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The Humboldt and Dixie Valley High-Temperature Geothermal Trends, Nevada, USA

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ABSTRACT

Two deep fluid-source high-temperature linear geothermal trends are identified in northern Nevada (Humboldt, Pershing and Churchill Counties) within the Basin and Range province, the Humboldt trend and the Dixie Valley trend. The attributes of these linear arrays are distinctive in that they discharge meteoric-source fluids, which have thermally equilibrated with temperatures within the crust at depths of 8 to 10 km, the lower region of the brittle crust. The process of meteoric water migrating to the depths indicated by fluid temperature and the collection structures necessary to accommodate broad scavenging of dispersed fracture-hosted crustal water are poorly understood. The large-scale tectonics controlling these two trends are also poorly understood. The economic potential for power generation from the entirety of the geothermal cells within these two trends is significant.

1. INTRODUCTION

The Basin and Range of Nevada hosts a large number of geothermal resources with a wide range of maximum temperatures (Garside and Schilling, 1979; Penfeld et al., 2010) as determined from both direct measurements and chemical geothermometry calculations. Geothermal fluid cycles in non-magmatic extensional terrains such as the Basin and Range can be separated into three components. The first is broad dispersed crustal fracture networks allowing meteoric water to flow downward through the crust. The second is a deep broad collector structure that can regionally scavenge water from crustal water-saturated fractures, such as an anticlinal structure or a horizontal to sub-horizontal fault plane. The third are dilation structures that penetrate downward, intersecting a collector structure. The dilation structures acts as host conduits of vertical geothermal fluid upflow. The maximum temperature potential for fluid at each geothermal resource site is constrained by the conductive temperature gradient of the crust and the depth from which the fluid ascends. The majority of the geothermal resources in the Basin and Range are of intermediate to moderate-temperature ($\leq$200°C). Two high-temperature ($\geq\approx$250°C) linear geothermal resource structural trends with multiple geothermal cells are identified as distinct and have significant economic potential. The Humboldt trend, approximately 80 km long, lies largely along a section of the Humboldt River in Humboldt and Pershing Counties. The Dixie Valley trend, approximately 75 km long, lies along the western edge of Dixie Valley, in Pershing and Churchill Counties (Figures 1 and 2). The higher fluid temperatures within these two trends reflect temperatures in the lower brittle crust, depths of 8 to 10 km. $^{3}He/^{4}He$ ratios (Kennedy and van Soest, 2005) point to a deep crustal structure associated with the Dixie Valley trend providing a pathway for mantel He to flow to the surface. Stable isotopic data suggest that the fluid ascending within the Dixie Valley trend is of meteoric origin. The duration of the meteoric water circulation through the total geothermal cycle has been reported to be 12,000 to 14,000 years (Nimz et al., 1999), based on the interpretation of ^{14}C data. Reassessment of the use of ^{14}C for dating crustal water should be considered because of ^{14}C generation within the crust.

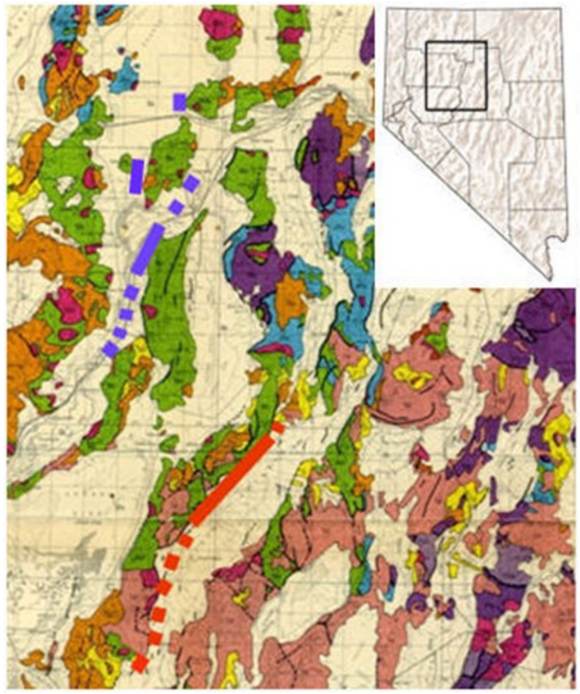

Figure 1. The locations of the high-temperature Humboldt linear geothermal trend (blue) and the Dixie Valley linear geothermal trend (red), northern Nevada. The base map is adapted from Stewart and Carlson, 1977. Inset identifies the portion of Nevada where these trend occur.

The metals mining industry has considered fluid movement within the crust as it relates to the formation of ore deposits. Three categories of ore deposits have been defined based on the temperature and depth of deposition. The deepest category is within and below the brittle-ductile boundary of the continental crust, identified as hypothermal by Lindgren (1933) and hypozonal by Goldfarb et al. (2001). These deep deposits are formed from pressure-pumped metamorphic fluid which can flow through shear-zone permeability within the ductile crust (Kolb, 2008). The intermediate category is from a depth of about 5 km downward to the brittle-ductile boundary, identified as mesothermal by Lindgren (1933) and mesozonal by Goldfarb et al. (2001). The shallowest category is from approximately 5 km depth to the surface is identified as epithermal by Lindgren (1933) and epizonal by Goldfarb et al. (2001). The mining industry uses these categories to define the depth and temperature for the formation of hydrothermal ore deposits within the crust. The geothermal industry, however, would be considering the depths, dynamics and tectonic structures that allows fluid movement within the crust that facilitate fluid flow in the geothermal cycle. The measured and projected maximum temperatures identified in the Humboldt and Dixie Valley geothermal trends would fall within the temperature-depth of the mesothermal/mesozonal category, with a regional crustal temperature at 10 km depth of between 245°C and 295°C, based on a regional temperature gradient of 25°C to 30°C per km and using an estimated 15°C average surface temperature. The measured conductive crustal temperature gradient from well 62-21, just east of the Dixie Valley production wells is 28.4°C/km (Blackwell et al, 2014).

The mining industry is able to view, sample and measure attributes of ore bodies formed at depth from surface exposures due to tectonic uplift and erosion. Chemical and isotopic analyses of fluid inclusions from vein minerals associated with some mesozonal ore bodies conclude that meteoric water was the original source of hydrothermal fluid in some mesozonal ore bodies formed at depths of 8 to 10 km (i.e. Burlinson, 2013; Kolb, 2008; Robb, 2012; Smith et al., 1991; Yardley et al., 2000). This is similar to the estimated depth for hydrothermal fluids in the Humboldt and Dixie Valley trends. Isotopic data from geothermal surface waters and production well water provide insights into the sources. Nimz et al. (1999) used isotopic data to demonstrate that the geothermal production fluid at Dixie Valley are of meteoric origin.

This paper will focus on the regional settings of the arrays of the geothermal cells that define the Humboldt and Dixie Valley trends, and on related fluid-flow issues. The paper is benefitted by data from many earlier individual studies which provide views that can be used to consider overall system resource models (e.g. Casteel et al., 2010; Kennedy et al., 2005; Moeck, 2014; Nimz et al., 1999; Person et al. 2008; Smith et al., 2011; Wannamaker, 2013). Two studies have synthesized large amounts of data in order to address the character and dynamics of thermal resources in the current production area of the Dixie Valley trend, Blackwell et al. (2014), addressing the geothermal resource and AltaRock Energy Inc. (2014), addressing its EGS potential. No comparable syntheses of data are available for resources in the Humboldt trend.

2. THE HUMBOLDT AND DIXIE VALLEY TRENDS

Figures 1, 2 and 3 identify the Humboldt and Dixie Valley trends of high-temperature geothermal systems. Both the Humboldt and Dixie Valley trends are documented as having high-temperature fluids comparable to temperatures in the lower part of the brittle crust, such as data from well 44-28 at Rye Patch (Michels, 2002) and for well 36-14 located southwest of the production area in Dixie Valley (Blackwell et al., 2014).

Both of these high-temperature geothermal trends host very few currently active hot springs. Many cell locations, however, are visually identifiable at the surface by recently active silicic sinter hot spring deposits, by fumaroles and by the low-pH alteration of soils and rock caused by chemical reactions associated with gasses and vapor escaping from subsurface boiling of geothermal water (Figures 4 through 12). Some of these alteration locations stand out while others are somewhat subtle. Additional geothermal cells are likely present along both of these trends with unrecognized subtle or no surface indications. At a few locations, such as Blue Mountain, Humboldt House, Rye Patch and at fumaroles southwest of the Dixie Valley power plant production area (Figures 5, 8 and 11) and recent silica sinter hot spring deposits no longer issue water, the result of a drop in the water table or structural uplift.

The Humboldt high-temperature geothermal resource trend is described here as extending from Blue Mountain south through Humboldt House, Rye Patch, and Colado at the southern end (Figure 2), a distance of approximately 80 km.

At Blue Mountain, he surface signatures of underlying active geothermal cell consist of pronounced low-pH mineral alteration and hot spring-deposited silicic sinter (Figure 4). The alteration is the result of chemical reactions between condensed vapor containing sulfuric acid discharging from subsurface boiling of geothermal brine, chemically reacting with surrounding rock and soils. Mapping of the surface distribution of the current population of secondary minerals at Blue Mountain is mildly complicated in that the active alteration is overprinting supergene alteration of an eroding older epithermal event. The overprinting resulting in two separate populations of some secondary minerals. Most of the wells at Blue Mountain are relatively shallow, with temperatures slightly below or above 200°C. The geothermal fluid chemical geothermometer suggests a temperature of near 250°C at depth within the cell (Casteel et al., 2010; Faulds and Melosh, 2008).

At Humboldt House, the Humboldt House thermal anomaly covers an area in excess of 13 $km.^2$ extending from the Florida Canyon Mine westward to the Humboldt River (Presco Energy, 2014). Surface expressions of the underlying geothermal resource consists of silicic sinter hot springs deposits to the west of I-80 highway (Figures 6, 7 and 8), and elevated temperature in shallow groundwater monitoring wells at the Florida Canyon Mine, east of I-80 highway. The hot spring deposits no longer discharge water due to the Holocene drop in the Lake Lahontan water level (Russell, 1885). One of the hot spring sinter sites (Figure 7) has active fumarole discharge, including deposition of native sulfur. No deep resource fluid chemistry is available for this area.

At Rye Patch, the geothermal area lies just to the south of the Humboldt House area (Figure 2). The history of exploration and development of this area has been covered in Blackwell and Waibel (2002) and Waibel et al. (2003). The most direct evidence for the deep high temperature fluid comes from the chemical analysis of water from the Rye Patch well 44-24, showing a chemical geothermometer of 274°C (525°F) and with a silica content of 510 ppm (Michaels, 2002). Surface evidence of an underlying geothermal resource is sparse here. Minor scattered silica sinter deposits are observed in small erosion gullies (Figure 9).

At Colado, on the southern end of the Humboldt trend is the Colado area. Limited exploration work has been carried out over this area (Sibbett and Bullett, 1980). A significant thermal anomaly was identified during a survey of livestock and temperature gradient wells. The surface evidence of the underlying resource is limited to low-pH alteration of alluvium caused by upward-flowing gasses and vapor from a subsurface boiling of geothermal brine..

2.1 Dixie Valley Trend

The Dixie Valley linear trend of high-temperature geothermal cells extends southwestward from the geothermal production plant (PP) along the western edge of the valley to Eleven Mile Canyon (Figure 2), a distance of about 75 km. Measured temperatures in Dixie Valley well 36-14 is 285°C (Figure 3, white "x") and temperatures within the wells supplying the Dixie Valley power plant is 250°C (Blackwell et al., 2014). Other geothermal cells along this trend are identified by fumaroles (Figures 10, 11 and 12) with alteration mineralogy associated with reactions between surface and near-surface valley fill and the venting gasses and steam condensate from subsurface boiling. Hot Springs are rare in Dixie Valley, though uplifted and incised silicic sinter deposits are observed along the range-front fault (Figure 10). Dixie Meadows Hot Spring is located in the general vicinity of the large Hare Canyon thermal site. Sou and Hyder Hot Springs are located north of the power plant, and may be cooler peripheral outliers to this trend. Figure 3 shows details of the thermal areas between the power plant and Hare Canyon in Dixie Valley.

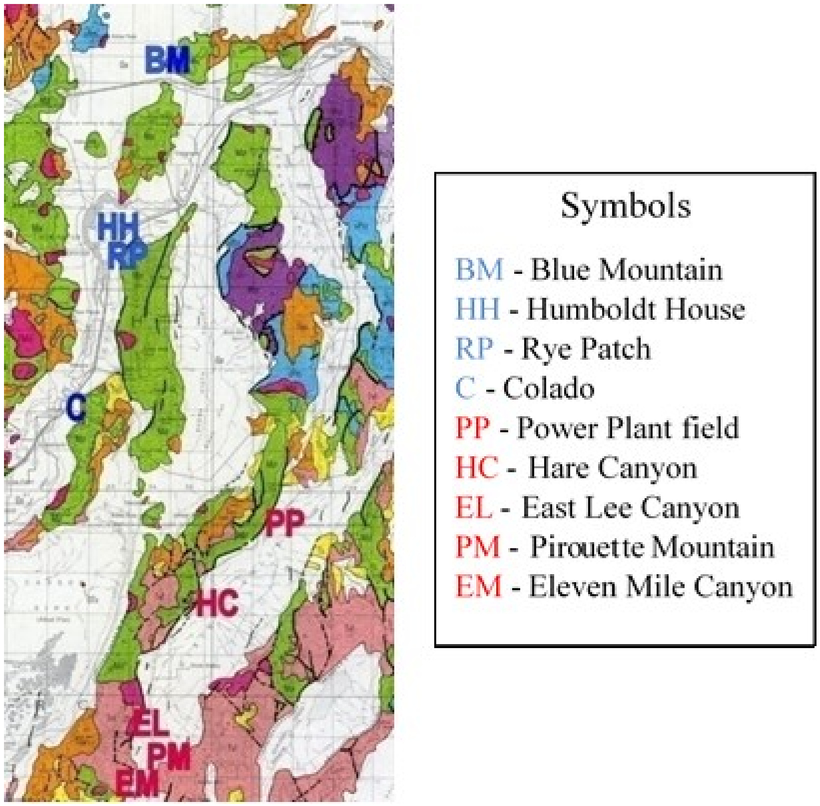

Figure 2. The known geothermal resource locations along the Humboldt (blue) trend and the Dixie Valley (red) trend. The base map is a portion of Stewart and Carlson, 1977. See Figure 3 for more detail of the distribution of geothermal resource locations lying between the power plant (PP) and Hare Canyon(HC) in Dixie Valley.

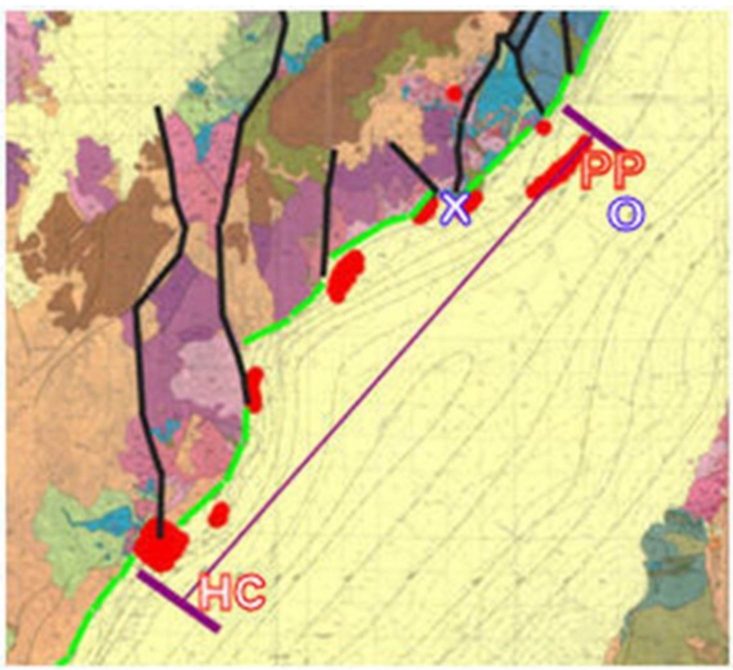

Figure 3. The central section of the Dixie Valley deep-sourced geothermal fluid trend (bracketed by dark magenta lines), is approximately 26 km in length from the power plant production cells (PP) southwest to the extensive Hare Canyon fumarole area (HC). Major north-striking Miocene normal faults (black) cross the Stillwater Range, and the current normal range front faults (green) bounding Dixie Valley and the Stillwater Range. Red shows those areas with fumaroles, shallow temperature

anomalies, hot springs deposits and the power plant production area. The white "x" marks the location of well 36-14, the white "o" marks the location of well 62-12. The base map is adapted from Speed (1976).

Figure 4. Blue Mountain, the northern limit of the Humboldt trend. The reddish areas are the result of currently active low pH alteration from gasses discharging from subsurface boiling of geothermal fluid. Partially obscured in the draw, left of center, are incised hot spring sinter deposits.

Figure 5. Surface alteration is the result of currently active chemical reactions with gasses ascending from subsurface boiling of geothermal fluid, part of the Humboldt trend.

Figure 6. Humboldt House, panorama looking west toward the Humboldt River, area of hot spring sinter deposits (Figure 8), now dry due to a drop in the water table, with one active fumarole (figure 8).

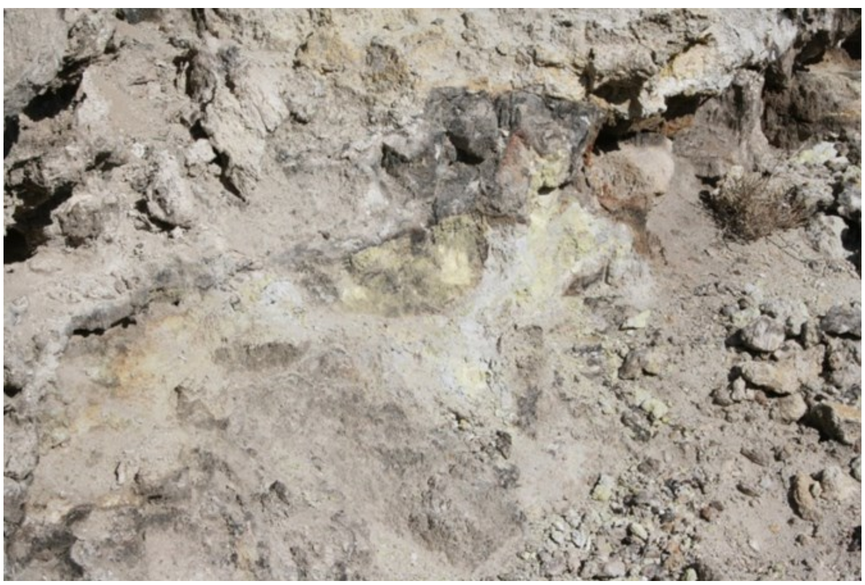

Figure 7. Humboldt House, older hot spring deposit, sinter overprinted with gypsum, no longer discharging hot water due to a drop in the water table. The site currently emits fumarole gas.

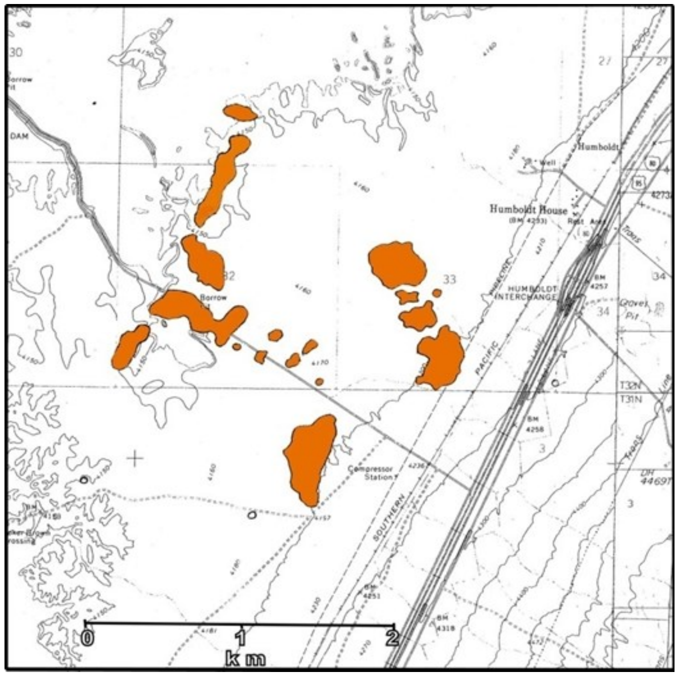

Figure 8. Map showing the distribution of hot spring sinter deposits and silicified lake sediments at Humboldt House west of the freeway, overlain on a U.S.G.S. topographic map. See Figure 6 for a panoramic view.

Figure 9. Silicic sinter (lower right) in eroding lake sediments in the vicinity of the Rye Patch well field.

Figure 10. Dixie Valley fumaroles and low-pH alteration overprinting hot spring sinter deposits after structural uplift, located southwest of the Dixie Valley power plant production area.

Figure 11. Dixie Valley, showing surface fumaroles in the foreground, well away from range-front faulting, and the extensive fumarole alteration at Hare Canyon, approximately 26 km SSW of the power plant.

Figure 12. Dixie Valley fumaroles located in the vicinity of East Lee Canyon.

3. ISOTOPES

Isotope ratios of δD, $\delta^{13}C$, $\delta^{18}O$, and $^3He/^4He$ and ^{14}C isotope data have been reported for a limited number of the thermal and non-thermal water sources within the two trends. Data from the Dixie Valley trend have been published for production field fluid (Goff, et al., 1998; Nimz et al., 1999; Kennedy and van Soest, 2005). Limited stable isotope data are also available for fluid from Blue Mountain (French, 2016) in the Humboldt trend. The δD and $\delta^{18}O$ values provided by Goff et al. (1998) for the Dixie Valley production fluid are -130 ‰ (δD) and -14 ‰($\delta^{18}O$) (Figure 13). The $\delta^{18}O$ values for Blue Mountain geothermal fluid ranges from -5.3 to -13.9 ‰ (French, 2016). The $\delta^{18}O$ and δD values of the geothermal brine from the Dixie Valley production field are shown as a red dot in Figure 15. Nimz et al. (1999) concluded that the geothermal brine is derived from meteoric water precipitated during cooler climactic conditions.

Kennedy and van Soest (2005) published $^3He/^4He$ ratios for the production fluids of Dixie Valley. They concluded that non-magmatic, mantle-derived helium is migrating into the brittle crust accommodated by shear zones acting as channels through the ductile crust. They also observed a similarly elevated $^3He/^4He$ ratio in fluid from the McGinnis Hills geothermal resource, east of the Dixie Valley area. No reported $^3He/^4He$ data are available for geothermal fluids from the Humboldt trend.

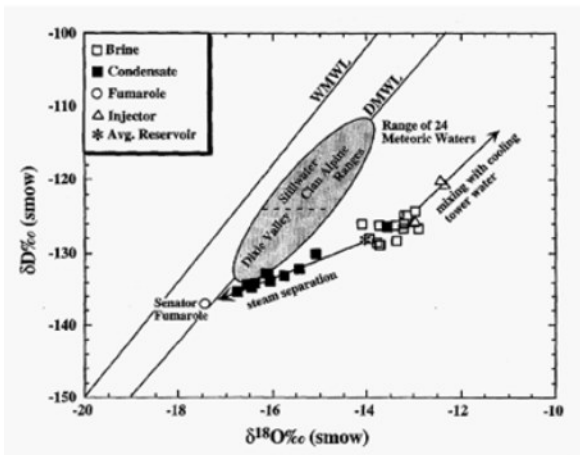

Figure 13. Goff et al. (1998) plot of δD and δ18O isotopic ratios for thermal and non-thermal waters in the Dixie Valley area. DMWL represents the Dixie Valley meteoric water line. Dixie Valley power plant production fluid values are shown as open squares (brine).

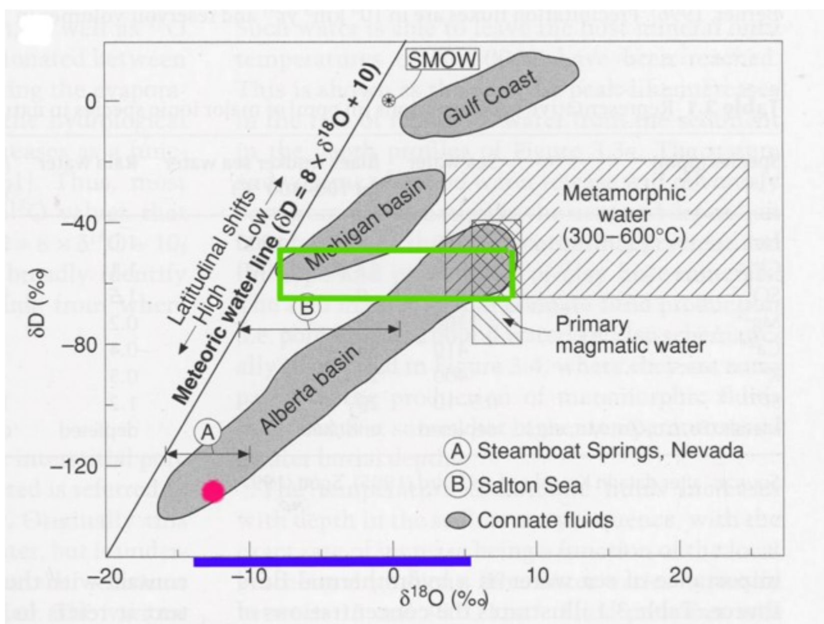

Figure 14. δD and δ18O isotopic ratios (adapted from figure 3.1 b of Robb, 2012). The plot Identifies a range of ratios for primary magmatic and metamorphic water (hatched areas), and water from the Alberta Basin, Michigan Basin and Gulf Coast (shaded areas). The red dot identifies the δD and δ18O data of Dixie Valley stable isotope data from Goff, et al. (199). The blue bar identifies the range of δ18O values for Blue Mountain reported by French (2016). The block outlined in green identifies a range of ratios for progressively rock-equilibrated meteoric waters from Menzies et al. (2014).

Figure 14 shows a plot of δD and $\delta^{18}O$ isotopic ratios from Robb (2012). The shaded areas represent isotopic ratios for connate waters from three sedimentary basins. Isotopic ratios for three geothermal fluids are shown, Steamboat Springs, Salton Sea, and Dixie Valley production fluid (Nimz et al., 1999) and $\delta^{18}O$ values for Blue Mountain (French, 2016). The hatched blocks identifying metamorphic and primary magmatic waters are largely derived from ore body sources. Data from Menzies et al. (2014) identifies an interesting block of ratios for progressively rock-equilibrated meteoric waters (green outlined rectangle). The interpretation of isotope ratios as water typing might not always be able to provide unique solutions.

Based on ^{14}C measurements a recharge age of 12,000 to 14,000 years has been proposed for geothermal water supplying the Dixie Valley power plant (Nimz et al., 1999). They suggest that meteoric water cycles down to a depth of 3,000 m, where it transitions into geothermal brine. This implies a meteoric water cycle flow-rate of ≈25 cm/yr. Production formation temperatures are around 250°C for wells supplying the Dixie Valley power plant. If 3,000 m were the depth of the cycling, the regional temperature gradient would be around 80°C/km, with a local anomalous shallow heat source. A measured temperature gradient from well 62-21, just east of the Dixie Valley production wells, of 28.4°C/km would suggest a crustal depth of water source to be in excess of 8 km, and for the measured temperature of 285°C in well 36-14 (Blackwell et al., 2014) suggests a crustal depth of 9.5 km. The proposed ^{14}C dates would require an average flow rate of 67 cm/yr for meteoric water descend to a 9.5 km depth (assuming no thermal energy loss during ascent). The application of ^{14}C dating for crustal water could be problematic. A neutron flux exists within the crust (Feige and Kastner, 1968; Zito, et al., 1980; Sramek et al., 2016) is capable of generating ^{14}C independent of the atmospheric-sourced ^{14}C, rendering the use of ^{14}C as a crustal water dating tool suspect.

4. CRUST

Heimgartner et al. (2006) used seismic refraction analysis to determine variations in crustal thickness across the Basin and Range (Figure 15). The crustal thickness along the northern end of the Humboldt trend at Blue Mountain is about 36 km, thinning to 30 km at Humboldt House and southward. The average crustal thickness along the Dixie Valley trend is about 30 km. Based on estimated regional temperature gradients of 25 to 30°C/km, the base of a 30 km thick crust would be at 750 to 900°C. The conductive temperature gradient measured in the Dixie Valley well 62-21 (Figure 3), just east of production wells, is 28.4°C/km, projecting a temperature of 850°C at the base of the crust. They conclude that there is a correlation between crustal thickness and heat flow. However they observed no relationship between crustal thickness and geothermal resource temperatures.

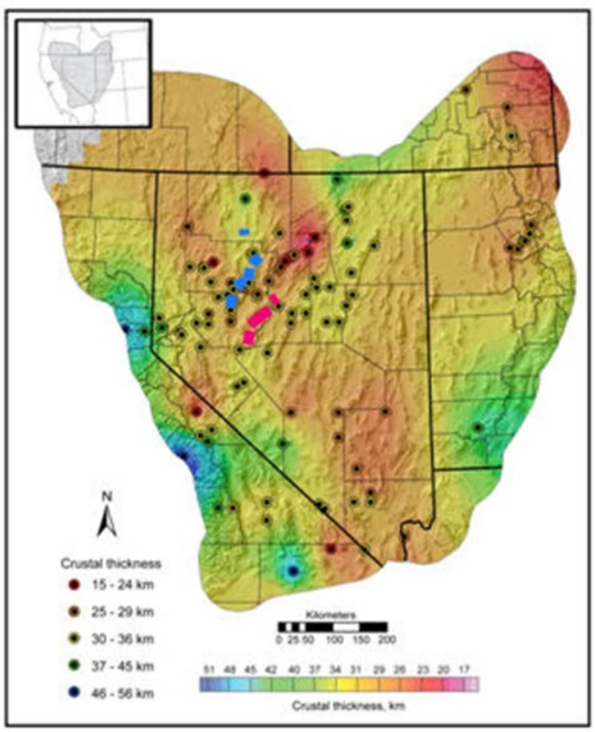

Figure 15. Crustal thickness map of the Great Basin from Heimgartner et al. (2006). Shown are the Humboldt linear geothermal trend (blue) and the Dixie Valley linear geothermal trend (red).

A regional magnetotelluric (MT) transect survey has been carried out, extending from east of Dixie Valley westward through the Trinity Range (Wannamaker, 2013). The transect (Figure 16) crosses the northern portion of the Dixie Valley trend (DV) and westward across the very southern end of the Humboldt trend (80). The section shows a break in the higher electrical resistive crust in the Dixie Valley area and a reduction of the electrical resistivity of the crust in the area of the southern terminus of the Humboldt trend. A broad low electrical resistivity horizon is shown to extend from the eastern portion of the Trinity Range eastward to Dixie Valley, a distance of about 70 km. This low electrically resistive horizon has been interpreted as magmatic underplating, with magmatic fluid leakage up through Dixie Valley (Wannamaker, 2013).

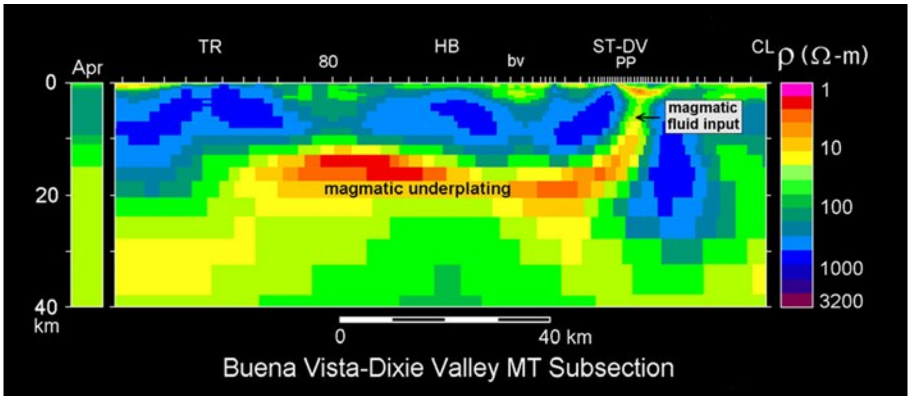

Figure 16. MT cross-section from the Clan Alpine Range (R) west through Dixie Valley (DV), Stillwater Range (ST) Buena Vista Valley (bv), Humboldt Range (HB) and I-80 (80) near the town of Lovelock, the southern terminus of the Humboldt trend, and the Trinity Range (TR), from Wannamaker, 2013.

Temperature gradient data are available from many wells located in the Dixie Valley region. The temperature measurements have been made in wells drilled as part of geothermal exploration programs, and are thus biased in their locations and distribution. The majority of the measurements are from shallow gradient wells, exploration test wells, production wells and injection wells. These are almost all in areas with temperatures affected by hydrothermal fluid flow and thus do not show the regional conductive temperature profile. Sunedco drilled one well, 62-21, to the east of the production wells (Figure 3), in order to test for possible geothermal fluid flow within the lower-angle antithetic faults to the east of the western graben faults associated with production wells (Blackwell et al., 2014). The well was drilled to a depth of approximately 3,300 m and showed a conductive gradient with a bottom-hole temperature of 185°C. No fluid with temperature above regional gradient were encountered. The conductive gradient as measured from the base of the valley-filling sediments (2000m, 148°C) to bottom of the hole is 28.4°C/km. This gradient is consistent with the regional average 25°C to 30°C conductive gradient for this portion of the Basin and Range. This temperature gradient does not support input from local magmatic fluid or of a broad crustal magma layer as hypothesized in the MT interpretation (Wannamaker, 2013).

5. FLUID SOURCE AND MIGRATION

A geologically meaningful hypothesis for fluid movement in a hydrothermal system that includes both water supply source and upflow discharge must take into account multiple components, including heat flow, temperature gradients, broad crustal tectonic conditions, site-specific changes in stress regimes, rock-water-gas chemical reactions in the ascending fluid, isotope equilibrations with lithologies, and variations in rock mechanic properties. It is easy to make a list of components. The efforts to construct an inclusive hypothesis for the entirety of the hydrothermal cycle becomes very interestingly challenging as conclusions of some components of the list contradict conclusions of other components of the list.

Fluid recharge hypotheses are often variations on simplistic topography-driven flow, rain in the range and up-flow along a normal fault (e.g. Figures 17 and 18). To date the subject is, at best, still poorly understood. Problems with this simplistic approach are threefold, thermal observations within the Stillwater Range, vertical permeability within the formations, and required depth of meteoric water descent. The hypothesis that the Stillwater Range is a location for substantive meteoric water down-flow has yet to be empirically demonstrated. Down-flow of meteoric water in the Stillwater Range of the sustained volume to support the adjacent high-temperature geothermal cells would result in depressed temperatures within the range block. However, limited data show the range has elevated rather than lower temperature. An area of active fumaroles and incised hot spring sinter deposits approximately 6 km southwest of the Dixie Valley power plant (Figure 10) show the geothermal fluid that fed the hot spring ascended through dilated fractures within the range block. Adits in the same area show the temperature in the range block to be in excess of 35°C, with the highest temperature at the back of the adit, approximately 40 m back into the block. Four km into the range near the Bolivia site, warm water flows from a shallow exploration well (Blackwell et al. 2014). These observations do not support the range as the source for large volumes of meteoric recharge water flowing downward.

Any hypothetical model of meteoric water recharge in the Stillwater Range that would supply fluid to the geothermal cells would also have to address vertical decent velocities. The formations within the Stillwater Range are not isotropic. Vertical permeability within the Stillwater Range is constrained by a labyrinth of fractures of variable size and density, impeded by low permeability bentonite-rich silicic tuff layers, sub-horizontal thrust plane aquitards, and low permeability Triassic shales and phyllites. Invoking high-volume downward fluid flow is not supported by visual observations of fault zone permeability at outcrops.

Some models of geothermal fluid flow are designed to fit empirical data from geothermal exploration and production, while others may be conceptual hypotheses. Figure 16 (Smith et al., 2011) relies on data from the Dixie Valley production area to show the up-flow must ascend from around 10 km depth in order to match actual well and fluid temperature measurements. The blue arrows are placed to acknowledge that meteoric water has to descend to those depths rather than identifying any actual proposed pathways.

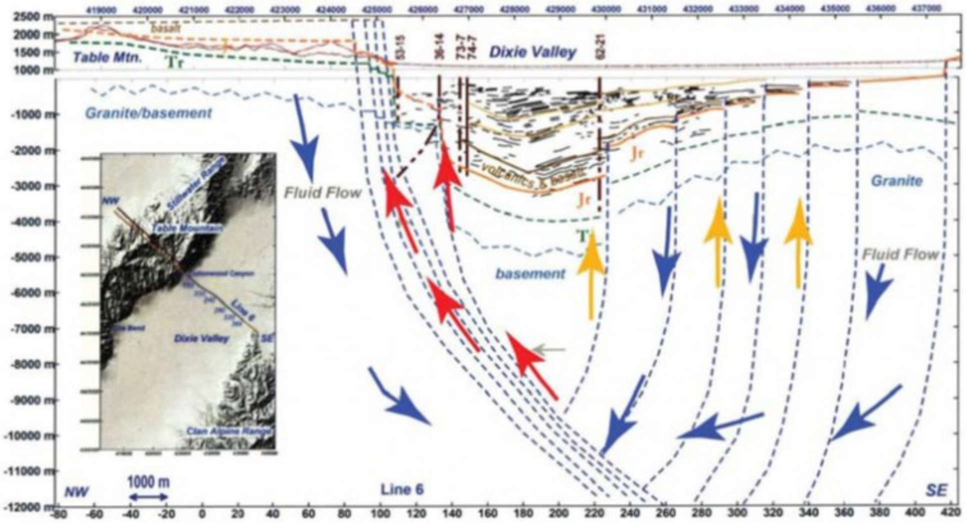

Figure 17. Smith et al. (2011) showing a generalized modeling of meteoric fluid flow supporting a geothermal resource; cold water flowing downward in both the Stillwater Range and Dixie Valley (blue arrows), and heated upflow water (red arrows) along normal faults. This diagram shows meteoric water descending to a depth of 8 to 10 km, the depth required for the water to reach temperatures observed within the wells.

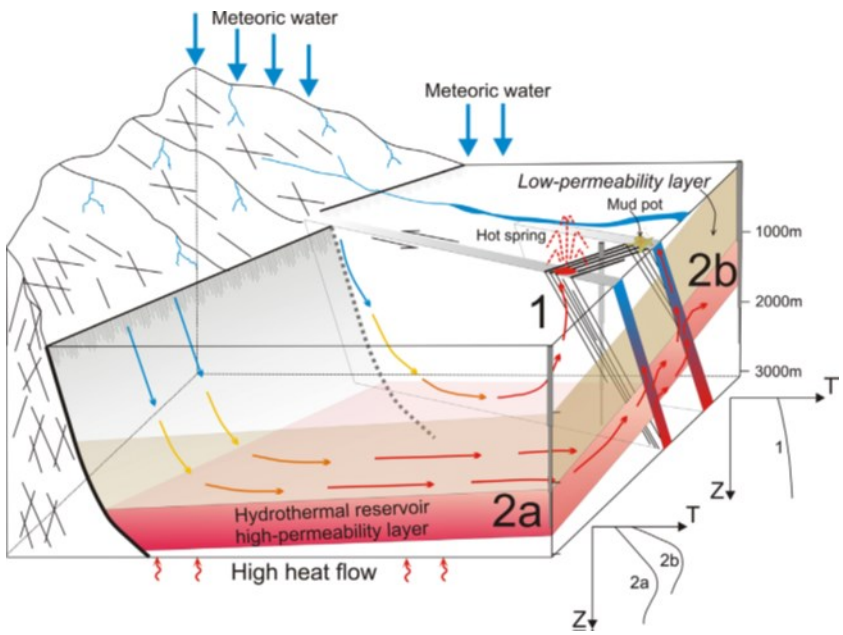

Figure 18. Moeck, 2014 An hypothesis for a Basin and Range geothermal model, with an expansive tabular horizontal "reservoir" at 3 km depth in the valley, with hydrothermal fluid leakage to the surface.

Moeck (2014) presents an hypothesis for Basin and Range geothermal resources (Figure 18) based on the proposal that hydrothermal resources are a variation on oil and gas trap reservoirs. This hypothesis for Basin and Range geothermal systems has the cold recharge water flowing down the range-front fault to a depth of about 3 km, where it recharges a broad horizontal tabular high-permeability reservoir capped by a low-permeability layer. The reservoir is heated by high heat flow from below. Following the premise of this hypothesis, a 200°C reservoir with the top at 2.5 km, and an estimated average surface temperature of 15°C would show a broad area with a conductive temperature gradient of 72°C/km. A resource such as the 250°C production area supplying the Dixie Valley power plant should show a conductive temperature gradient of 94°C over the entirety of the broad horizontal reservoir. The regional crustal conductive temperature gradient is 25 to 30°C/km, producing a temperature at 3 km of 90 to 105°C, assuming an average surface temperature of 15°C. The oil and gas reservoir hypothesis does not survive the integration of the large body of available Basin and Range data.

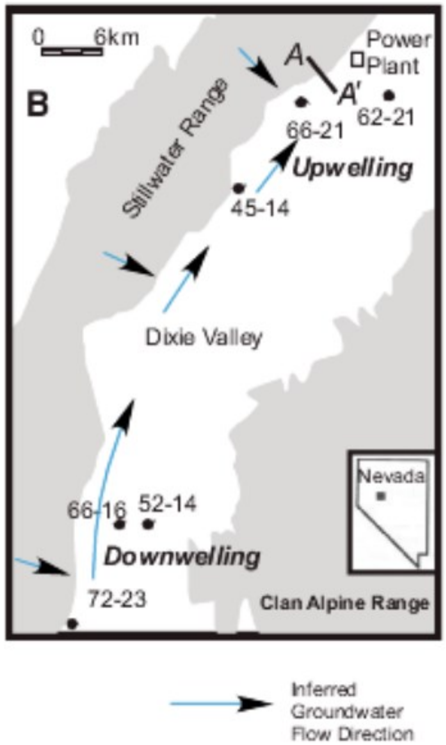

Figure 19. Person et al.(2008) presents an hypothesis for meteoric water recharge for the Dixie Valley power plant wells. The proposed recharge source is juxtaposed to the Eleven Mile Canyon, Pirouette Mtn. and East Lee Canyon geothermal cells (Figure 2).

Person et al. (2008) presents an hypothesis for descending meteoric recharge water in the area juxtaposed tothe active Eleven Mile Canyon, Pirouette Mtn. and East Lee Canyon geothermal cells (Figures 2, 12, 19 and 20) at the southern end of the Dixie Valley trend, supplying geothermal water to the producing cells for the power plant at the northern end of the of the Dixie Valley trend, a distance of about 75 km. The hypothesis cites temperature gradients from holes in the area of "downwelling" (Figure 19). The cited temperature gradient profiles show elevated shallow temperatures, the lateral outflow from nearby geothermal cells (Williams and Blackwell, 2012). The temperature/depth plots show that the proposed meteoric water starting the descend with very high shallow temperature gradients, reaching temperatures of between 60 and 80°C by a depth of 400 to 600m and then cooling slightly with increased depth. The hypothetical "downwelling" site is proposed to supply recharge water to the power plant geothermal cells to the northeast, with the recharge water passing through the areas of other geothermal cells (Figure 3).

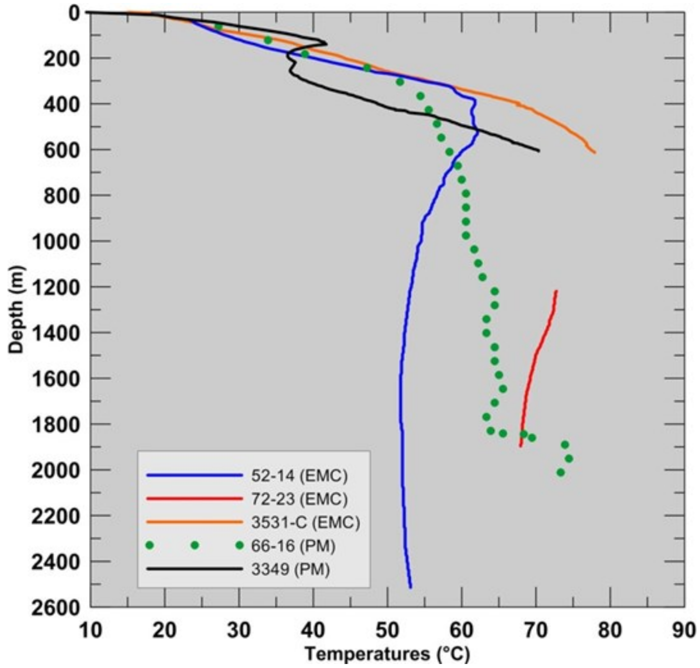

Figure 20. Williams and Blackwell 2012, showing the temperature gradient profiles ofgeothermal exploration wells drilled by the Hunt Energy Corp. starting in the late 1970's. These profiles include three of the wells from the southern end of Dixie Valley cited by Person et al., 2008 (Figure 19) as demonstrating cold meteoric water recharge for the producing wells at the northern end of the Dixie Valley trend.

5.1 Deep Crustal Fracture Permeability

Meteoric-source water movement at 5 to 10 km within the crust is poorly understood. Direct sources for fracture permeability deeper within the crust are limited to a few deep crustal drilling programs such as the wells drilled at the Kola site in Russia the KTB site in Germany (Morrow et al., 1994; Kontny et al., 1997). Fracture permeability and water are reported to have been encountered deep within the Kola well. However difficulties exist in attempting to characterize in-situ fracture permeability in recovered core from the deep holes. As the core sections are retrieved changes in compression and stress may result in fractures forming within the core samples as they are brought to the surface, leading to unreliable fracture permeability measurements (Morrow and Lockner, 1997). Fracture size and density may change with depth as lithostatic load is increased. Studies of fracture variations within granitic and gneissic rock (Stober, 1996) suggests that fracture permeability within granitic rock does not appear to vary with depth, whereas it does with gneissic rock.

Robb (2012) summarized data on deep crustal permeability in fractures and shear-zones in areas of uplifted hypozonal and mesozonal hydrothermal ore bodies. Deep crustal ore bodies and deep crustal wells provide certainty that water is present at these depths and is flowing through permeable structures, but they provide no functional constraints regarding geometry, density and permeability of fractures within crustal rock down to 10 km which might host meteoric water recharge to deep geothermal resources, such as those in the Basin and Range. The number of rock mechanic and stress regime variables affecting fracture permeability within the crust in the vicinity of the brittle-ductile boundary are too poorly constrained to produce a reliable hypotheses. Stober and Bucher (2014) point out that it is easy to construct a numerical model, but very difficult to generate anything that is geologically meaningful.

The majority of the geothermal resources within the Basin and Range are readily identified systems of circulating meteoric water. Precipitation supports a broad disbursed regional downward percolation of the meteoric water. The downward velocity of this water varies greatly with the range of physical lithologic properties of the underlying formations and the decreasing fracture permeability with depth. The downward flow is slow enough that it probably does not significantly suppress the regional crustal thermal gradient (Blackwell, personal communication). This downward flow continues through broad dispersed non-isotropic crustal fractures until it reaches a point of extremely low flow rates, near-zero hydraulic pressure gradient. To facilitate water migration from broadly disbursed water-saturated fractures to a localized geothermal resource two structural components are needed. The first component would be some form of deep broad collector structure. This might be an anticlinal structure, or a horizontal to sub-horizontal boundary. The low-angle boundary could be a low-angle orogenic thrust detachment, low-angel thrust fault planes where the upper plate has undergone reverse extension movement. The second component would be a dilation structure that penetrates downward, intersecting a collector structure. The dilation structure then acts as host conduit of vertical geothermal fluid upflow. The maximum temperature of ascending geothermal fluid is defined by the depth of the intersect of the two structures and the crustal conductive temperature gradient. The two high-temperature geothermal trends are unusual in that the resource water ascends from 8 to 10 km and thus have higher temperatures than do most other non-magmatic geothermal resources in the Basin and Range.

6. CONCLUSION

Two distinct linear geothermal trends characterized by multiple high-temperature geothermal cells are identified in northern central Nevada, the Humboldt trend (Humboldt and Pershing Counties), and the Dixie Valley trend (Pershing and Churchill Counties). These two Basin and Range trends are distinguished by the initial up-flow depth required to support the measured and estimated temperatures ($\geq$250°C) of the geothermal cells within these trends. These fluid temperatures coupled with the conductive thermal gradient for this region of the Basin and range are consistent with source depths of 8 to 10 km for these fluids. The up-flow and discharge processes of the geothermal cells within these geothermal trends are accommodated by deep high-angle structural dilation conduits that act as flow paths for deep hot water to ascend to the surface. The deep aquifer support systems supplying water to the geothermal cells within the structural trends are, at best, poorly understood. Water within the deep brittle crust is likely ubiquitous, with volume constrained by fracture size and density. Not well understood is the dynamics of meteoric water cycling to near the brittle-ductile crustal depth, and the deep collection structures that accommodates broad scavenging of dispersed fracture-hosted crustal water. When these collector structures are intersected by overlying localized dilation structures a vertical conduit can form, resulting in a geothermal cell. The maximum temperature of the resource is largely determined by the depth of the collector structure and the regional crustal conductive temperature gradient. The Basin and Range hosts an abundance of high-angle dilation structures. Most of them do not host geothermal cells. Only those structural dilation zones that intersect extensive fluid collection structures are likely to host geothermal cells.

The economic potential for power generation from the entirety of the geothermal cells within these two trends is significant. When fully developed the economies of Pershing, Humboldt and Churchill Counties would benefit greatly. Laying the scientific groundwork to support development of these two high-temperature geothermal trends would require coordinated teamwork.

6.1 Recommendations for Future Research

The Humboldt and Dixie Valley trends are exceptional in that they access crustal water from near the brittle-ductile boundary in the crust and that they host multiple individual geothermal cells along the length of each linear trend. The long-term economic value of the electrical generation capacity from high-temperature geothermal cells within these two trends is substantial, both from a base-load renewable energy contribution and as an economic stimulus to the State of Nevada.

To date there are only two studies addressing the character and dynamics of thermal resources in the current production area of the Dixie Valley trend, Blackwell et al. (2014), addressing the geothermal resources and AltaRock Energy Inc. (2014) addressing the EGS potential. There are no equivalent studies available for geothermal resources along the Humboldt trend. Coordinating research that leads to an understanding of the crustal structures and fluid flow dynamics throughout the entirety of these two high-temperature geothermal resource trends will result in long-term, large-scale financial benefit to the local, state and regional economies. The program should include:

Detailed surface mapping of all thermal and thermal-related features along both trends.

Expanded heat flow and temperature gradient data characterizing changes along and between the two high-temperature geothermal trends.

Seismic 3-D analyses identifying mid-crustal and deep-crustal characteristics.

Seismic 3-D surveys addressing details of shallow and mid-crustal structures.

Seismic monitoring, looking for deeper seismicity above and below the brittle-ductile boundary at and near the linear high-temperature geothermal trends.

Magnetic and electrical resistivity (including MT) studies addressing details of structure.

Fluid chemistry analyses for chemical and isotopic signatures of the various geothermal cells along the two high-temperature geothermal trends.

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