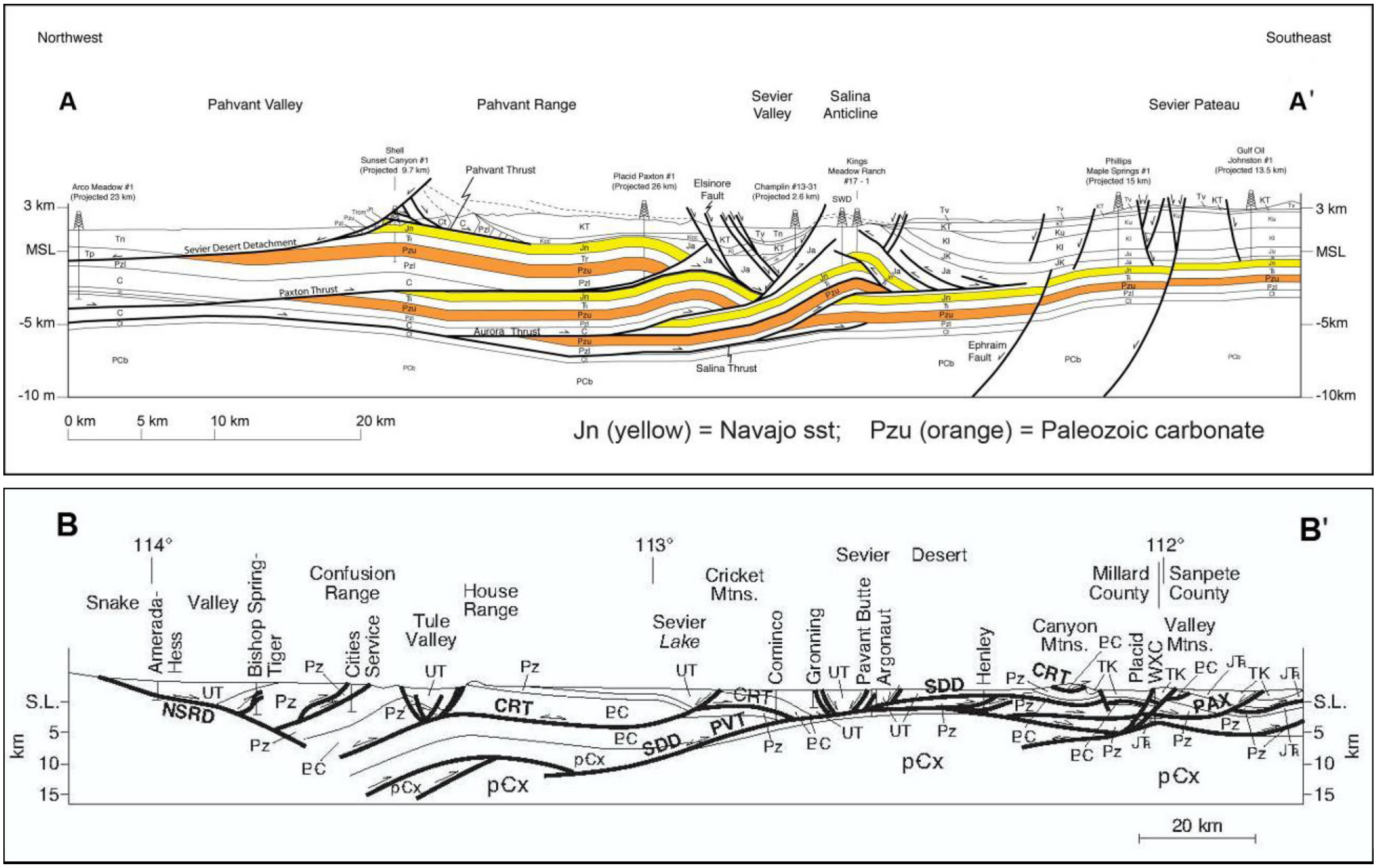

Figure 6. Interpretations of seismic profiles across the eastern Great Basin (locations on Figure 2). Profile A-A′ (Schelling et al., 2007) extends from relatively simple layer-cake stratigraphy of the Colorado Plateau in the southeast, through the Sevier thrust belt and into eastern Great Basin stratigraphy. Sedimentary units known to have characteristically high permeability are highlighted. The Pavant Butte Arco well has a similar location to the Arco Meadow #1 well at the northwest end of the section. Profile B-B′ is based on the interpretation of Allmendinger (1992; redrawn by Hintze and Davis, 2003), and highlights the Sevier thrust sheets and their possible reactivation as detachments.

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